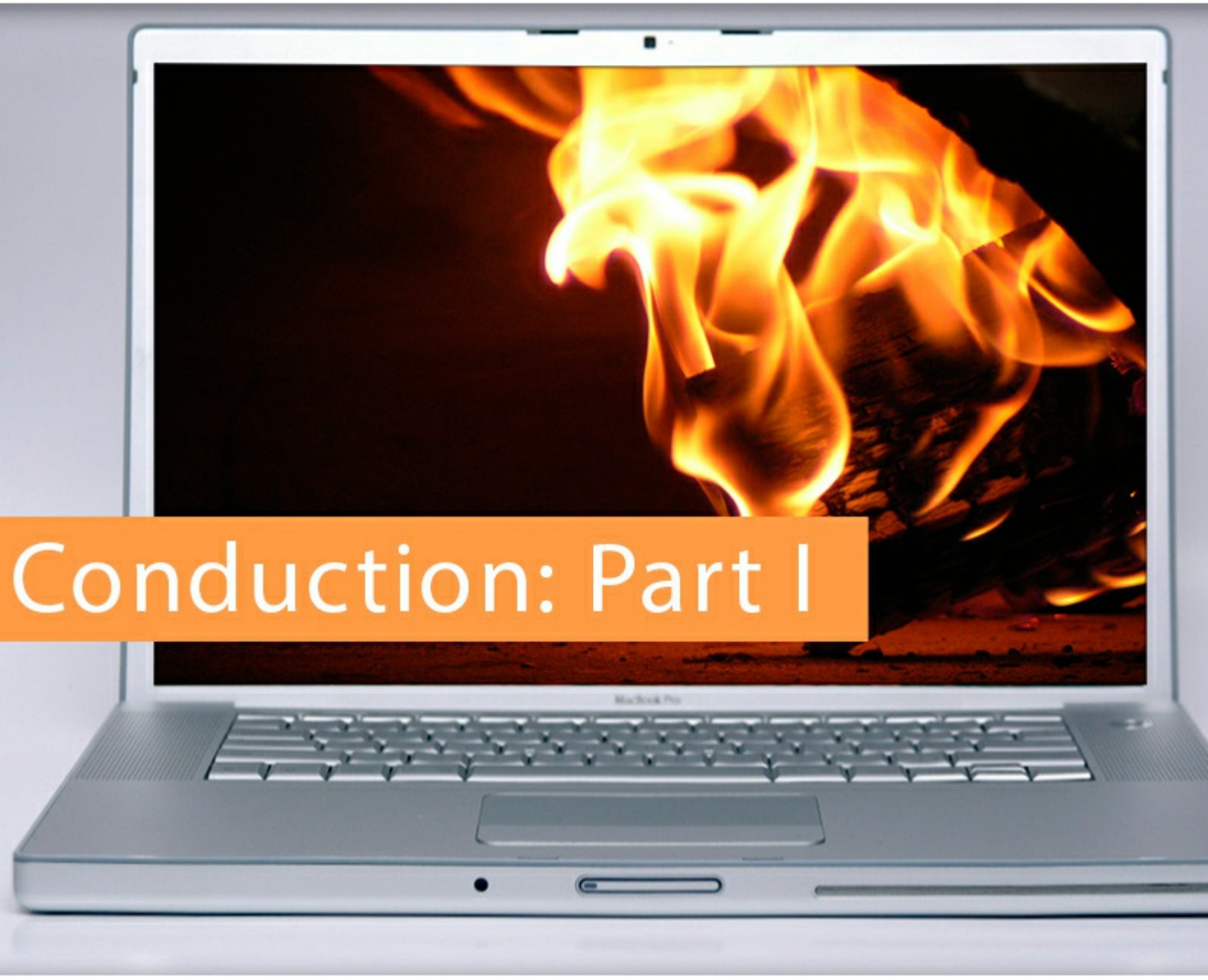

Software Solutions to Problems on Heat Transfer

Conduction: Part I

Dr. M. Thirumaleshwar

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Dr. M. Thirumaleshwar

Software Solutions to Problems on Heat Transfer

Conduction: Part I

Fourier's Law, 1D steady conduction with no heatgeneration

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Software Solutions to Problems on Heat Transfer
Conduction: Part I
Fourier's Law, 1D steady conduction with no heat generation
1st edition
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Software Solutions to Problems on Heat Transfer

Vol. I: CONDUCTION

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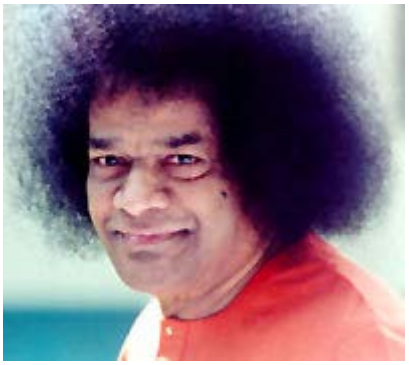
Dedication

This work is lovingly dedicated at the lotus feet of

Bhagavan Sri Sathya Sai Baba



"God gave you the time, space, cause, material, idea, skill, chance, and fortune.

Why should you feel that you are the doer?

Man falsely imagines "I am doing this", "I am planning this".
It is the supreme, all pervasive consciousness that motivates,
unfolds the skills and operates the intellect."

…Bhagavan Sri Sathya Sai Baba

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Preface

Heat Transfer is an important subject in engineering studies since it has applications in diverse fields of engineering, such as: Mechanical, Metallurgical, Electrical, Civil, Chemical, Nuclear, Aerospace, Cryogenic engineering etc. As such, it is included as a 'core subject' in the engineering syllabi of many Universities.

Heat transfer is a problem – intensive subject. It is better learnt by solving a large number of problems. But, most of the Text books give attention to the descriptions of theoretical aspects and derivations and the number of problems solved is minimum, primarily because of restrictions on the size of the book. Instructors have to cover the prescribed syllabus within the time allotted and, therefore, do not find sufficient time to solve all types of problems in the class. Therefore, a book devoted to solving problems in heat transfer would be useful to students as well as teachers.

This book contains solutions to problems in the area of Heat Transfer, as per the syllabus of B.E. and M.Tech. courses in Visweswaraya Technological University, Karnataka, India (and other Universities as well).

Problems are solved using four popular software, viz. **"Mathcad"**, **"Engineering Equation Solver (EES)"** and **"Finite Element Heat Transfer (FEHT)"**, **and MS EXCEL spreadsheet**. Comments are included generously in the codes so that the logic behind the solutions is clear. An introductory chapter gives a brief overview of the softwares used.

Use of computer software helps in solving the problems fast and accurately. More importantly, parametric analysis (what – if analysis) and graphical visualization is done to make an in–depth analysis of the problem. Once a particular type of problem is solved, solving similar problems later becomes extremely easy. In addition, one can plot the data, curve fit, write functions for various properties or calculations and re-use them. These possibilities create interest, curiosity and wonder in the minds of students and enthuse them to know more and work more.

This book is an out-growth of the teaching notes of the author, who has taught this subject over the past many years, to Engineering students. As such, the material presented here is class tested and continuously improved as a result of the feed-back received from the students.

S.I. Units are used throughout this book. Wide variety of worked examples presented in the book should be useful for those appearing for University, AMIE and Engineering Services examinations.

It is suggested that this particular book may be used in conjunction with any of the standard Text Books on Heat Transfer (including the Text Book "Fundamentals of Heat and Mass Transfer" written by author, which is adopted as a Text Book in Visweswaraya Technological University (VTU), Karnataka, India).

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The topics included cover the syllabi of Undergraduate and Post Graduate courses in Heat Transfer, and should therefore be useful to students in UG and PG courses in Engineering and the teachers who teach this subject.

The book should also be useful as a Reference book for practising engineers for whom thermal calculations and understanding of heat transfer are necessary; eg. in the areas of Thermal Engineering, Metallurgy, Refrigeration and Air-conditioning, Insulation etc.

Readers can download the trial-editions of Mathcad, EES and FEHT from the web sites mentioned and try the examples. EXCEL is generally pre-installed as a part of MS OFFICE in the PC's.

The book is presented in ***three Volumes*****:**

Vol.-I contains solved problems on CONDUCTION.

Vol.-II will contain solved problems on the topics of **CONVECTION** (i.e. Forced convection, Natural or Free convection) and **BOILING and CONDENSATION**), and,

Vol.-III will contain problems on **HEAT EXCHANGERS** and **RADIATION**.

Further, Vol.-I contains 3 parts:

Part-1 contains problems on following topics:

1A. Fourier's Law, heat conduction equation and Multi-mode heat transfer

1B. One-D, Steady State heat transfer without heat generation – Thermal resistance concept – Plane wall with constant k and variable k

1C. One-D, Steady State Heat transfer in Cylindrical and Spherical systems

1D. Critical radius problem

Part-2 contains problems on following topics:

1E. Heat transfer with Fins

1F. One-D, Steady State heat transfer with heat generation

1G. Transient conduction (Lumped system analysis, Heisler charts, Semi-infinite slabs etc.)

1H. Two-D heat conduction – Shape factor

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Part-3 contains problems on following topics:

1I. Numerical Methods in heat conduction

Acknowledgements: Firstly, I would like to **thank all my students**, who have been an inspiration to me and without whose active involvement, this work would not have been possible. When I solved these problems in the class, they suggested that this material should be put on the Internet, so that all those who are interested could download the same and get benefited.

I am grateful to **Rev. Fr. Valerian D'Souza,** former Director of St. Joseph Engineering College (SJEC), Mangalore, for his love, deep concern and support in all my academic pursuits.

Sincere thanks are due to **Rev. Fr. Joseph Lobo**, Director, SJEC, for his kindness, regard and encouragement, and for providing a very congenial and academic atmosphere in the college.

I would also like to thank **Dr. Joseph Gonsalves**, Principal, SJEC, for giving me all the facilities and support.

Also, I should thank **Dr. Thirumaleshwara Bhat**, Head, Dept. of Mechanical Engineering, SJEC, and other colleagues in Department, for their cooperation and encouragement in this venture.

I am thankful to **Dr. Girish Kumar**, Professor and Head, Dept. of Mechanical Engineering, SDM Institute of Technology, Ujire, Karnataka, India, who read the manuscript and gave useful suggestions.

Also, my special thanks to **Bookboon.com** for publishing this book on the Internet. **Ms. Sophie** and her editorial staff have been most helpful.

Finally, the author would like to express his sincere thanks and appreciation to **his wife, Kala,** for her continuous support and encouragement, and for the many sacrifices she made during the period of writing this book.

M. Thirumaleshwar
August 2013

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About the Author

Dr. M. Thirumaleshwar graduated in Mechanical Engineering from Karnataka Regional Engineering College, Surathkal, Karnataka, India, in the year 1965. He obtained M.Sc (cryogenis) from University of Southampton, U.K. and Ph.D.(cryogenics) from Indian Institute of Science, Bangalore, India.

He is a Fellow of Institution of Engineers (India), Life Member, Indian Society for Technical Education, and a Foundation Fellow of Indian Cryogenics Council.

He has worked in India and abroad on large projects in the areas involving heat transfer, fluid flow, vacuum system design, cryogenic engineering, cryo-pumping etc.

He worked as **Head of Cryogenics Dept. in Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology (CAT), Indore, from 1966 to 1992.**

He worked as **Guest Collaborator with Superconducting Super Collider Laboratory of Universities Research Association, in Dallas, USA from 1990 to 1993.**

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He also worked at the **Institute of Cryogenics, Southampton, U.K. as a Visiting Research Fellow from 1993 to 1994.**

He was **Head of the Dept. of Mechanical Engineering, Fr. Conceicao Rodrigues Institute of Technology, Vashi, Navi Mumbai, India for eight years.**

He also worked as **Head of Dept. of Mechanical Engineering and Civil Engineering, and then as Principal, Vivekananda College of Engineering and Technology, Puttur (D.K.), India.**

Presently, he is Professor and coordinator of Post-graduate program in the Dept. of Mechanical Engineering in St. Joseph Engineering College, Vamanjoor, Mangalore, India.

A book entitled **"Fundamentals of Heat and Mass Transfer"** authored by him and published by M/s Pearson Education, India (2006) **has been adopted as a Text book** for third year engineering students by the Visweswaraya Technological University (V.T.U.), Belgaum, India.

He has also written and published three booklets entitled as follows:

1. Towards Excellence… How to Study (A Guide book to Students)
2. Towards Excellence… How to teach (A guide book to Teachers)
3. Towards Excellence… Seminars, GD's and Personal Interviews (A guide book to Professional and Management students)

Dr. Thirumaleshwar has attended several National and International conferences and has more than 50 publications to his credit.

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About the Softwares used

Following three softwares are used while solving problems in this book:

1. Mathcad 2001 (Ref: www.ptc.com)
2. Engineering Equation Solver (EES) (Ref: www.fchart.com), and
3. Finite Element Heat Transfer (FEHT) (Ref: www.fchart.com)
4. MS EXCEL – (2007) Spreadsheet (Ref: Microsoft)

Trial versions of the first three softwares and detailed Instruction Manuals may be downloaded from the websites indicated. EXCEL is a very popular spreadsheet which comes bundled with MS OFFICE software, and is generally available in every computer.

In the following pages, brief introduction is given to these four softwares.

While this information is enough to get going, for detailed instructions one should consult the respective Instruction manuals.

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1 About Mathcad

(Ref: "Mathcad software and some Mathcad functions useful for heat transfer calculations – Part-I", by M. Thirumaleshwar, The Indian Jl. of Technical Education, Vol. 35, N0. 3, July-Sept. 2012)

This short note on Mathcad is not a tutorial on Mathcad; many specialized books are available for that purpose (eg. 'Introduction to Mathcad for Scientists and Engineers' by Sol Wieder, McGraw Hill, Inc., 1993), in addition to the Instruction manual supplied along with the software. Mathcad software itself contains a tutorial on its use.

Purpose of this note is to make the reader comfortable with the Mathcad worksheets shown in the text.

1.1 What is Mathcad?

Mathcad is a very powerful and popular problem solving tool for students of Science and engineering. It turns the computer screen in to a 'live Maths note pad', and has a 'free form interface', i.e. you can add equations, text and graphs in a single document. One *great advantage* of Mathcad is that equations are entered in 'real Math' notation (i.e. as you would enter in a note pad by hand) and not in a single line, complicated manner as in programming languages such as FORTRAN. This makes it very easy to see if there is any mistake committed while entering the equation. There are built-in functions and formulae and there is facility for user-defined functions too. Unlimited vectors and matrices, ability to solve problems numerically and symbolically , root finding, quick and very easy 2-D and 3-D graphiig, click selecting of greek and other symbols from palettes are some other high-lights. All this is done without any programming, but, just with a few clicks in Windows. Opening screen of Mathcad worksheet is shown below:

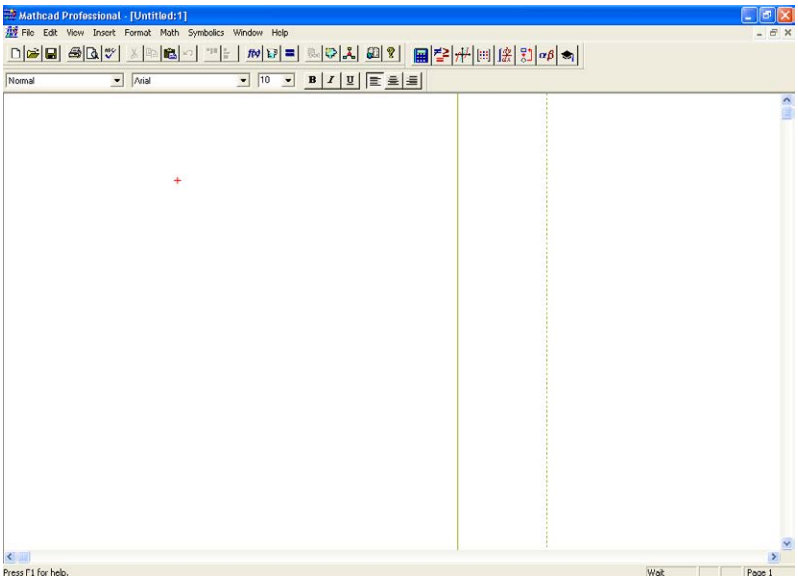

Fig.1. Opening screen of Mathcad

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Menu-bar and Toolbar containing various palettes are shown below:

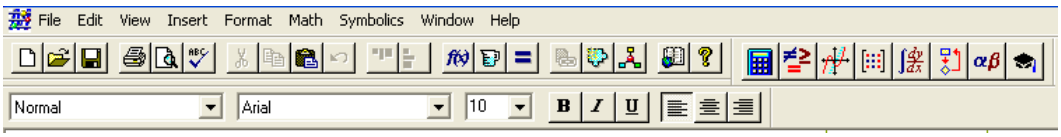

Fig.2. Menubar and Toolbar of Mathcad

Various palettes are:

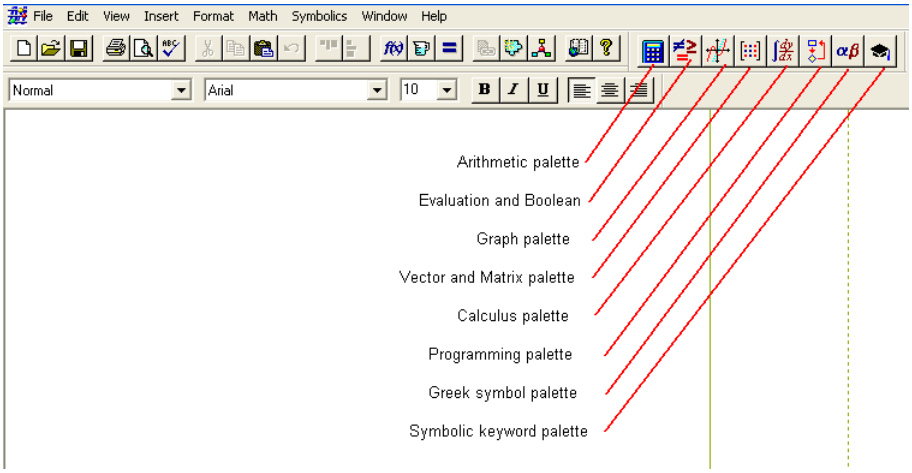

Fig.3. Various palettes in Mathcad Toolbar

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When you click on each palette, different functionalities are presented, from which you choose the desired one by clicking on it:

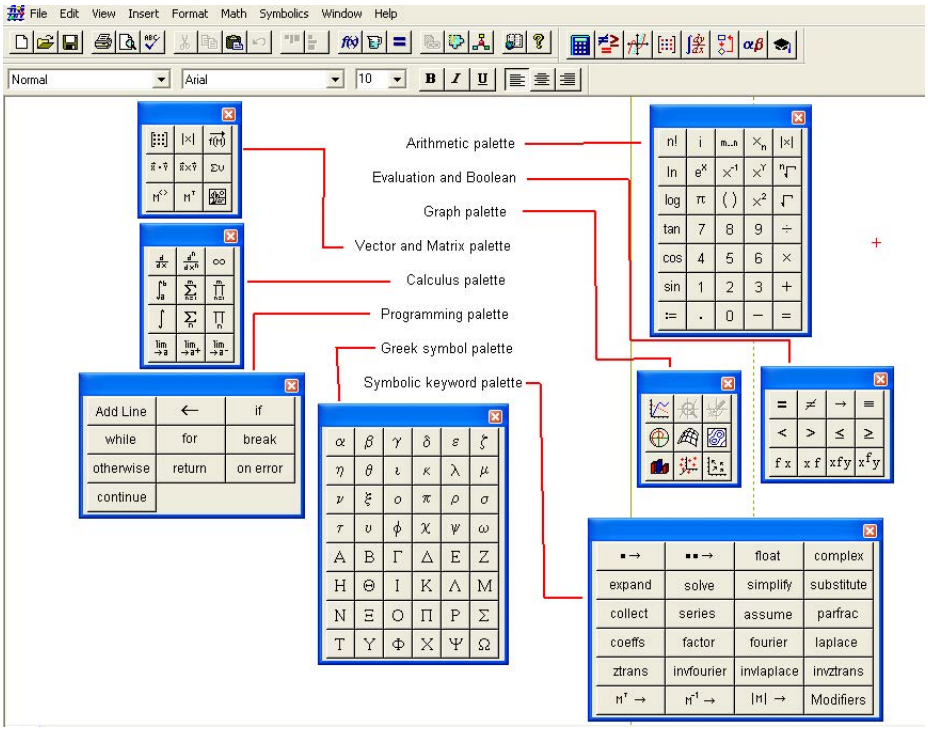

Fig.4. Functionalities of different palettes

1.2 Symbols in Mathcad worksheet:

Mathcad uses usual math notations. +, -, * and / have usual meaning: addition, subtraction, multiplication and division. One advantage in Mathcad is that you can assign a value to a variable and use that variable subsequently throughout your worksheet. Symbol for assignment is := i.e. a colon combined with 'equal' sign.

Consider the following example: Let variables A, B and C be assigned values of 3, 5 and 7 respectively. Then, the product A .B. C is obtained by simply typing A.B.C = , i.e. result is obtained by typing the desired mathematical operation, followed by = (i.e. equals sign of maths). Some typical calculations using A, B and C are shown below:

$A := 3 \quad B := 5 \quad C := 7$ ….assigning values to variables A, B and C

$A \cdot B \cdot C = 105$ ….multiplication

$2 \cdot A + 8 \cdot B - 4 \cdot C = 18$ ….multiplication, addition and subtraction

$\frac{A \cdot B}{C} = 2.143$ ….division

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$B^2 - 4 \cdot A \cdot C = -59$ ….exponentiation

$\sqrt{A^3 + B^3 + C^3} = 22.249$ …taking square root

$\exp\left(\frac{A}{B \cdot C}\right) = 1.089$ ….using 'built-in' exponential function

Note that typing the equals sign (' = ') after typing the mathematical operation, gives the final result immediately and accurately.

1.3 'What – if' analysis in Mathcad:

Consider, for example, the heat flow by conduction through a rod.

Heat flow rate Q, through the rod is given by:

$$Q = k \cdot A \cdot \frac{(T_1 - T_2)}{L} \quad \ldots W$$

where, k = thermal conductivity of the material, (W/(m.K)
A = area of cross-section of the rod, m^2
$(T_1 - T_2)$ = temperature difference between the two ends of rod, (where T1 > T2), and
L = Length of rod, m

Now, suppose that we wish to find out the value of Q for rods made of different materials, say, copper, Aluminium and stainless steel. i.e. we would like to study the variation of Q with k, rest of the variables being held constant. This is done very easily and quickly in Mathcad, as follows: Let $T_1 = 300$ K, $T_2 = 200$ K, L = 05 m, $A = 0.785 \times 10^{-4}$ m^2.

First, define Q as a function of all variables. Then, write the data, assigning values for T_1, T_2, L and A. Next, assign the first value of k (i.e. for copper), and type 'Q(k) = ' (i.e. Q(k) followed by an 'equals' sign), and the value of Q appears immediately. Now, to see the change in Q for the next value of k, again, assign the new value for k, followed by 'Q(k) = ', and the new value of Q appears immediately. Similarly, repeat for other values of k. Entire worksheet of these calculations is shown below:

$Q = k \cdot A \cdot \frac{(T_1 - T_2)}{L}$ …W….heat transfer rate by conduction

$T_1 := 300$ K, $T_2 := 200$ K, $L := 0.5$ m, $A := 0.785 \cdot 10^{-4}$ m^2

$Q(k, A, T_1, T_2, L) := k \cdot A \cdot \frac{(T_1 - T_2)}{L}$ ….define Q as a function of variables involved

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Copper: $k := 407$ W/(m.K) ….mean value of k between 300 K and 200 K

Then, $Q(k, A, T_1, T_2, L) = 6.39$ **W.…Ans.**

Aluminiumm: $k := 237$ W/(m.K)….mean value of k between 300 K and 200 K

Then, $Q(k, A, T_1, T_2, L) = 3.721$ **W.…Ans.**

S.S (AISI 304): $k := 13.75$ W/(m.K)….mean value of k between 300 K and 200

Then, $Q(k, A, T_1, T_2, L) = 0.216$ **W.…Ans.**

In a similar manner, by individually changing other values viz. area of cross-section (A), end temperatures (T_1, T_2) and length (L), effect on the heat transfer rate (Q) can be studied.

1.4 Producing the results in tabular form:

Many times, we need the results to be presented in a tabular form. This is done very easily in Mathcad. Let us say, we need to produce a table of values for Gaussian error function. Gaussian error function is defined as follows:

$$erf(y) := \frac{2}{\sqrt{\pi}} \cdot \int_0^y \exp(-V^2)\, dV$$ ….Gaussian error function, defined

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(Note: In the above definition, integral sign is obtained by clicking on the appropriate button on the calculus palette.)

To present the values of erf(y) for values of y ranging from zero to 1, first define a range variable y, varying from 0 to 1, with an increment of 0.05. Then typing 'y =' immediately gives the values of y one below the other; similarly, type 'erf(y) =', and values of erf(y) appear one below the other. Arrange these two sets side by side, and we have the required results in a tabular form. This worksheet procedure is shown below:

$$\mathrm{erf}(y) := \frac{2}{\sqrt{\pi}} \cdot \int_0^y \exp\left(-V^2\right)$$ ….Gaussian error function, defined

$y := 0, 0.05 .. 1$ …define range variable y, varying from 0 to 1 with an increment of 0.02

y	erf(y)
0	0
0.05	0.0564
0.1	0.1125
0.15	0.168
0.2	0.2227
0.25	0.2763
0.3	0.3286
0.35	0.3794
0.4	0.4284
0.45	0.4755
0.5	0.5205
0.55	0.5633
0.6	0.6039
0.65	0.642
0.7	0.6778
0.75	0.7112
0.8	0.7421
0.85	0.7707
0.9	0.7969
0.95	0.8209
1	0.8427

1.5 Graphing in Mathcad:

Graphing in Mathcad is very easy. Let us say, we would like to produce a graph of the effectiveness (ε) of a parallel flow heat exchanger, which is a function of number of transfer units (N) and the capacity ratio (C). Mathematical expression for the effectiveness of parallel flow heat exchanger is:

$$\varepsilon = \frac{1 - \exp(-N \cdot (1 + C))}{1 + C}$$

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Then, first express ε as a function of N and C; this is done in Mathcad by simply typing:

$$\varepsilon(N, C) := \frac{1 - \exp(-N \cdot (1 + C))}{1 + C}$$ ….express ε as a function of N and C

Let us draw a graph of variation of ε with N for a value of C = 1, say:

First step is to define a 'range variable' N, varying from say, 0 to 6, in steps of 0.1. In Mathcad, it is written in the form:

$$N := 0, 0.1 .. 6$$ ….define a range variable N, varying from 0 to 6 in increments of 0.1

Then click on the graphing palette, and select the x-y graph:

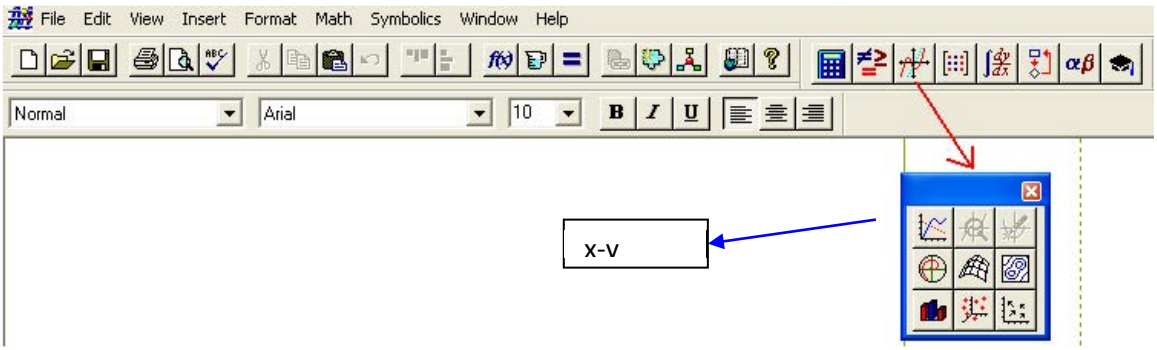

Fig. 5 (a). Graphing palette

A graphing area appears with two 'place holders', one on the x-axis and the other on the y-axis:

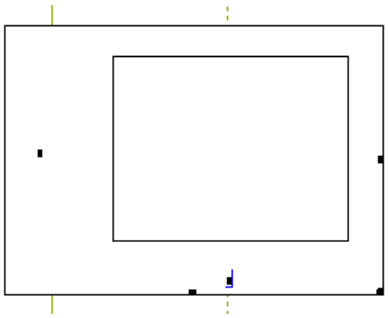

Fig. 5 (b). Empty graph with x and y place-holders

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Fill in the x-axis place holder with N. On the y-axis place holder, fill in ε(N,1). Click anywhere outside the graph and immediately the graph appears. If we desire to draw in the same graph, the next curves for C = 0.8, 0.4 and zero, just type a comma after the already typed ε(N,1) and type ε(N,0.8), ε(N,0.4), ε(N,0), and click anywhere outside the graph area, and immediately the graph is redrawn with all the 4 curves. Further, there are simple mouse-click commands for giving titles for the graph, x-axis and y-axis, and also for showing grid lines and legend. Logarithmic scaling also can be applied by simple mouse click commands. Entire worksheet is shown below:

$$\varepsilon(N,C) := \frac{1 - \exp(-N\cdot(1+C))}{1+C}$$ ....express ε as a function of N and C

N := 0, 0.1.. 6 ....define a range variable N, varying from 0 to 6 in increments of 0.1

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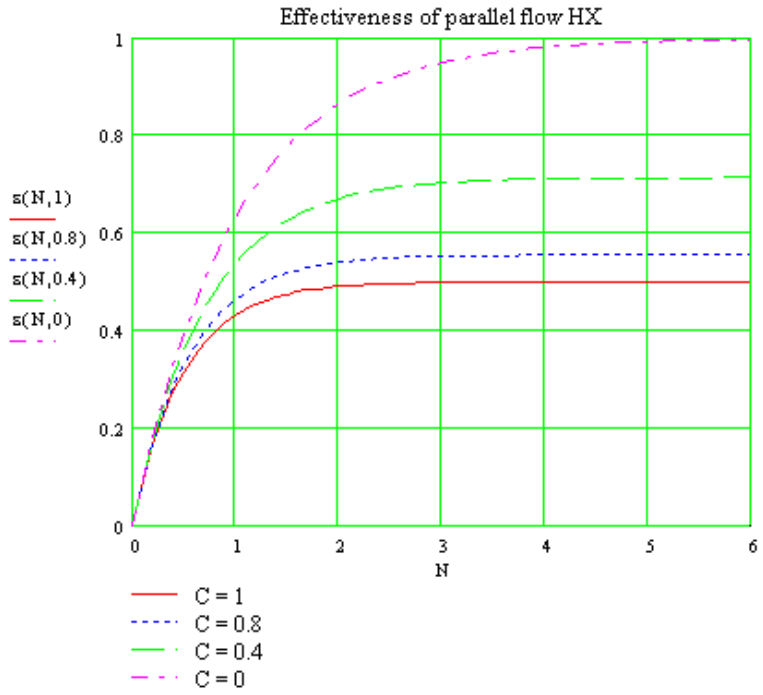

Fig.6(a). Example of graphing in Mathcad

1.6 Modifying the graph:

Once the graph has been drawn, it can be modified easily by changing the various parameters as follows: 'Double click' on the graph and the following screen (Fig. 6-b) appears presenting four tabs, viz. X-Y Axes, Traces, Labels and Defaults. Clicking on each tab will present a set of variables which can be changed as shown in the following screen prints:

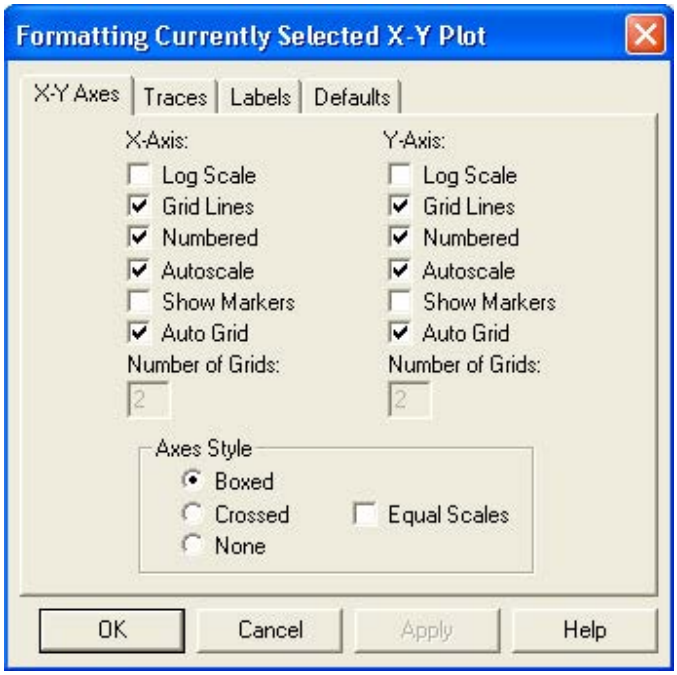

Fig.6(b). Modifying the graph – X-Y Axes tab

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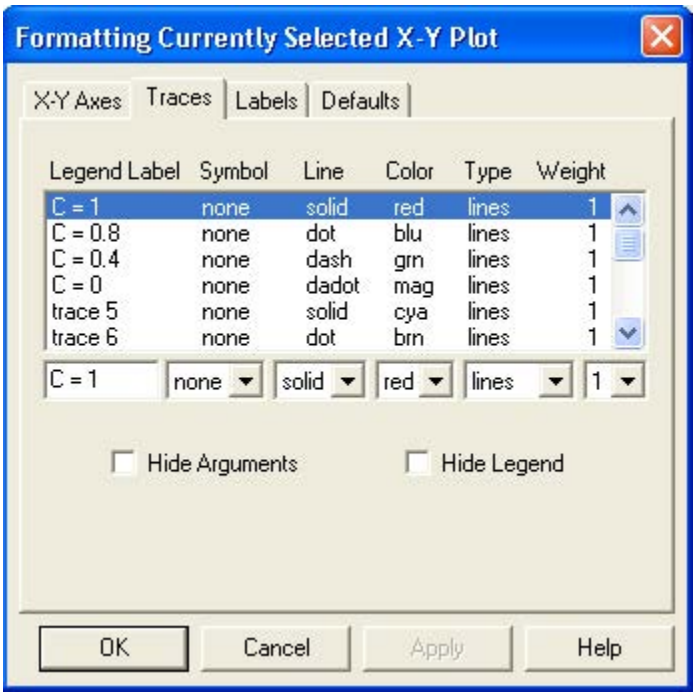

Fig.6(c). Modifying the graph – Traces tab

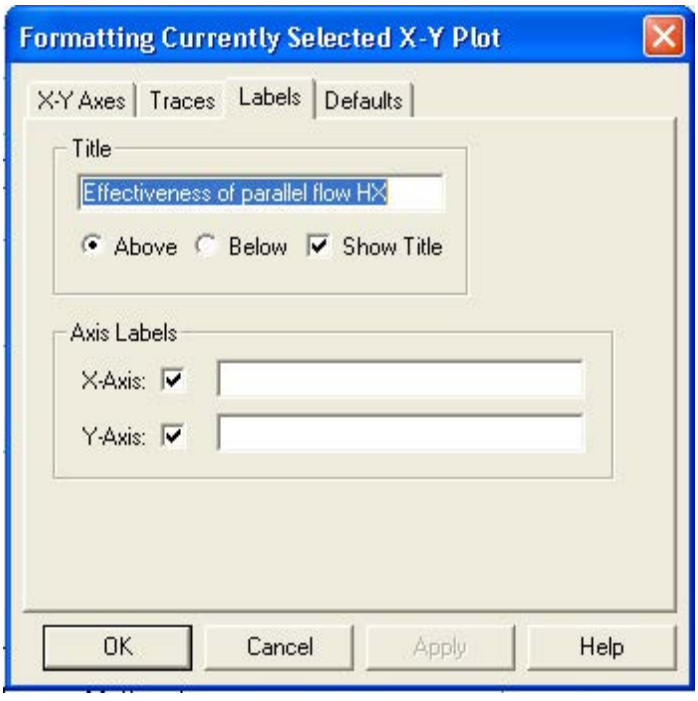

Fig.6(d). Modifying the graph –Labels tab

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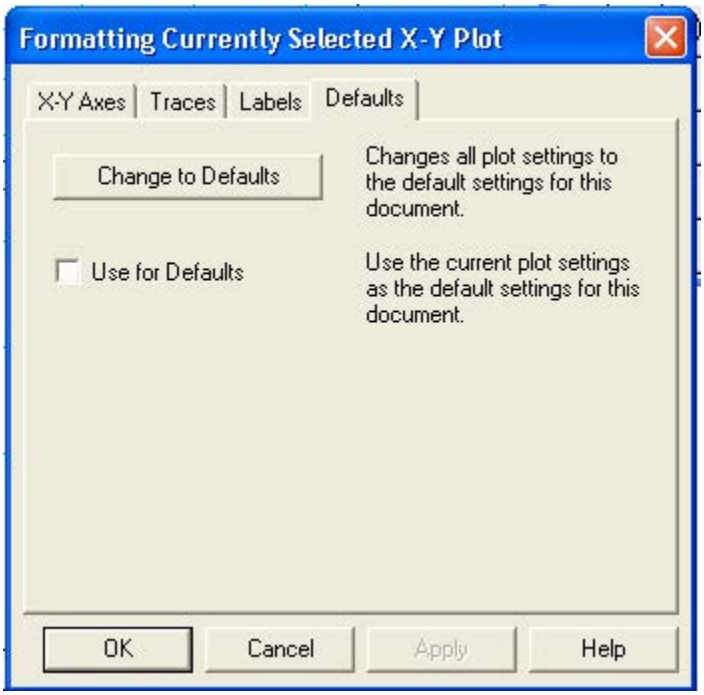
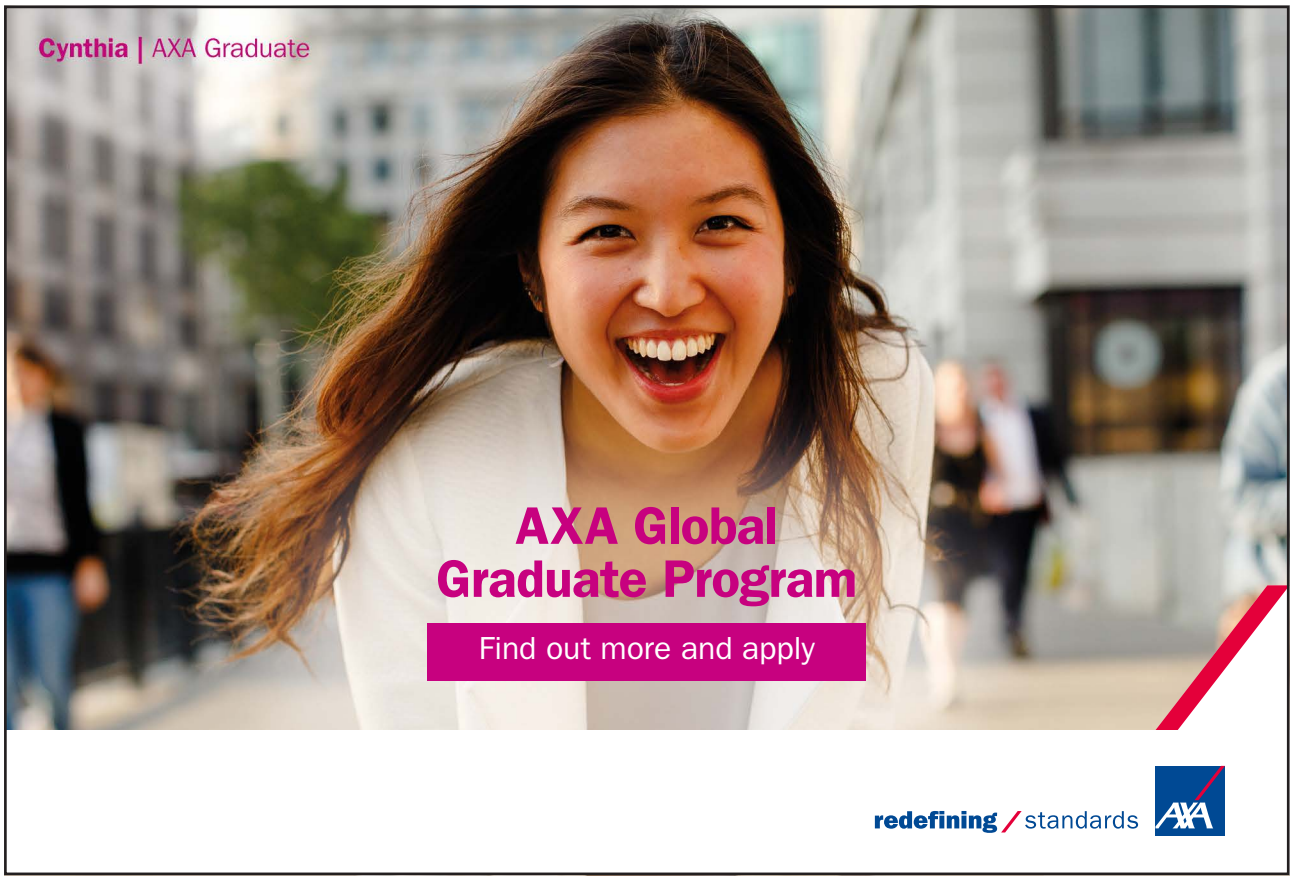


Fig.6(e). Modifying the graph – Defaults tab



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1.7 Solving equation with one variable (Root finding):

To solve an equation with one variable, we can use the 'root' function:

Let us say, we would like to solve:

$$x + \ln(x) = 0$$

This is a transcendental equation and solution requires a trial and error procedure.

We first define a function: y(x) = x + ln(x); then, assume a guess value for x, and apply the root function to get the root in a single step. Of course, guess value for x must be assumed carefully, to facilitate a correct solution, since many times, there is a possibility that more than one root may exist. Quickly drawing a graph of y(x) for some values of x will help in choosing a 'good' guess value. In the above case, let us draw the graph of y(x) for x = 0 to 5, with an increment of 0.1. We see from the graph, that the curve crosses y(x) = 0 at around a x value of 0.5. So, let us assume the guess value of x as 0.5. Then apply the root function, i.e. simply type: 'root(y(x),x) = ', and the solution appears immediately. We get x = 0.567 as the solution. Entire worksheet of this solution is shown in Fig. 6:

$y(x) := x + \ln(x)$ ...define the function y(x)

$x := 0, 0.1 .. 5$ ....define a range variable x, varying from 0 to 5, in increments of 0.1

Draw the graph, to guess the approximate root of y(x) = 0:

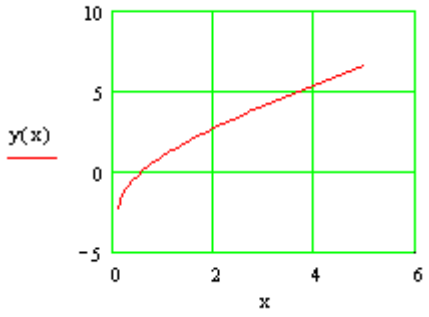

Fig.7. y(x) vs. x, to get approx. solution of y(x) = 0

$x := 0.5$ ....guess value of root, after seeing Fig. 6

$root(y(x), x) = 0.567$ ...correct value of root from the root function...Ans.

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Remember that numerical methods are used by Mathcad in the above solution. Calculations are terminated by the computer when a set value of 'tolerance' is achieved. Built-in tolerance is 0.001. You can easily change this value of tolerance by re-assigning its value, say: TOL := 0.0001, for example.

1.8 Solving a set of simultaneous equations (both linear and non-linear):

To solve a set of simultaneous equations, we use the **'Solve block'** of Mathcad. Again, the procedure is very simple: start with guess values for the variables involved say x_1, x_2. Then type 'Given' and immediately below it, type the constraints, i.e. the set of equations to be solved. Here, while typing the constraints, take care to use the ' = ' sign, and not the assignment sign, ' : = '. Then type 'Find(x_1,x_2) = ', and immediately, the answer appears, in vector form, giving values of x_1, x_2, in that order. Entire worksheet of solving a set of two equations is shown below:

Solve the following set of equations:

$$4 \cdot x_1 - 2 \cdot x_2^2 = -2$$

$$x_1 + x_2 = 3$$

Start with guess values for x_1 and x_2, type 'Given', and below that write the two constraint equations, finally type 'Find(x_1, x_2) = ', and the values of the two variables appear in that order:

$x_1 := 1$ $x_2 := 1$ …guess values for x_1, x_2

Given

$$4 \cdot x_1 - 2 \cdot x_2^2 = -2$$

$$x_1 + x_2 = 3$$

$$\text{Find}(x_1, x_2) = \begin{bmatrix} 1.172 \\ 1.828 \end{bmatrix}$$

i.e. $x_1 = 1.172$ $x_2 = 1.828$ **….Ans.**

Note that to solve equation with one variable also we can use the 'Solve block', instead of 'root' function.

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1.9 Differentiation in Mathcad:

Differentiation of a function, y(x), is done easily in Mathcad. On the calculus palette, click on the d/dx button and a format for the first derivative appears, as shown:

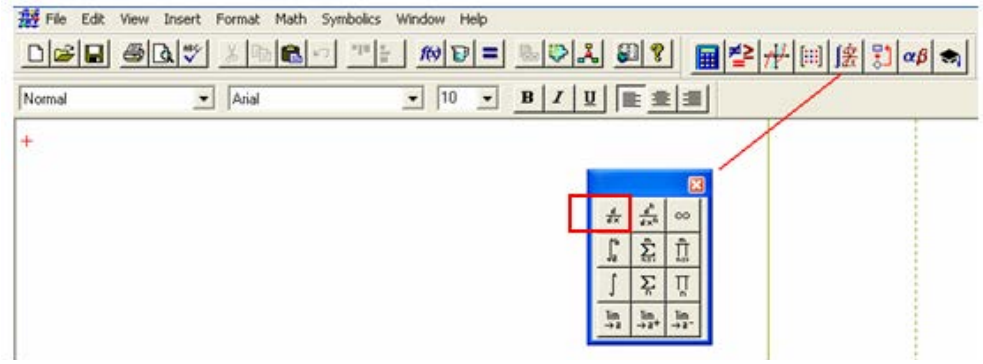
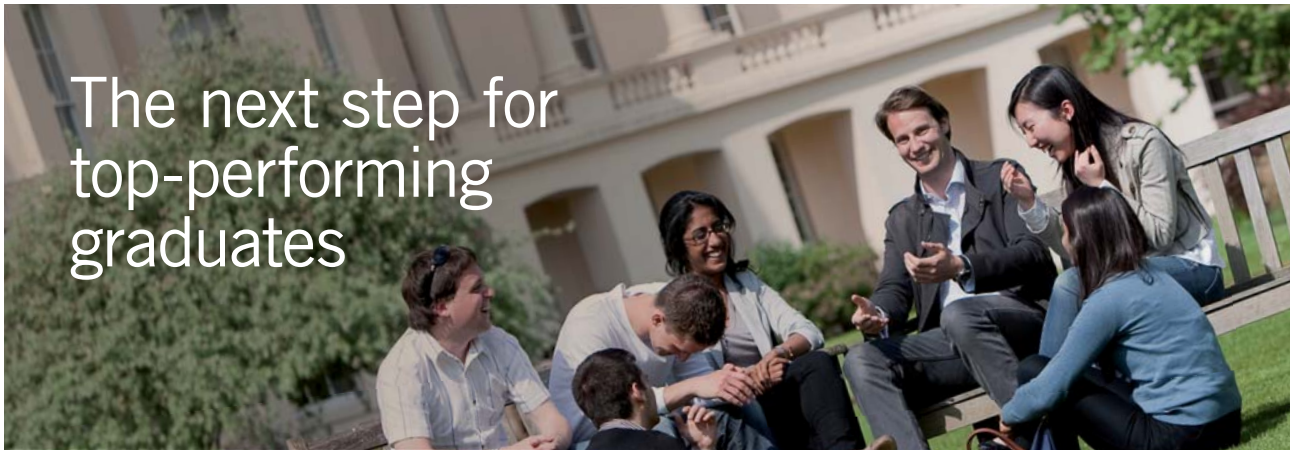


Fig.8. Calculus palette

$$\frac{d}{d\blacksquare}\blacksquare$$

Now, fill in the place holders with y(x) and x as shown:

$$\frac{d}{dx}y(x)$$



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As an example, let us say, we would like to find the value of the first derivative of the following function at x = 2:

$$y(x) = 4 \cdot x^3 + 8 \cdot x^2 - 5 \cdot x + 6$$

First, define the function which has to be differentiated; next, define the first derivative, y`(x) using the calculus palette, as explained above. Then, simply type: y`(x) = , and the result appears immediately. See the following worksheet:

$y(x) := 4 \cdot x^3 + 8 \cdot x^2 - 5 \cdot x + 6$ …define a function

Then, let: $y'(x) := \frac{d}{dx} y(x)$ …define the first derivative of y(x)

i.e. $y'(2) = 75$ ….**value of first derivative at x = 2….Ans.**

1.10 Integration:

Integration between given limits is an operation required very often while solving heat transfer problems. Again, this is done simply by clicking the appropriate button from the calculus palette, and a format for integration appears as shown:

$$\int_{\square}^{\square} \square \, d\square$$

Now, just fill in the place holders, type ‘ = ‘ (i.e. ‘equals’ sign) and the result appears immediately.

For example, let us say, we would like to integrate the function y(x) = 1+ sin(x) between the limits x = 0 and x = π/2. We proceed as shown in the following worksheet:

$y(x) := 1 + \sin(x)$ ….define the function

Click the appropriate button on the calculus palette, fill in the place holders, and type ‘ = ‘, and the result appears immediately:

$$\int_{0}^{\frac{\pi}{2}} y(x)\,dx = 2.571$$ **….Ans.**

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Matrices:

To start with, let us have a few preliminaries/definitions about matrices:

A **matrix** is an array of numbers arranged in rows and columns.

A (m x n) matrix has 'm' rows and 'n' columns.

If m = 1 (n > 1), it is a **row matrix**, and if n = 1 while m > 1, it is a **column matrix**.

Row and column matrices are also known as **vectors**.

Element of a matrix is referred by two subscripts, first one indicating the row number, and the second subscript indicating the column number. Thus, A_{ij} is the element of a matrix A, located at row 'i' and column 'j'.

A **square matrix** has the same number of columns as it has rows, i.e. m = n.

For a square matrix:

1) **Main diagonal** consists of numbers from upper left to lower right corner.
2) **Trace of a matrix** is the sum of elements on the main diagonal; it is denoted by: tr(A).
3) **Determinant of a matrix A,** is the determinant formed by the elements of A and is denoted by: det(A) or |A|
4) **Identity or unit matrix (I)** is a square matrix with each of the elements on the main diagonal equal to 1, and rest of the elements are all zero.
5) **Inverse of a square matrix A**, is that matrix which when multiplied by A gives the identity matrix. Note that $A.A^{-1} = A^{-1}.A$ = Identity matrix, I.
6) If det(A) = 0, then inverse of A does not exist. Such a matrix is called **singular**.

Matrix Algebra:

1) To add or subtract two matrices A and B, both of them should be (m × n) matrices. Elements of the resulting matrix C are obtained by adding or subtracting the corresponding elements of A and B. C also is a (m × n) matrix.
2) Note that (A + B) = (B + A).
3) Matrix A can be multiplied by matrix B if the number of columns in A is the same as the number of rows in B. Resulting matrix C has the same number of rows as in A, and the same number of columns as in B. Elements of C are determined by the following rule:

$$C_{ij} = \sum_{k} A_{ik} \cdot B_{kj}$$

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4) If A, B and C are three matrices which can be multiplied, following holds good:

$A \cdot (B \cdot C) = (A \cdot B) \cdot C$ …obeys associative law

$A \cdot (B + C) = A \cdot B + A \cdot C$ …obeys distributive

$A \cdot B \neq B \cdot A$ …does not obey commutative law

5) To multiply a matrix A by any number 'b', multiply each of the elements of A by the number b and obviously, the resulting matrix C has the same structure as A.
6) Matrices can not be divided; as such, A/B has no meaning.
7) **Transpose** of a matrix A, denoted by A^T, is a matrix obtained by interchanging the rows and columns of A.
8) If two matrices A and B are placed side by side, we get the **augmented matrix** C, denoted by: C = augment(A,B). Note that A and B must have the same number of rows.

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1.11 Assigning a matrix in Mathcad:

Let us say, we need to define a matrix A. Then write A:= , and in the 'Vector and Matrix palette', click on the Matrix button, choose the number of rows and columns, and a blank matrix with place holders for the elements appears:

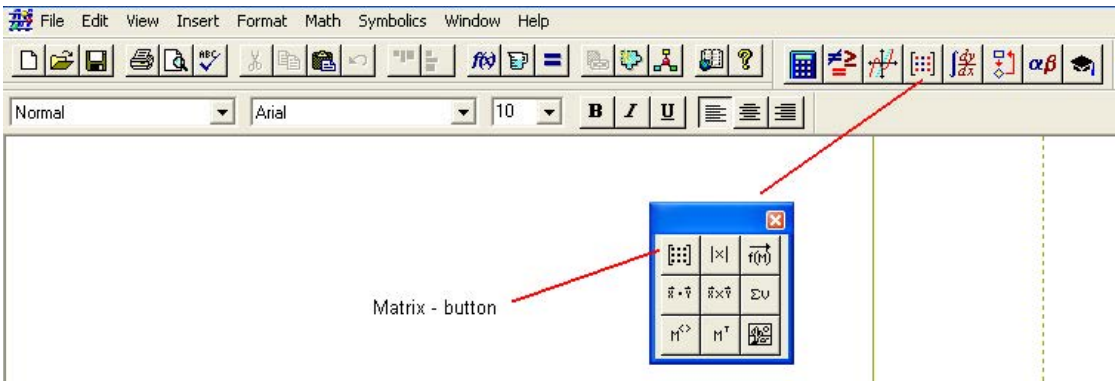

Fig.9. Vector and Matrix palette and Matrix button

If we choose the number of rows and columns as 3 each, we would get the following:

$$A := \begin{bmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{bmatrix}$$

Now, fill in the place holders to assign the desired matrix.

Following worksheet shows a few examples of matrix operations:

$$A := \begin{bmatrix} 4 & 4 & 6 \\ 1 & 4 & 2 \\ 2 & -2 & 6 \end{bmatrix} \qquad B := \begin{bmatrix} 2 & 1 & 5 \\ 6 & 4 & 2 \\ 7 & 2 & 1 \end{bmatrix}$$ ….define Matrices A and

$$A + B = \begin{bmatrix} 6 & 5 & 11 \\ 7 & 8 & 4 \\ 9 & 0 & 7 \end{bmatrix}$$ …matrix addition

$$A - B = \begin{bmatrix} 2 & 3 & 1 \\ -5 & 0 & 0 \\ -5 & -4 & 5 \end{bmatrix}$$ …matrix subtraction

$$A \cdot B = \begin{bmatrix} 74 & 32 & 34 \\ 40 & 21 & 15 \\ 34 & 6 & 12 \end{bmatrix}$$ …matrix multiplication

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$$B \cdot A = \begin{bmatrix} 19 & 2 & 44 \\ 32 & 36 & 56 \\ 32 & 34 & 52 \end{bmatrix}$$ …Note that A.B is not equal to B.A.

$$A^T = \begin{bmatrix} 4 & 1 & 2 \\ 4 & 4 & -2 \\ 6 & 2 & 6 \end{bmatrix}$$ …transpose of matrix A. Click on the Transpose button in the Vector and Matrix palette.

$$\text{augment}(A, B) = \begin{bmatrix} 4 & 4 & 6 & 2 & 1 & 5 \\ 1 & 4 & 2 & 6 & 4 & 2 \\ 2 & -2 & 6 & 7 & 2 & 1 \end{bmatrix}$$ …matrix obtained by augmenting A and B

$$\text{identity}(3) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ …Identity or unit matrix is generated by this simple command; 3 denotes the no. of rows (and columns) desired

$|A| = 44$ …determminant of A. Choose the determinant button from the Vector and Matrix palette.

Inverse of a square matrix, A: Often required while solving a set of simultaneous algebraic equations.

$$A^{-1} = \begin{bmatrix} 0.636 & -0.818 & -0.364 \\ -0.045 & 0.273 & -0.045 \\ -0.227 & 0.364 & 0.273 \end{bmatrix}$$ …Inverse of matrix A; obtained by simply typing A-1 = .

Check: A. A^{-1} must be equal to identity matrix.

$$A \cdot A^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ …checked.

Similarly, $$B^{-1} = \begin{bmatrix} 0 & -0.125 & 0.25 \\ -0.111 & 0.458 & -0.361 \\ 0.222 & -0.042 & -0.028 \end{bmatrix}$$

Check $$B \cdot B^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ …checked.

Also, $$B^{-1} \cdot B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ …Note that $B.B^{-1} = B^{-1}.B$, since both B and B^{-1} are square matrices, inverse of each other.

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To extract elements of a matrix:

Matrix rows and columns are generally numbered starting from 1. However, default origin of Mathcad starts from 0. So, we change the origin to 1 by the command:

ORIGIN = 1 ….change the ORIGIN to 1

We have: $A = \begin{bmatrix} 4 & 4 & 6 \\ 1 & 4 & 2 \\ 2 & -2 & 6 \end{bmatrix}$

Then, $A_{1,2} = 4$ …element in 1st row and 2nd column of matrix A

$A_{3,3} = 6$ …element in 3rd row and 3rd column of matrix A

$A_{2,2} = 4$ …element in 2nd row and 2nd column of matrix A

To extract columns of a matrix:

Click on the relevant 'column extraction button' in the Vector and Matrix palette and fill in the place holder by the number of column desired

$A^{<2>} = \begin{bmatrix} 4 \\ 4 \\ -2 \end{bmatrix}$ …second column of matrix A

$B^{<3>} = \begin{bmatrix} 5 \\ 2 \\ 1 \end{bmatrix}$ …third column of matrix A, etc.

1.12 Programming in Mathcad:

Mathcad-7 Professional version (and, later versions) has programming capability too. Just as in the case of other programming languages, there is facility for conditional branching, looping constructs, error handling, using other programs as sub-routines etc.

A Mathcad program is a special kind of expression, which returns a value – a scalar, vector, array, nested array or string. An 'expression' in Mathcad is only a simple statement, whereas a 'program' can consist of as many statements as required to compute the answer.

Programs are written using the 'programming palette'.

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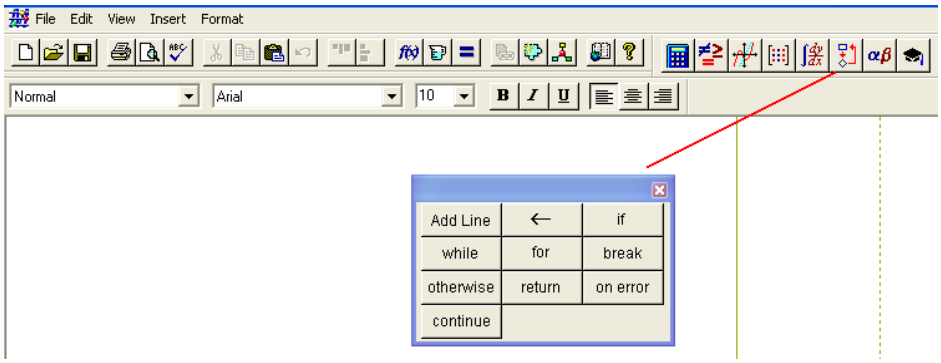

Fig.10. Programming palette

Programming palette has only 10 buttons: add line, ← (assignment), if, while, for, break, otherwise, return, on error, continue. However, with its very wide mathematical and graphing functionality, coupled with programming capability and the convenience of Windows platform, Mathcad is a very powerful and versatile tool for engineering and scientific calculations.

It is impossible to illustrate all the programming capabilities of Mathcad in this short introduction. However, we shall give only two small examples:

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Consider the problem of calculating the friction factor for flow of fluid in a smooth tube. Friction factor depends on the Reynolds number (Re_D) based on tube diameter (D). If the Reynolds number is less than 2300, the flow is termed 'laminar' and the friction factor is given by: $f = (64/ Re_D)$; if $Re_D > 2300$, flow is turbulent, and the expression for friction factor is: $f = 0.184. (Re_D)^{-0.2}$.

We would like to write a Mathcad program to return the value of f for any input value of Re_D i.e. $f(Re_D)$. Worksheet for this program is developed as explained below:

We start with the definition of friction factor as a function of Re_D on the LHS; then, click on 'add line' button in the programming palette. Two place holders appear as shown:

$$\text{ffactor}(Re_D) := \begin{cases} \blacksquare \\ \blacksquare \end{cases}$$

Now, position the cursor in the top place holder and click on the 'if' button in the programming palette. We see:

$$\text{ffactor}(Re_D) := \begin{cases} \blacksquare \text{ if } \blacksquare \\ \blacksquare \end{cases}$$

Fill in the place holders on the left and right of 'if' by $64/Re_D$ and $Re_D < 2300$ respectively as shown:

$$\text{ffactor}(Re_D) := \begin{cases} \frac{64}{Re_D} \text{ if } Re_D < 2300 \\ \blacksquare \end{cases}$$

Next, position the cursor on the bottom place holder and click on the 'otherwise' button in programming palette. We see:

$$\text{ffactor}(Re_D) := \begin{cases} \frac{64}{Re_D} \text{ if } Re_D < 2300 \\ \blacksquare \text{ otherwise} \end{cases}$$

Now, fill in the remaining place holder by $0.184.Re_D^{-0.2}$. We get, finally:

$$\text{ffactor}(Re_D) := \begin{cases} \frac{64}{Re_D} \text{ if } Re_D < 2300 \\ 0.184 Re_D^{-0.2} \text{ otherwise} \end{cases}$$

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Entire worksheet is given below:

Program to compute the friction factor (ffactor) for a smooth tube as a function of Reynolds number(Re_D):

$$\text{ffactor}(Re_D) := \begin{cases} \dfrac{64}{Re_D} & \text{if } Re_D < 2300 \\ 0.184 \cdot Re_D^{-0.2} & \text{otherwise} \end{cases}$$

Now, for any value of Re_D, we can get the value of f by simply typing ffactor(Re_D) = .

For example,

$Re_D := 2000$ $\quad$ $\text{ffactor}(Re_D) = 0.032$ …friction factor when $Re_D = 2000$

$Re_D := 4000$ $\quad$ $\text{ffactor}(4000) = 0.035$ ..friction factor when $Re_D = 4000$

$Re_D := 2 \cdot 10^6$ $\quad$ $\text{ffactor}(2 \cdot 10^6) = 0.01$ …friction factor when $Re_D = 2 \times 10^6$

Consider one more example of programming in Mathcad:

This program to find the sum of the series, S = 1 + 2 + 3 + 4 +…..+ N, illustrates the use of 'for' loop:

Worksheet containing the program is shown below:

Problem: Write a Mathcad program to find the sum of the series: S = 1 + 2 + 3 +….+

```
Sum(N) := | S ← 0
          | for i ∈ 1.. N
          |   S ← S + i
          | S
```

Examples:

Sum(2) = 3 ….sum of first two terms, i.e. S = 1 + 2

Sum(3) = 6 ….sum of first three terms, i.e. S = 1 + 2 + 3

Sum(5) = 15 ….sum of first five terms, i.e. S = 1 + 2 + 3 + 4 +5

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Sum(10)=55 ….sum of first ten terms

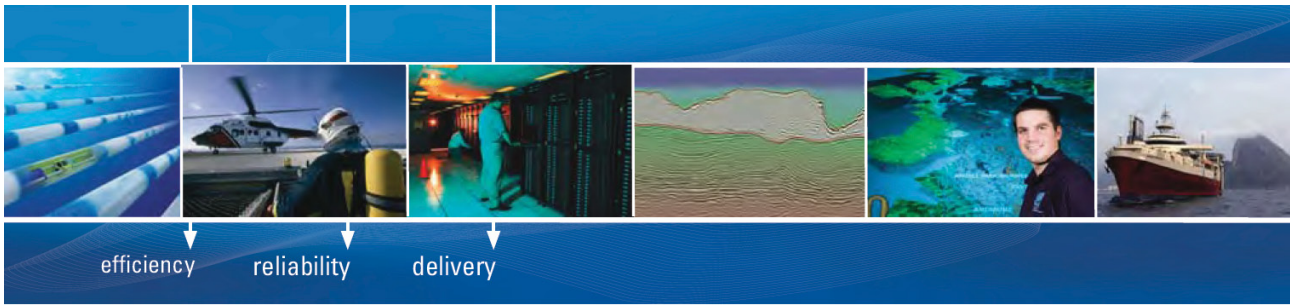
Sum(50) = $1.275 \cdot 10^3$ ….sum of first fifty terms

Sum(100) $5.05 \cdot 10^3$ ….sum of first hundred terms

Note how brief and succinct is the program.

Two programs given above are simple enough; but, they illustrate the way the program is built up in Mathcad. For longer programs, more lines are added simply by clicking on 'add line' button, as and when required.

Mathcad has several features, such as sequences, series, sums, products, factorials, derivatives and integrals, finding maxima and minima, vectors and matrices, capability to draw x-y, bar, scatter, polar, surface and contour plots, etc.…all by just a few clicks on the mouse. Only the most essential features, used in the present context, are described above.



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2 About Engineering Equation Solver (EES)

(Ref: "Use of Software in teaching Thermodynamics", by M. Thirumaleshwar, The Indian Jl. of Technical Education, Vol. 32, N0. 3, July–Sept. 2009)

2.1 What is EES?

EES is developed by Prof. Klein and his colleagues who teach Thermodynamics and Heat Transfer at Wisconsin University, USA, and is supplied by M/s F-Chart Software, USA. It is basically an equation solver, which gives numerical solutions of a set of linear or non-linear algebraic or differential equations. EES also provides built-in functions for thermodynamic and transport properties of many fluids such as water/steam, dry and moist air, refrigerants, cryogenic fluids, fuels and others, making it an extremely useful tool in solving problems in Thermodynamics. User written data and functions can also be added to the library. Parametric study can easily be conducted to provide optimum design solutions. There is good graphing capability and publication quality graphs of different types can easily be generated. Combined with this is the programming capability, as in other computer languages such as 'Fortran' or 'C', making EES a powerful tool to solve problems in Thermodynamics.

Equations Window of EES:

As you start EES, equations window appears. Here, you enter your equations. Formatting rules are as follows [Ref: EES Manual]:

1. Upper and lower case letters are not distinguished. EES will (optionally) change the case of all variables to match the manner in which they first appear.
2. Blank lines and spaces may be entered as desired since they are ignored.
3. Comments must be enclosed within braces { } or within quote marks " ". Comments may span as many lines as needed. Comments within braces may be nested in which case only the outermost set of { } are recognized. Comments within quotes will also be displayed in the Formatted Equations window.
4. Variable names must start with a letter and consist of any keyboard characters except ( ) ' | * / + – ^ { } : " or ;. Array variables are identified with square braces around the array index or indices, e.g., X[5,3]. String variables are identified with a $ as the last character in the variable name. The maximum length of a variable name is 30 characters.
5. Multiple equations may be entered on one line if they are separated by a semi-colon (;). The maximum line length is 255 characters.
6. The caret symbol ^ or ** is used to indicate raising to a power.
7. The order in which the equations are entered does not matter.
8. The position of knowns and unknowns in the equation does not matter.

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Unit System:

Initially, EES is configured for SI system. Go to 'Unit System' under OPTIONS menu, if you need to check or change the unit system. See screen shot below:

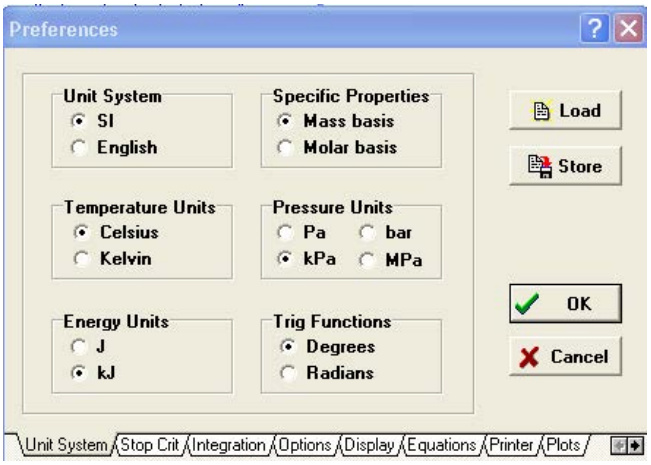

Fig. 1. EES screen shot-- setting Unit system

Also, go to 'Variable Info' under OPTIONS menu and set the units of all variables; this makes sure that all units are consistent and avoids unnecessary error messages popping up.

Formatted equations Window:

In this window, under the WINDOWS menu, you can see the equations entered in the equations window, in a formatted manner. This is useful to quickly check if you have entered the equations correctly.

Solutions Window:

After entering the equations successfully, press F2 to solve; solutions window will appear with all variables shown.

As an example, let us now solve in EES a system of three equations. Equations window, Formatted equations window and Solutions window are shown below:

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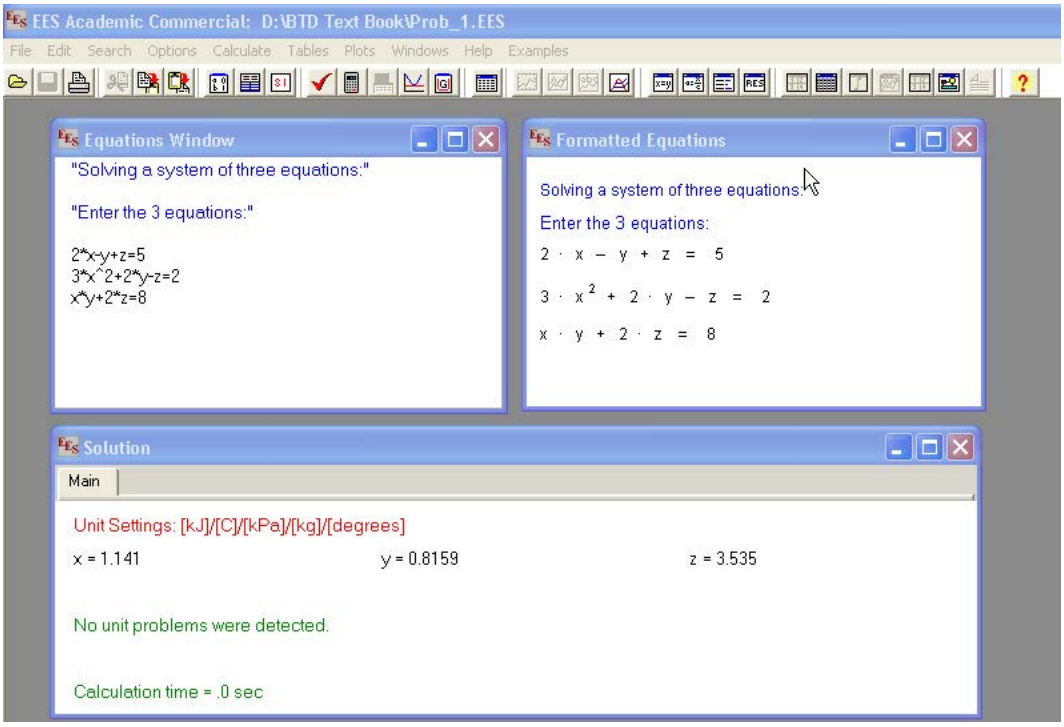

Fig. 2. EES Worksheet to solve a system of simultaneous equations

Fluid property functions in EES:

As mentioned earlier, EES has built-in functions for thermodynamic and properties of a variety of fluids, making it very convenient to solve problems in Thermodynamics.

As an example, let us find out the isentropic work produced in a turbine when steam expands from 30 bar, 350 C to 10 kPa. Also, find out the quality of exit steam.

Procedure is as follows: We know that isentropic turbine work = (h1 -h2) per kg of steam, where h1= enthalpy at inlet to the turbine, and h2 = enthalpy at exit. In EES, open the Equations window. Enter the given data:

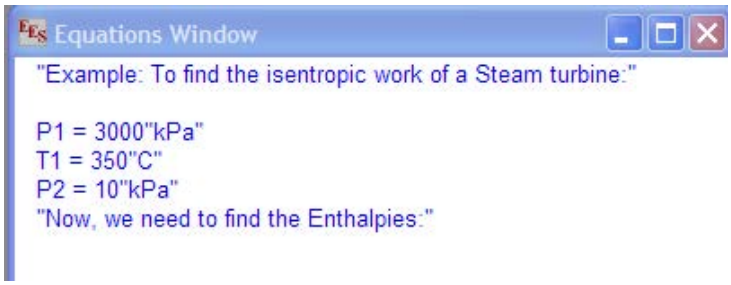

Fig. 3. EES Worksheet to find Isentropic work of Turbine

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Now, to get enthalpies of steam/water we have to use the built-in functions of EES. Before doing so, it is *important to confirm* that the unit settings are alright. So, under OPTIONS menu, click on 'unit system' and check that units are set to SI, as shown earlier.

Now, go to 'Function Info' in OPTIONS menu: Select 'Fluid properties' button. On the RHS, names of several fluids appear. Select Steam_NBS. On the LHS, select the property required viz. Enthalpy. To get enthalpy, you have to input any two independent properties. You can choose the independent properties, using the selection arrows at the bottom of screen. We have chosen P and T for state 1, since the same are given as data. Format for entering the function is also shown at the bottom line. (see the screen shot below).

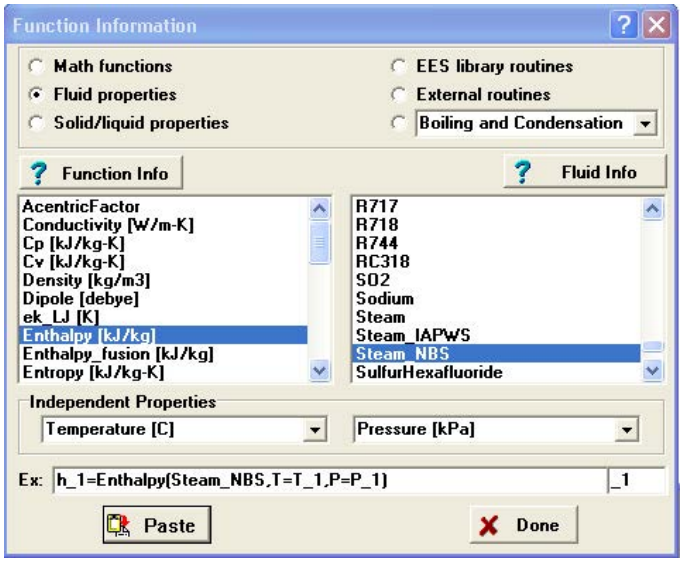

Fig. 4. EES – Function Info window

Now, paste the format on the equations window, taking care to enter the same notations for P and T as used earlier. For state 2 at the exit of the turbine, input the pressure and entropy; the pressure at exit of turbine, P2, is given as 10 kPa and we know that s2 = s1 for isentropic expansion in turbine. To determine quality at state 2, input pressure P2 and enthalpy h2.

Go to 'Variable Info' under OPTIONS menu and set the units of all variables to make sure that all units are consistent and no unnecessary error messages pop up. Screen shot is shown below:

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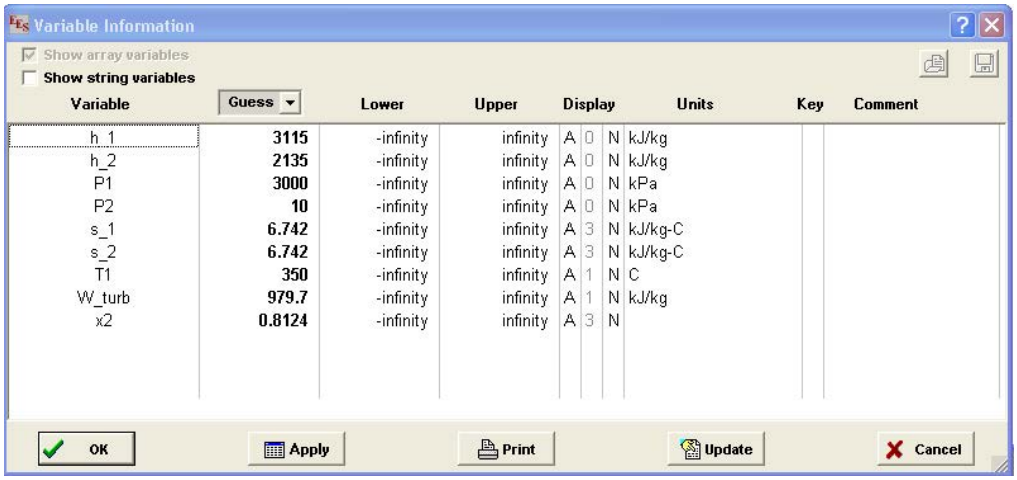

Fig. 5. EES – Variable Info window to set Units

Now, press F2 to calculate. Solutions window will appear, where we read the isentropic turbine work as 979.7 kJ/kg and the 'quality' at exit of turbine, x2 as 0.8124. See the screen shot below:

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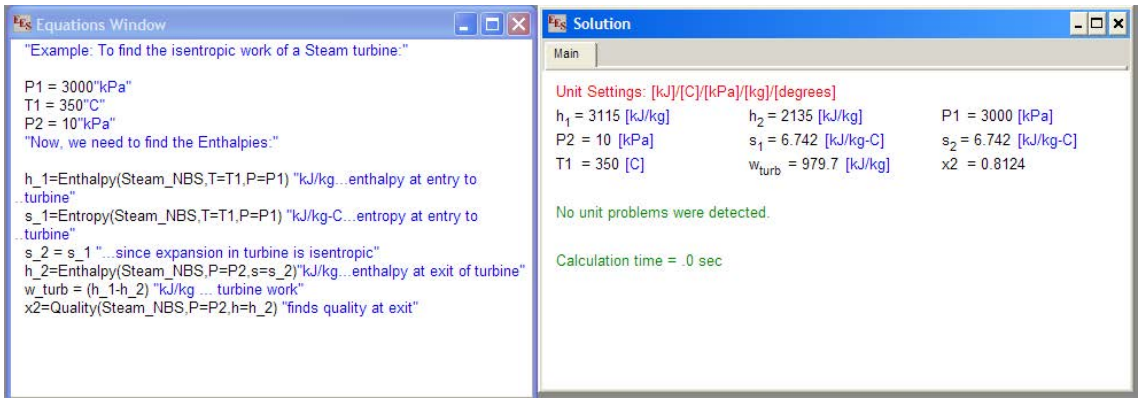

Fig. 6. EES Solution Window – Isentropic work of Turbine

Now, with this background, let us solve the following problem using EES:

Example problem: Consider a steam power plant operating on the ideal reheat Rankine cycle. Steam enters the high pressure turbine at 15 MPa and 600 deg.C and is expanded to 4 MPa. Then, it is reheated to 600 deg.C and is further expanded in the turbine to 10 kPa and is condensed in the condenser at a pressure of 10 kPa. Determine: (a) the moisture content at the end of expansion in the second stage of the turbine, and (b) the thermal efficiency of the cycle.

Note: This is an adapted version of a worked-out problem in the well known Text book, 'Thermodynamics' by Cengel and Boles.

Let us demonstrate the capabilities of EES by working out this problem, and by extending the problem to plot the efficiencies and moisture content at turbine exhaust for various reheat pressures.

Solution:

1. A schematic diagram and the reheat Rankine cycle on the T-s diagram are shown in Fig. 10 below.

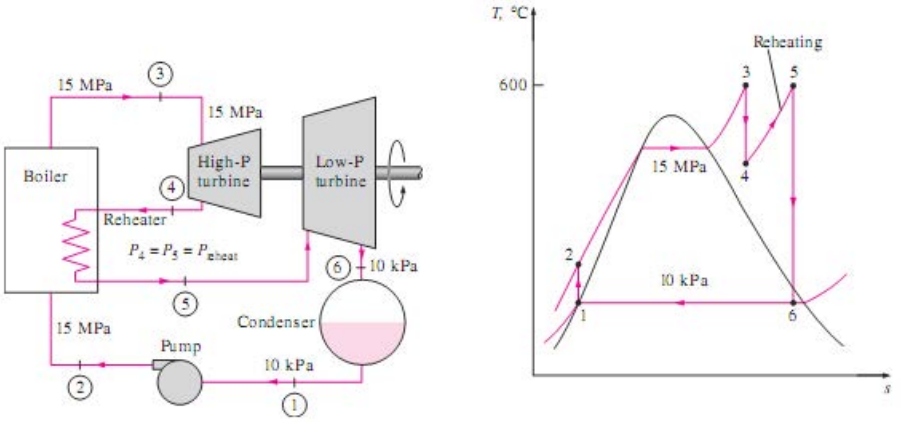

Fig. 7. Reheat Rankine cycle – schematic diagram and T-s diagram

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2. Choose the Unit system as SI (Ref: Fig.1), T (deg.C), P (kPa), and Energy (kJ)
3. Enter the equations in Equations window. Write comments against each equation, for clarity.

```
"Reheat Rankine cycle: "
T[3]=600[C]"Turbine inlet temp."
P[3]=15000[kPa]"Turbine inlet pressure"
P[2]=P[3]
P[4]=4000[kPa]"Reheat pressure"
P[5]=P[4]
P[6]=10[kPa]
P[1]=P[6]
T[5]=T[3]
T[6]=T[1]
x[1]=0"State point 1 is sat.liquid"
"-----------------------------------"
"State point 1:"
T[1]=T_sat(Steam_NBS,P=P[1])"finds sat. temp.  T[1]....Note that Property function T_sat( ) is used for fluid Steam_NBS"
s[1]=Entropy(Steam_NBS,x=x[1],P=P[1])"finds entropy s[1]...Note that Property function Entropy( ) is used"
h[1]=Enthalpy(Steam_NBS,T=T[1],s=s[1])"finds h[1].....Note that Property function Enthalpy ( ) is used"

"Pump Work:"
v_f=VOLUME(steam_NBS,P=P[1],x=x[1])"m3/kg..... sp. vol. of sat. liq. at State point 1"
w_p=v_f*(P[2]-P[1])"kJ/kg.....Pump work"



"State point 2:"
h[2]=h[1]+w_p"finds h[2]"
T[2]=TEMPERATURE(steam_NBS,P=P[2],h=h[2])"finds T[2].....Note that Property function Temperature ( ) is used"
s[2]=s[1] "....isentropic compression from 1 to 2"

"State point 3:"
h[3]=Enthalpy(Steam_NBS,T=T[3],s=s[3])"finds h[3]"
s[3]=Entropy(Steam_NBS,T=T[3],P=P[3])"finds s[3]"

"State point 4:"
s[4]=s[3]"....isentropic expansion from State point 3 to 4"
h[4]=Enthalpy(Steam_NBS,s=s[4],P=P[4])
T[4]=TEMPERATURE(steam_NBS,P=P[4],h=h[4])"finds T[4]"
x[4]=Quality(Steam_NBS,T=T[4],h=h[4])"finds x[4]....Note that Property function Quality ( ) is used"

"State point 5:"
h[5]=Enthalpy(Steam_NBS,T=T[5],P=P[5]) "finds h[5]"
s[5]=Entropy(Steam_NBS,T=T[5],P=P[5])"finds s[5]"

"State point 6:"
s[6]=s[5]"....isentropic expansion from State point 5 to 6"
h[6]=Enthalpy(Steam_NBS,s=s[6],P=P[6])"finds h[6]"
x[6]=Quality(Steam_NBS,T=T[6],h=h[6])"finds x[6], quality at State point 6"

"Turbine Work:"
w_turb=(h[3]-h[4])+(h[5]-h[6]) "kJ/kg.....Turbine work"
"Thermal effcy.:"
q_in=(h[3]-h[2])+(h[5]-h[4])"kJ/kg....Total heat input"
q_out=h[6]-h[1]"kJ/kg.... Total heat rejected"
w_net=w_turb-w_p"kJ/kg....Net heat input"
eta_th=w_net/q_in"....Thermal efficiency of cycle"
"Steam rate:"
SSC=3600/w_net"kg/kWh.....Specific Steam Consumption"
```

Fig. 8. Reheat Rankine cycle – Equations window

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Note that properties at various State points are entered in array notation (ex: P[1], T[1], s[1]…etc.). By doing this, all such variables are grouped together in 'Arrays table', available under WINDOWS menu.

4. Go to 'Formatted eqns' under WINDOWS menu and check that equations are entered correctly.
5. Go to 'Variable Info' under OPTIONS menu, and enter the Units against all variables.
6. Press F2 to Calculate. We get the following 'Solution Table':

Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]

η_{th} = 0.4499	q_{in} = 3896 [kJ/kg]	q_{out} = 2143 [kJ/kg]	SSC = 2.053 [kg/kW-h]
v_f = 0.00101 [m3/kg]	w_{net} = 1753 [kJ/kg]	w_p = 15.14 [kJ/kg]	w_{turb} = 1768 [kJ/kg]

Fig. 9. Reheat Rankine cycle – Solutions window

Note that Thermal efficiency is 44.99%; and turbine work is 1768 kJ/kg.

And, the Array Table gives properties at all State points. Note that quality at the end of expansion in turbine, x6, is 0.896, i.e. moisture content is 10.4%:

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Sort	1 h_i [kJ/kg]	2 P_i [kPa]	3 s_i [kJ/kg-K]	4 T_i [C]	5 x_i
[1]	191.7	10	0.6489	45.79	0
[2]	206.9	15000	0.6489	46.3	
[3]	3581	15000	6.677	600	
[4]	3153	4000	6.677	374.6	100
[5]	3674	4000	7.369	600	
[6]	2335	10	7.369	45.79	0.896

Fig. 10. Reheat Rankine cycle – Arrays Table

2.2 Parametric study in EES:

One of the most useful features of EES is its ability to provide parametric studies. For example, let us work out the Thermal efficiency and the moisture content at the turbine exhaust for the above mentioned Reheat Rankine cycle for various values of Reheat pressures P[4].

Select the New Parametric Table command under the TABLES menu. A dialog will be displayed listing the variables appearing in the Equations window.

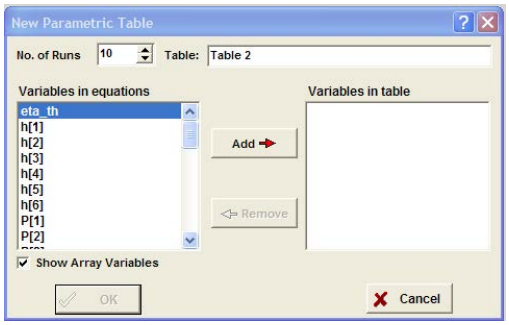

Fig. 11. EES screen shot – setting up the Parametric Table

Choose the variables eta_th, P[4] and x[6] for the Table and click Add and OK. The Parametric Table works much like a spreadsheet. You can type numbers directly into the cells. Numbers which you enter are shown in black and produce the same effect as if you set the variable to that value with an equation in the Equations window. *Delete the P[4] = 4000[kPa] equation currently in the Equations window or enclose it in comment brackets { }.* This equation will not be needed because the value of P[4] will be set in the table. Now enter the values of P[4] for which eta_th and x[6] are to be determined. Values of P[4] = 8600 to 3200 kPa have been chosen for this example. Now, select Solve Table from the CALCULATE menu. The Solve Table dialog window will appear allowing you to choose the runs for which the calculations will be done. Click the OK button. A status window will be displayed, indicating the progress of the solution. When the calculations are completed, the values of eta_th and x[6] will be entered into the table.

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Table 1

1..10	1 P_4 [kPa]	2 x_6	3 η_{th}
Run 1	8600	0.8445	0.4428
Run 2	8000	0.8495	0.4439
Run 3	7400	0.8549	0.445
Run 4	6800	0.8607	0.446
Run 5	6200	0.8669	0.447
Run 6	5600	0.8738	0.4479
Run 7	5000	0.8813	0.4488
Run 8	4400	0.8897	0.4495
Run 9	3800	0.8993	0.4501
Run 10	3200	0.9105	0.4505

Fig. 12. EES Worksheet – calculations in Parametric Table

2.3 Graphing in EES:

We are interested to know how the thermal effciency of the cycle varies with reheat pressure. Further, moisture content after expansion in the second stage of the turbine should not exceed about 15% to avoid damage to turbine blades. Therefore, let us plot graphs of eta_th and x[6] against Reheat pressure P[4]:

Select New Plot Window from the PLOTS menu. The New Plot Window dialog window shown below will appear. Choose P[4] to be the x-axis by clicking on P[4] in the x-axis list. Click on eta_th in the y-axis list. Select the scale limits for P[4] and eta_th, if required. Grid lines make the plot easier to read. Click on the Grid Lines control for both the x and y axes.

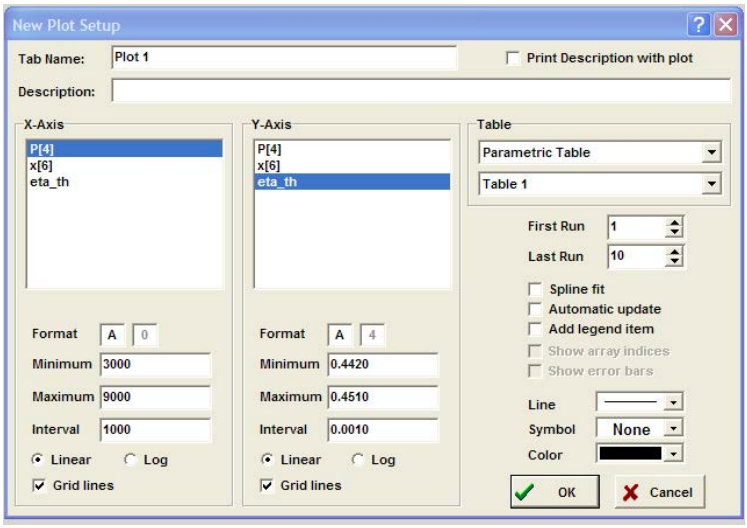

Fig. 13. EES Worksheet – New Plot set up

When you click the OK button, the plot will be constructed and the plot window will appear.

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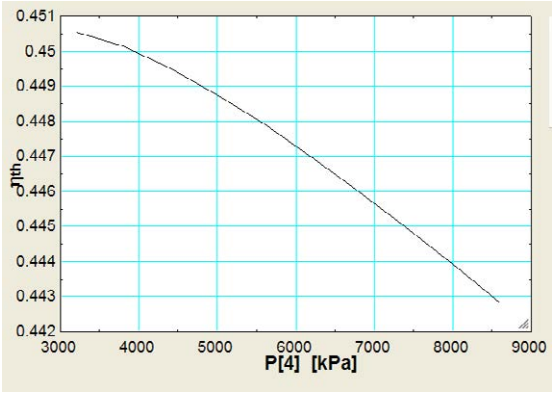

Fig. 14. EES graph – screen shot

Now, create an **overlay plot** on the plot just drawn, with P[4] on the x-axis and x[6] on the right hand y-axis: Click 'Overlay plot' under PLOTS menu; choose P[4] for x-axis and x[6] for the y-axis, with Y2-(right Y scale):

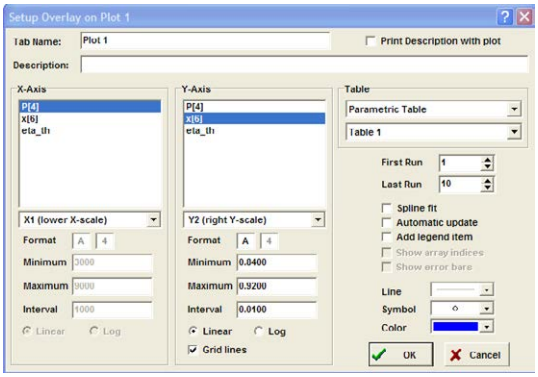

Fig. 15. EES graph – set up Overlay plot

Click OK and you get:

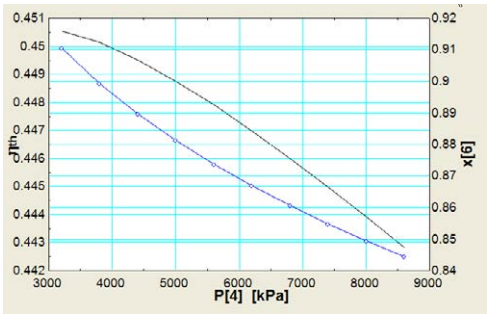

Fig. 16. EES graph – Overlay plot

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Once created, there are a variety of ways in which the appearance of the plot can be changed. Refer to the EES manual for further study. Help can also be obtained at any time by pressing F1. Fig. below shows the line and annotations added to the graph:

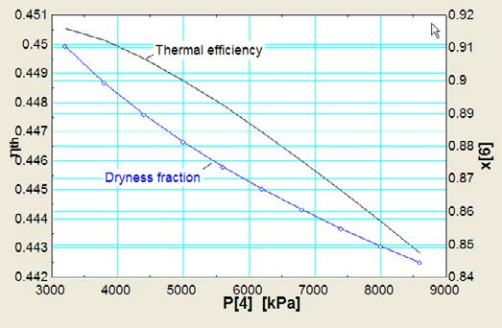
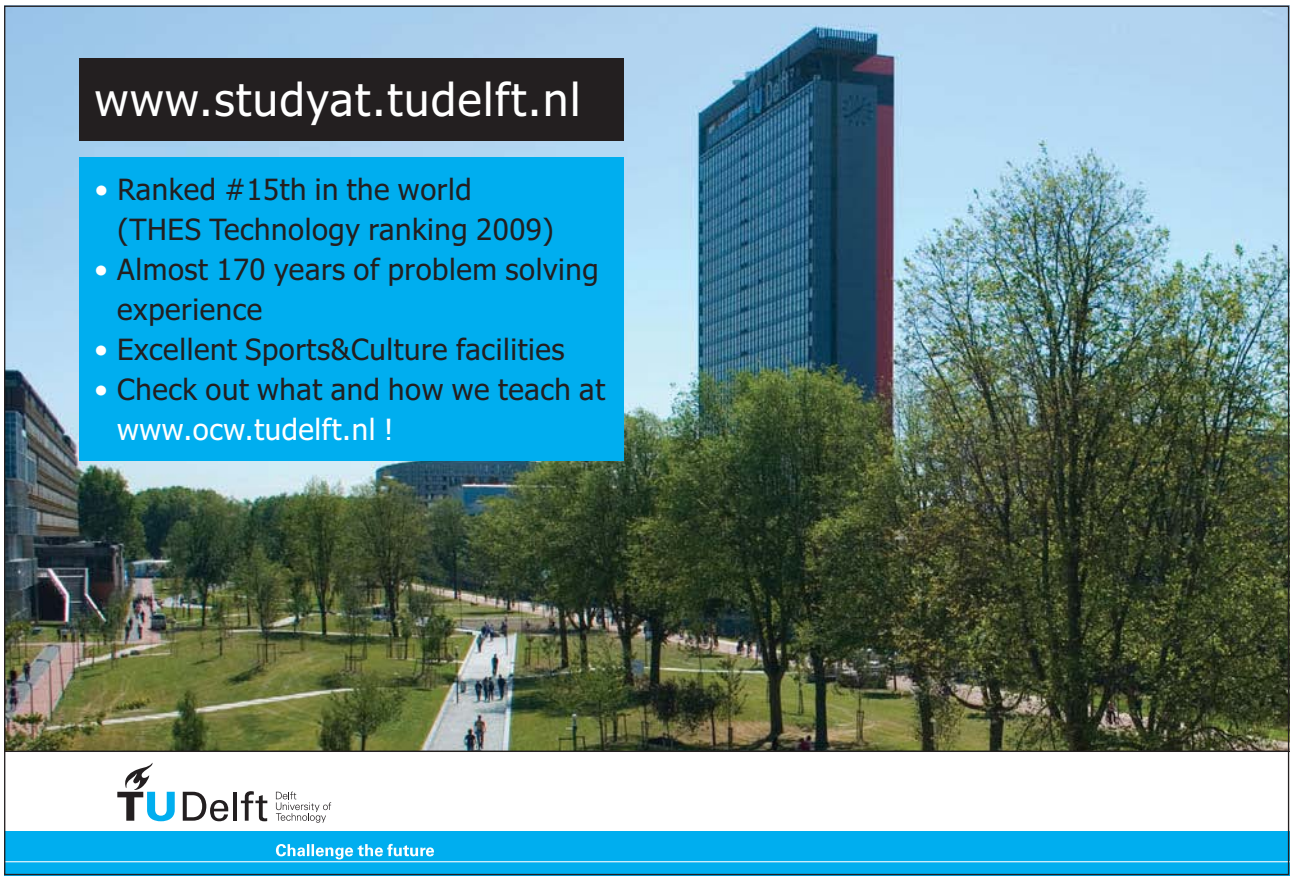


Fig. 17. EES graph – with annotations

Thus, we see that EES is a very versatile software. It is easy to learn, has an intuitive interface, and is particularly suited to solve problems in Thermodynamics and Heat Transfer because of its built-in functions for a large number of substances.



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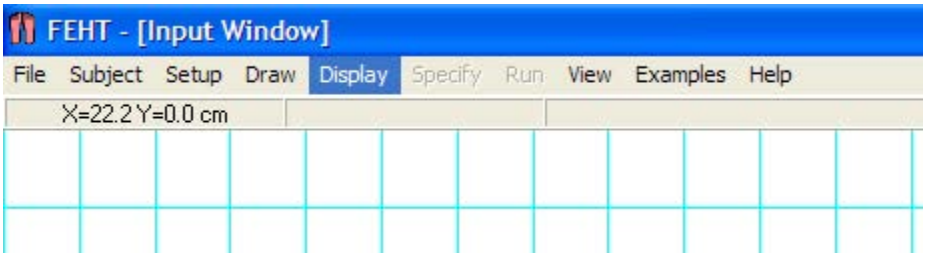
3 About Finite Element Heat Transfer (FEHT)

(Refer to an excellent write up on FEHT: Appendix-4, Introduction to FEHT, in the Text book "Heat Transfer" by Nellis and Klein, Cambridge University Press)

FEHT is a finite element, numerical analysis program to solve 1D and 2D steady state or transient conduction problems. You need to draw the geometry and divide it into a mesh of triangular elements. You can have coarse or fine mesh. Select the material, properties, boundary conditions etc. Check and run the program. In the post processing activity, you can view the temperatures at different nodes, of fluxes, or temperature distribution in color bands.

3.1 Using FEHT:

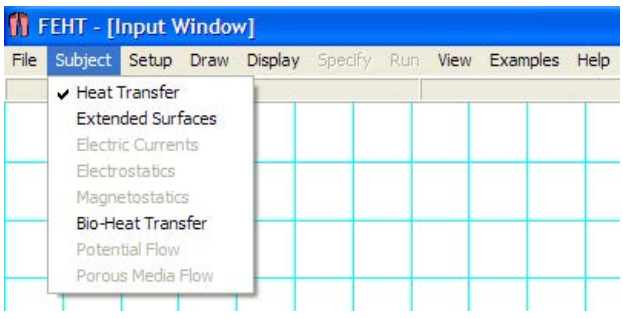
As you start FEHT, following screen is presented:



Observe that in the Menu bar, we have: File, Subject, Setup, Draw, Display, Specify, Run, View, Examples and Help.

Following are the different steps in solving the problem:

1. Choose Subject – Heat Transfer, Setup – Scale and Size:



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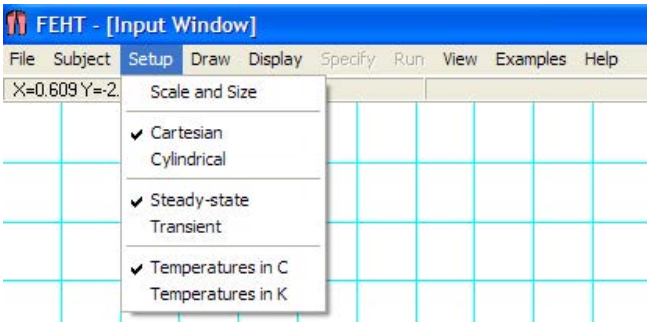
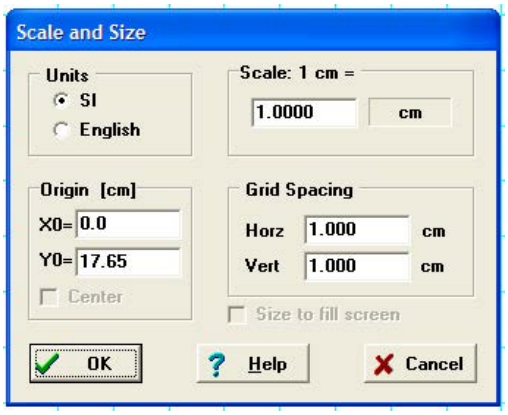
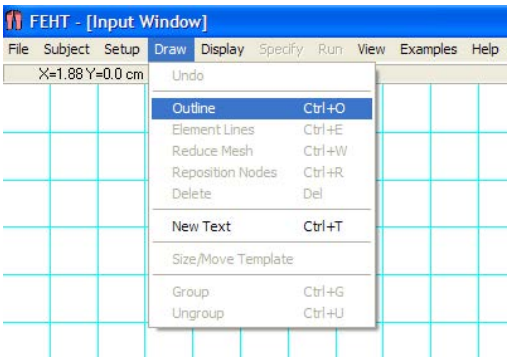
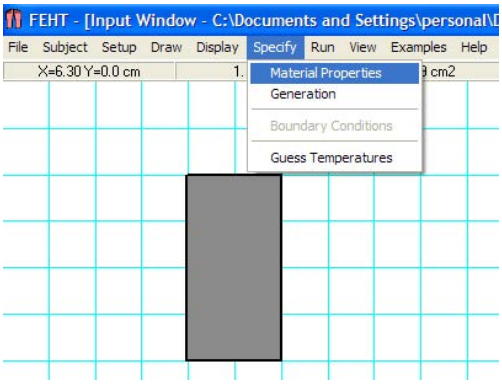


Clicking on Scale and Size, you get the following screen. Choose the desired Scale:



2. Draw Geometry (Draw – Outline) and Specify material properties (Specify – Material props):





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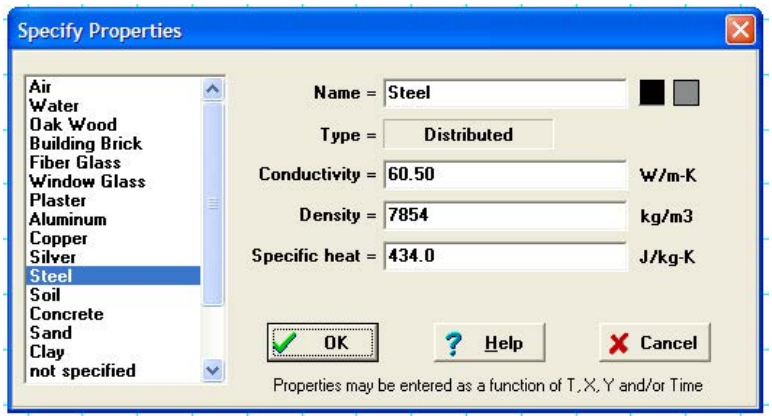

If the material used is not listed, use: 'not specified' and fill up the values of conductivity etc.

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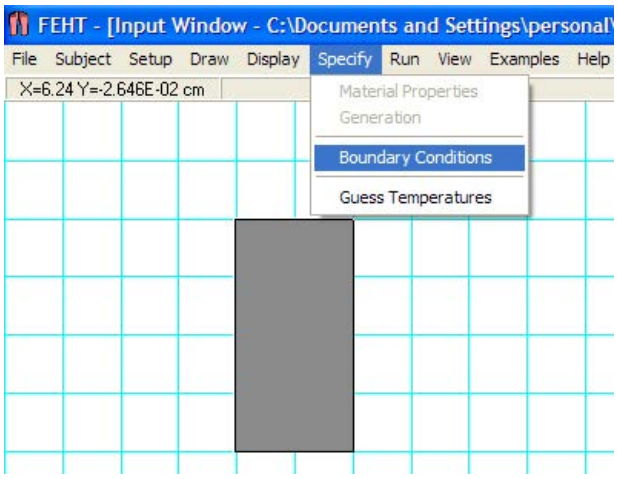
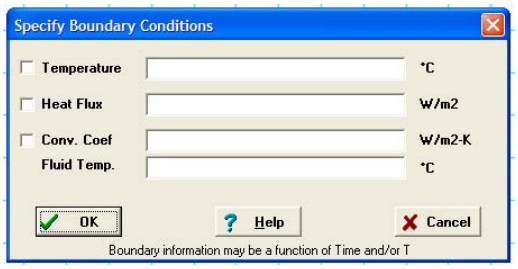
3. Select Boundary conditions: (Click on each segment of boundary and then click: Specify – Boundary conditions):

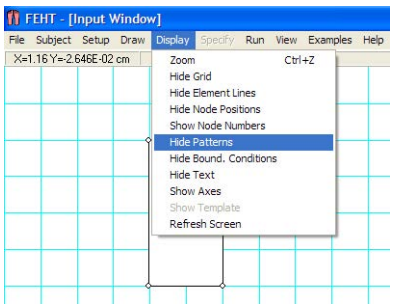


Clicking on Boundary Conditions, we get:



Fill up the Temp, heat flux or convection conditions as the case may be for each boundary outline.

4. Hide the Material patterns (click: Display – Hide Patterns)



Note that from the Display menu, you can show or hide: Grid, Element lines, Node positions and numbers, Patterns, Boundary conditions, Text etc.

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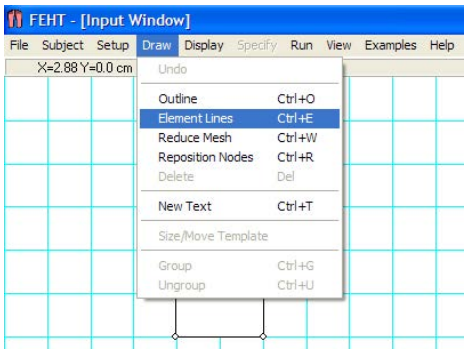
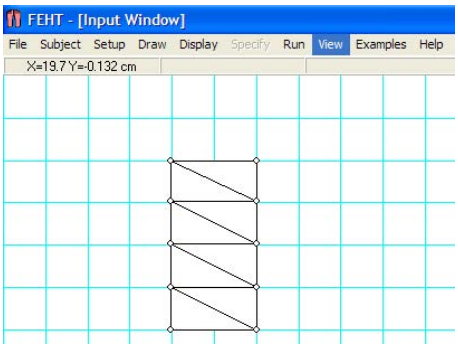
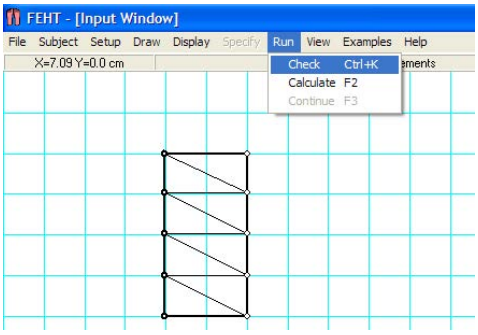
5. Click on: (Draw Element Lines) to discretize Geometry for Numerical solution:



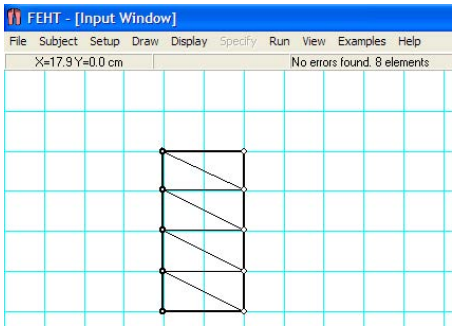


Note that from the Draw menu, you can also 'Reduce mesh', i.e. increase the no. of Elements and see if the results are improved.

6. Check for errors i.e. Click on: (Run – Check):



We get:



No errors are found. No. of Elements is also shown. If any problems are indicated, correct them.

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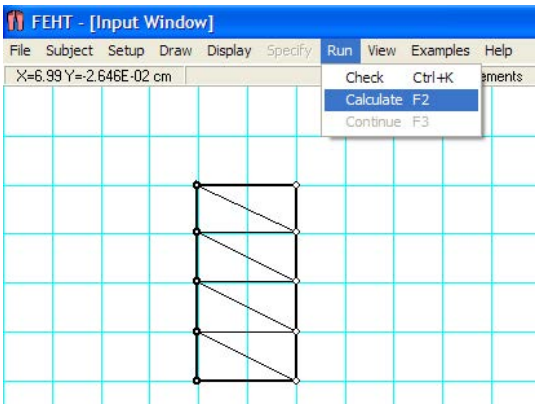
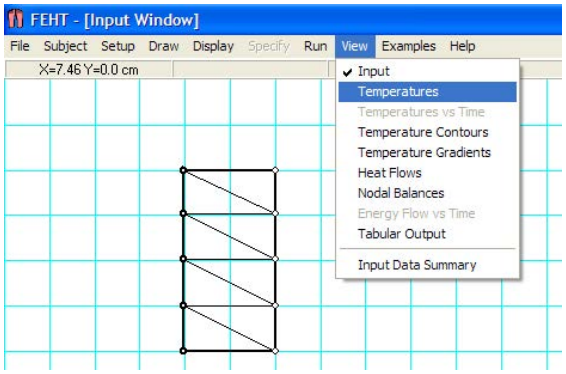
7. Next, click: (Run – Calculate):



You get:

Click: Continue

8. Now, view Results: Click on: (View – Temperatures) or (View – Temp contours) or (View – Heat flows):
   For ex: View-Temps:



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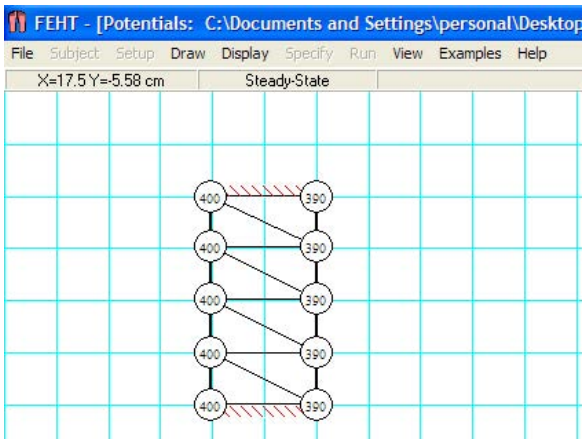
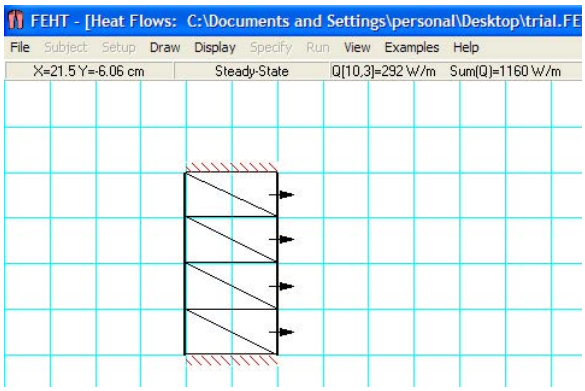
We get Temps at different Nodes:

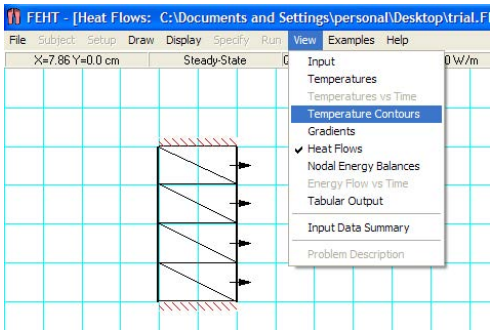


View_Heat flows:



See that heat flow direction is outwards on RHS, Total heat flow being: Q = 1160 W/m.

View-Temp contours: This gives the temp contours in a color band. We get:



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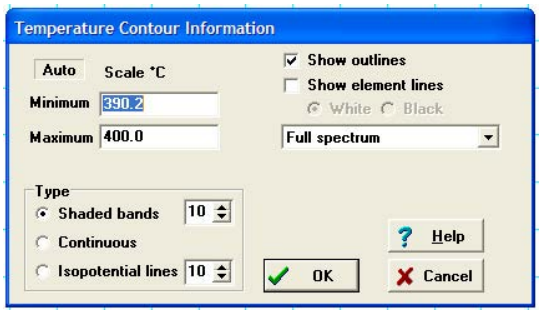
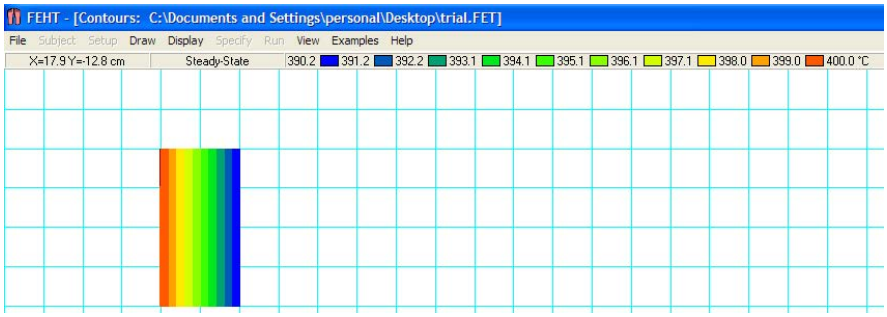
And:



Accept the default and press OK.

Then, we get:



Note that legend for temp colors is given on top of the screen.

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To further illustrate the use of FEHT, a worked-out problem from this book is shown below:

Prob. 1B.1. The inside surface of an insulating layer is at 270 C and the outside surface is dissipating heat by convection into air at 20 C. The insulation is 40 mm thick and has a thermal conductivity of 1.2 W/m.C. What is the minimum value of heat transfer coeff. at the outside surface, if the surface temperature should not exceed 70 C? Also calculate the rate of heat transfer. [VTU-7th Sem-B.E.-Dec.2007/Jan.2008]

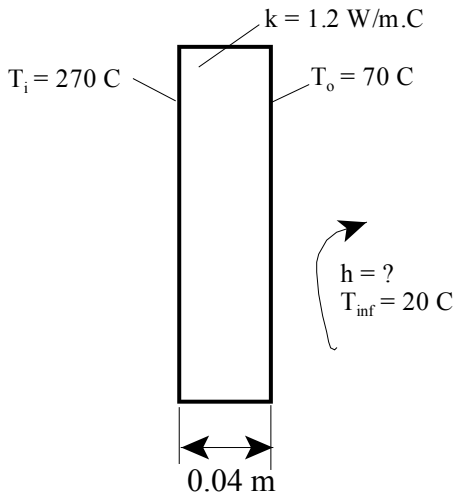
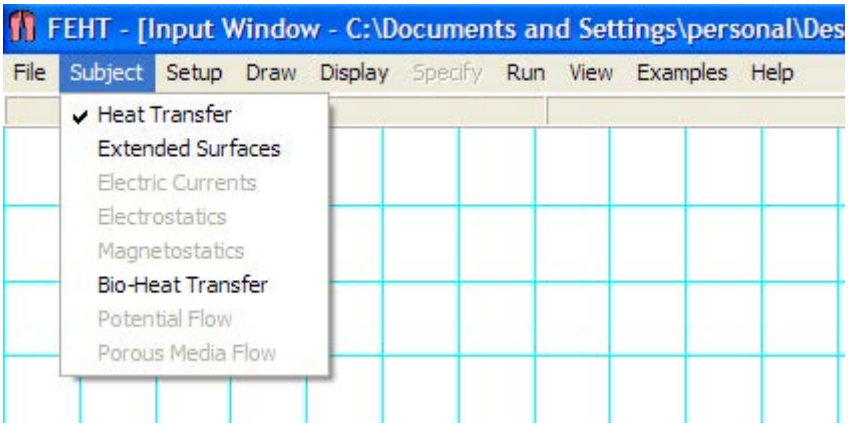


Fig. Prob.1B1.

Now, let us solve this problem with Finite Element Heat Transfer (FEHT) software:

Following are the different steps:

1. Start FEHT; In the Subject menu, Heat transfer is automatically selected:



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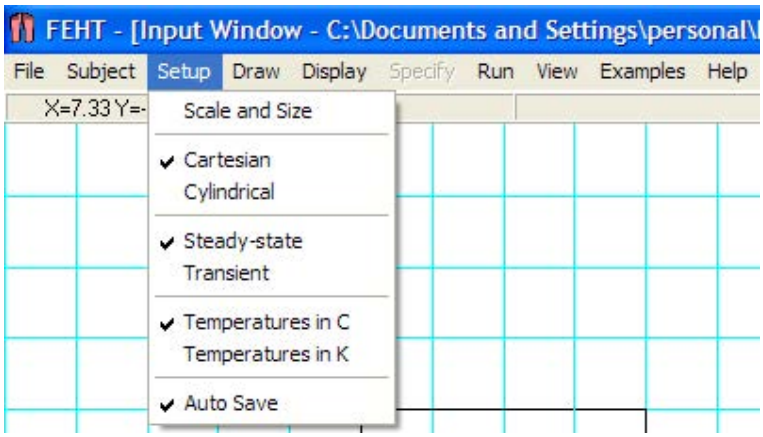
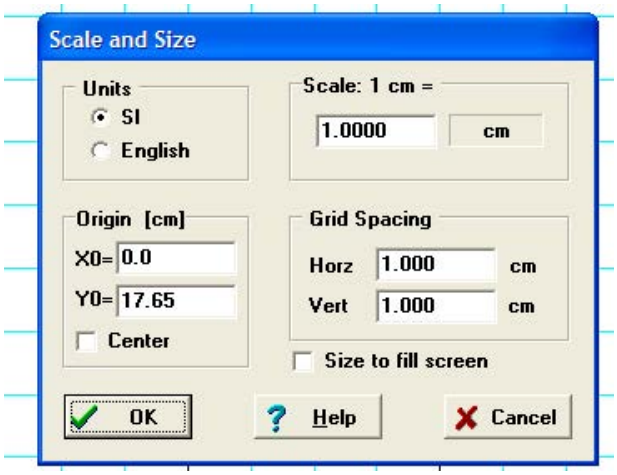
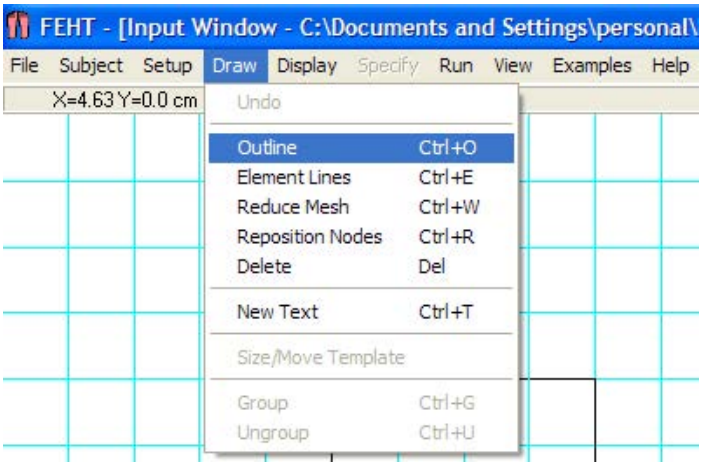
2. From the Setup menu, select: Cartesian coords, steady state as shown:



3. From the Setup – Scale and Size, choose the scale 1 cm = 1 cm:



4. Then, from the Draw menu, select Outline and draw the outline of the material:



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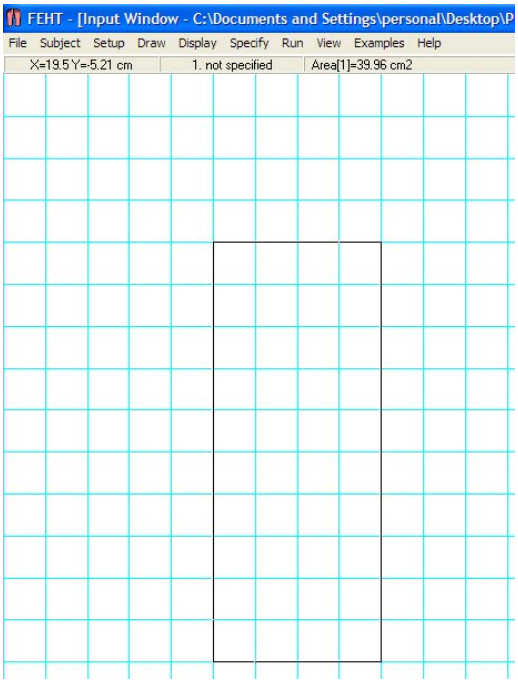
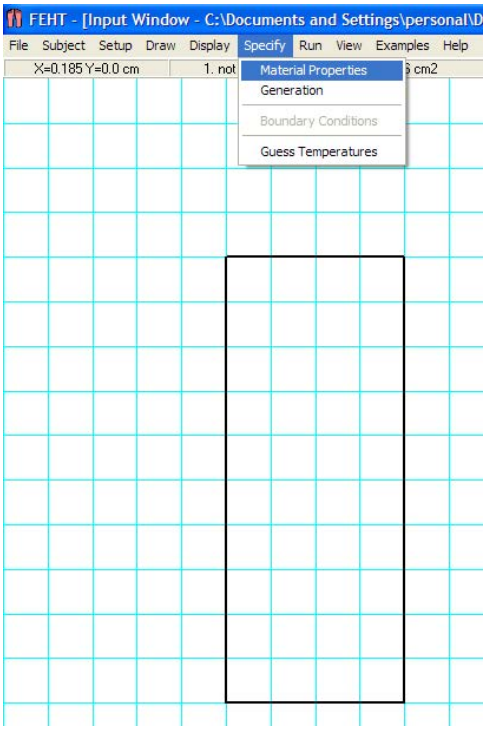


Note that we have chosen the height of the section arbitrarily as 10 cm. By default, depth perpendicular to paper is 1 m.

5. Now, specify the material properties from the Specify menu:



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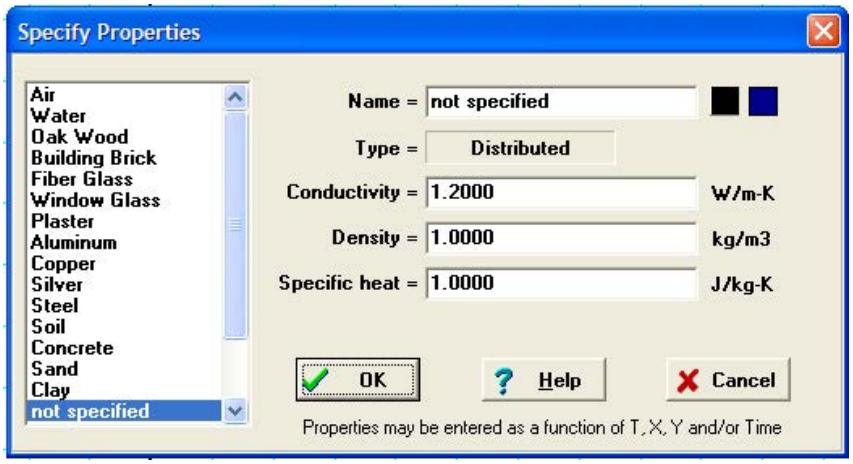

Note that we have selected material as 'not specified'. Conductivity (k) is entered as 1.2 W/m.K, as per data. Density and sp. heat are left as already entered *since they are not required for steady state calculations*. Hit OK to confirm.

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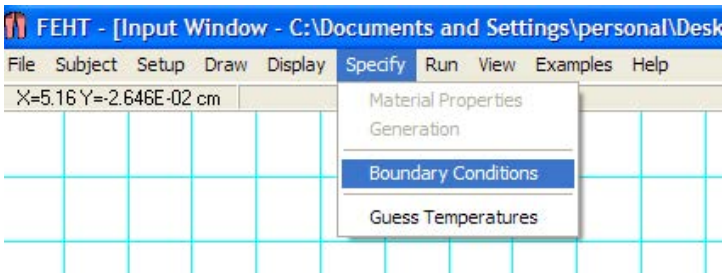
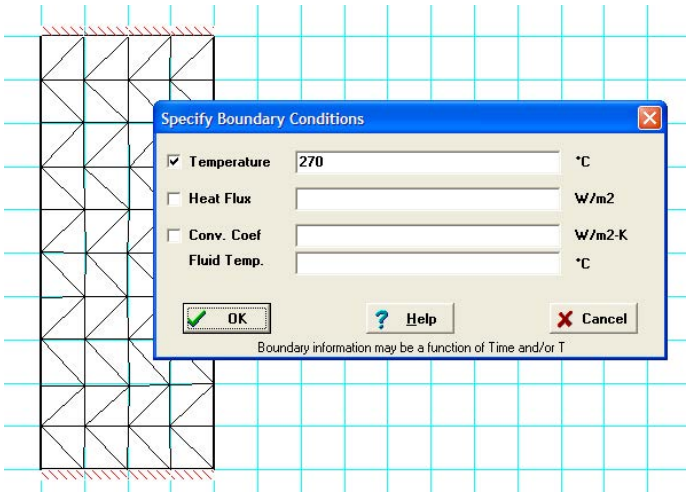
6. Now, choose the Boundary conditions from Specify menu:

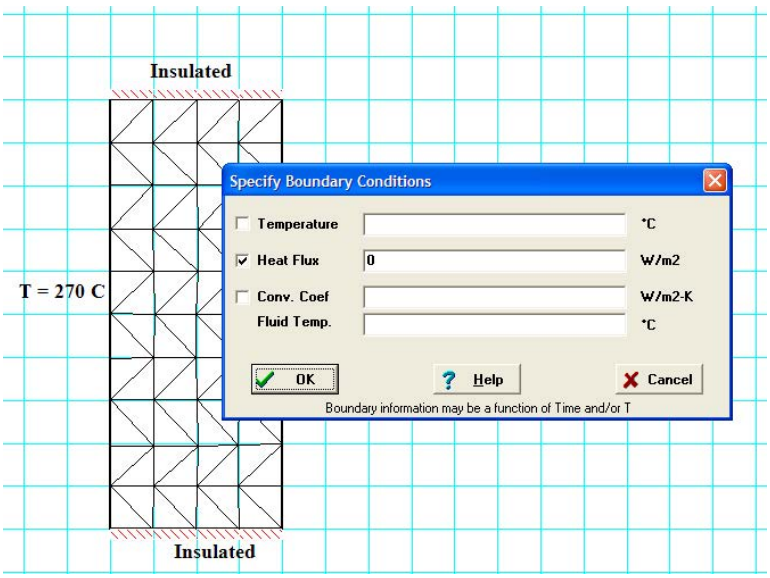


We have:

LHS is at a constant temp of 270 C:



And, top and bottom surfaces are shown as insulated (i.e. zero heat flux) to force 1D conduction:



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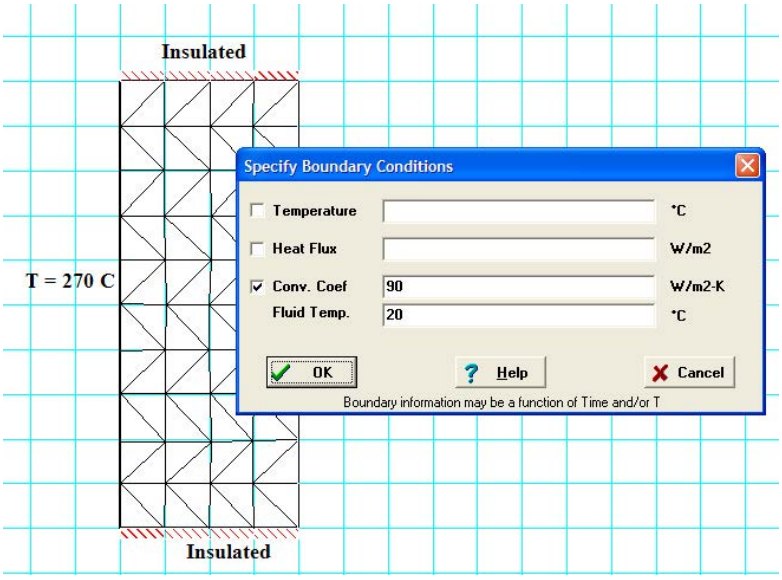
And, on RHS, we impose the convection conditions.

Here, h is unknown and surface temp T_0 is given as 70 C. However, we assume a value for h = say, 90 W/m^2.K. (And, later, solve repeatedly for different values of h such that we get the surface temp T_0 as 70 C):



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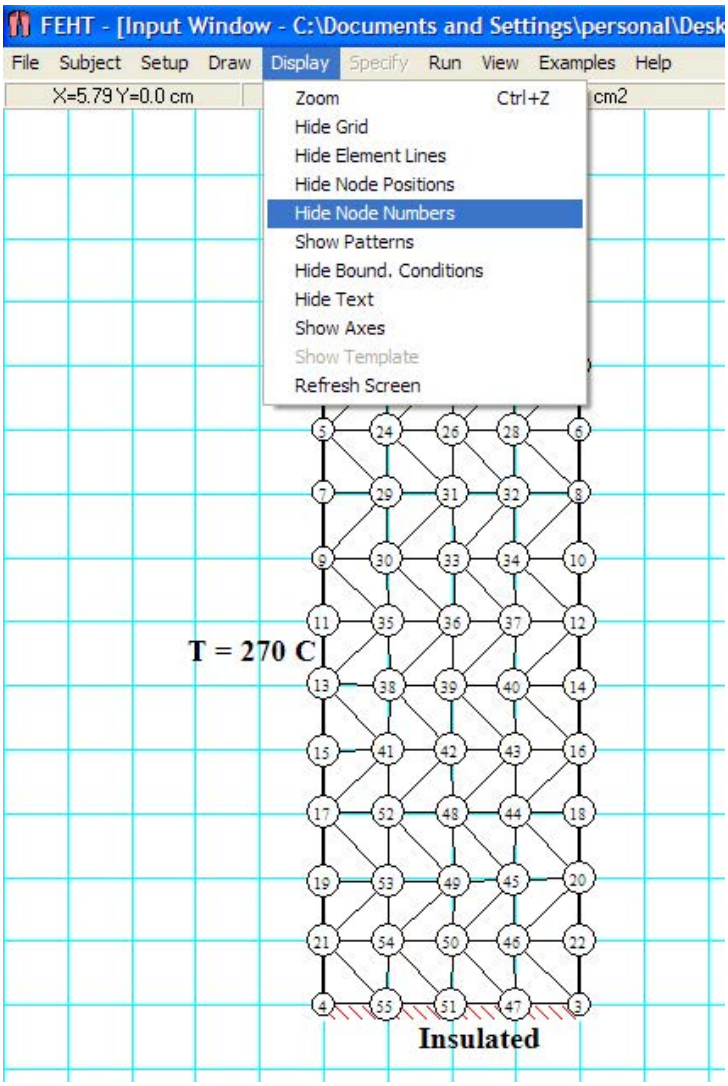
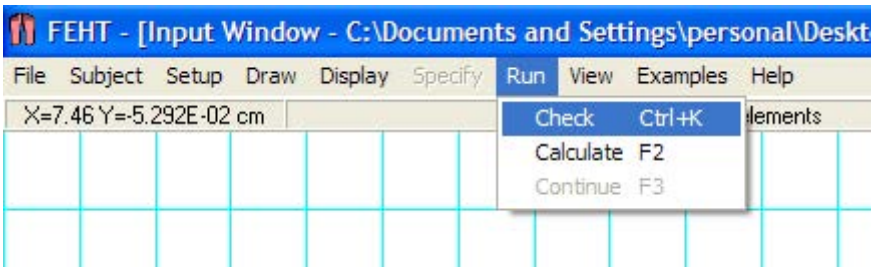
7. From the Display menu, you can show or hide Node positions, Node Nos. etc:



8. Now, check that everything is OK before final calculations from the Run menu:



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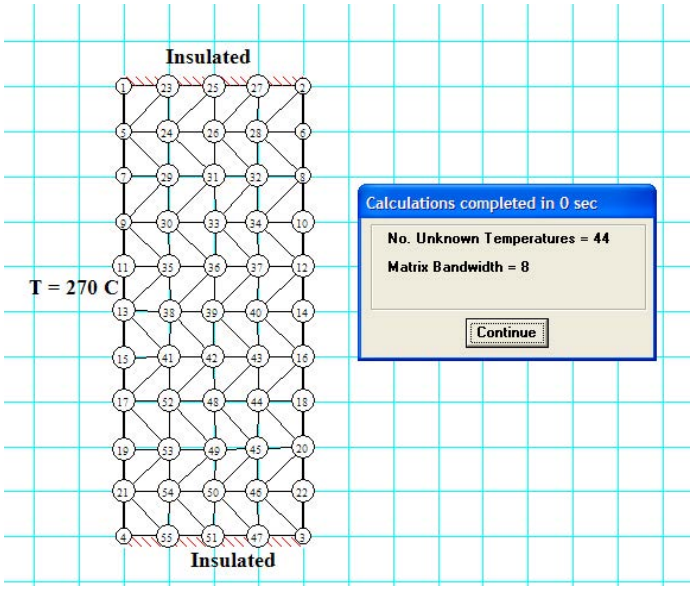
We see:

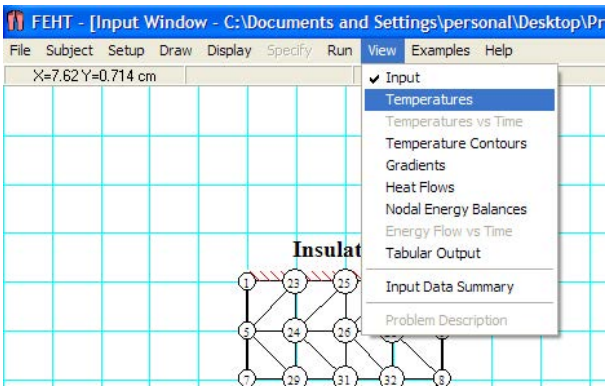
i.e. there are 80 elements and no errors are found.

9. Now, give the Calculate command from the Run menu: We get:



Press 'Continue'.

10. Go to the View menu and press Temp to see the temps at different Nodes:



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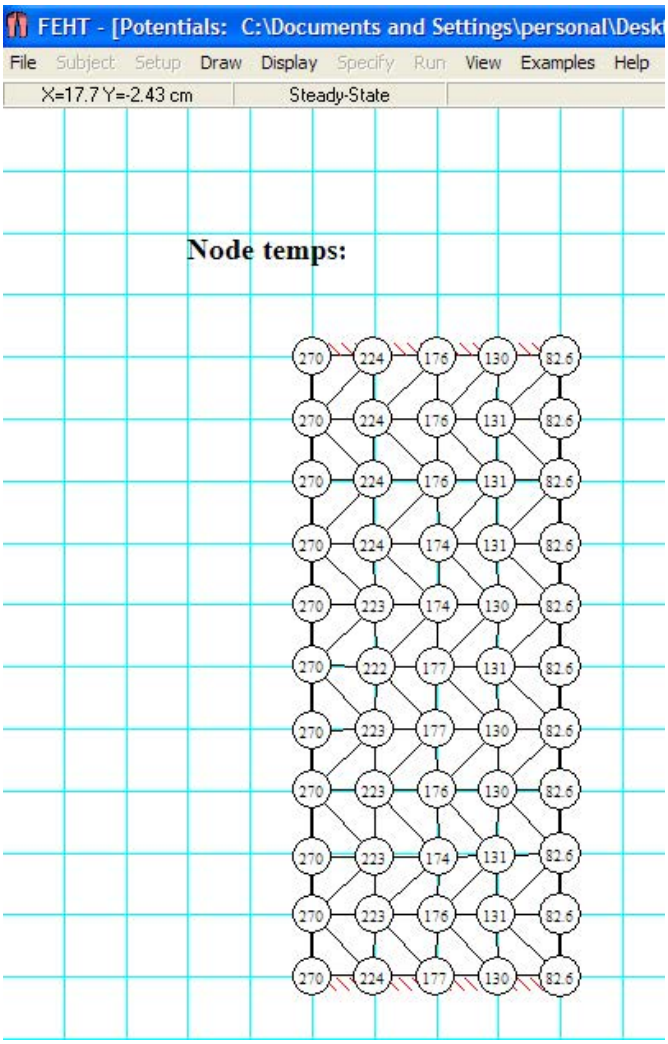
We see:



You can observe and correlate the Node Nos. and the corresponding temperatures.

However, according to the problem, temp on the RHS should be 70 C.

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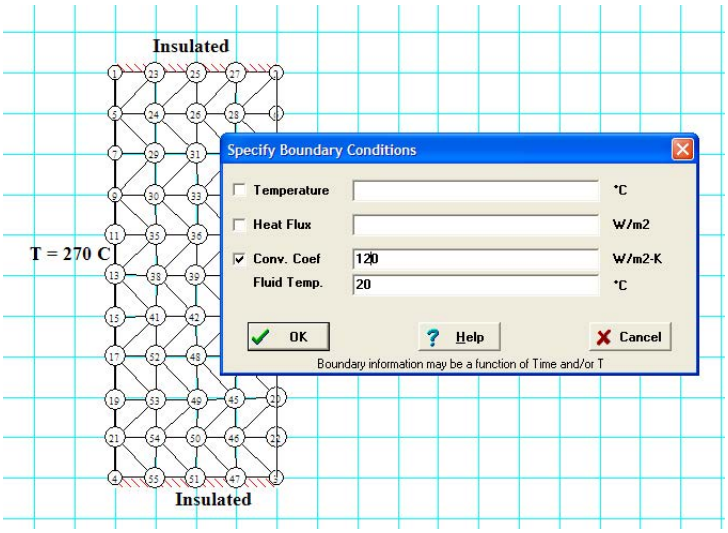
So, now, we change the value of h from the Specify – Boundary conditions menu such that T_0 becomes 70 C. ***This is a trial and error process***: Finally, we get:



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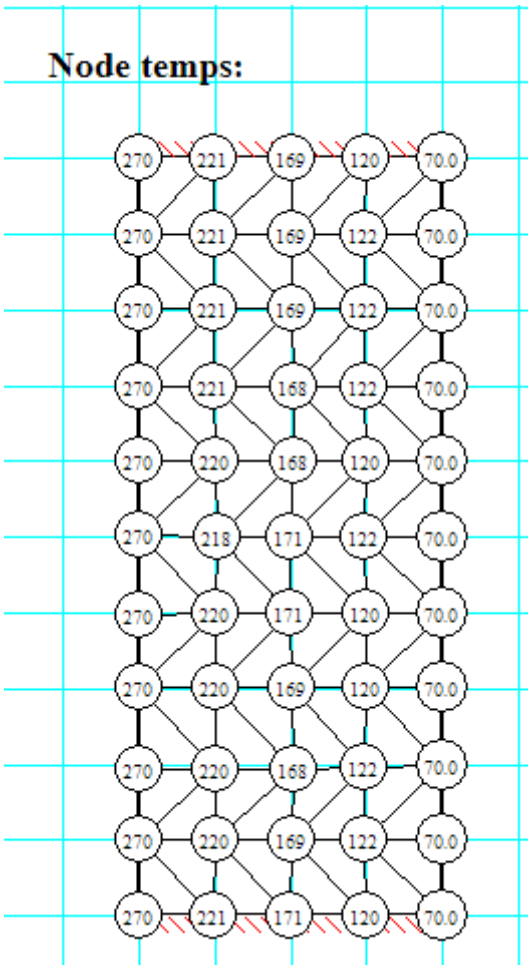
And Calculate from Run menu and then, Temps from the View menu:



Now, the temp on RHS is 70 C, as required.

Therefore: the value of h = 120 W/m^2.K….. Ans.

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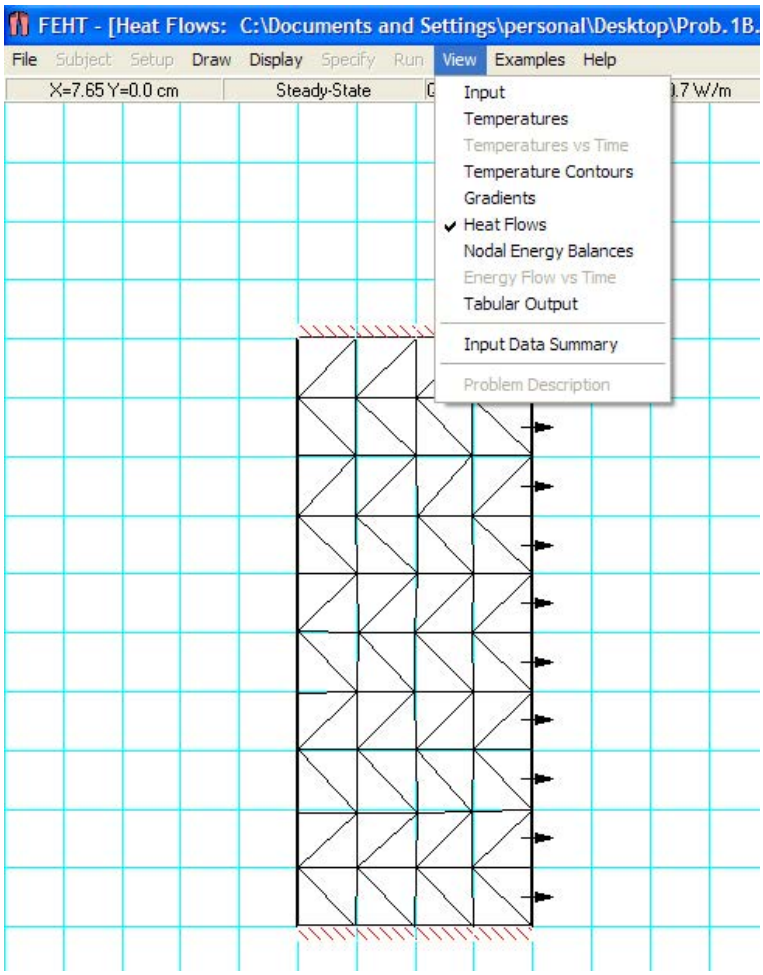
Heat transfer, Q is obtained by choosing View – Heat flows:



On the RHS, as we can see, the heat flow is outwards. Its value is shown on the top of the same screen as 600.7 W/m:

The section extends to 1 m depth perpendicular to paper, and the height of the section was arbitrarily taken as 10 cm.

Therefore, area for heat transfer is: 1 x 0.1 = 0.1 m^2.

i.e. **Q = 600.7 / 0.1 W/m^2 = 6007 W/m^2. ….Ans.**

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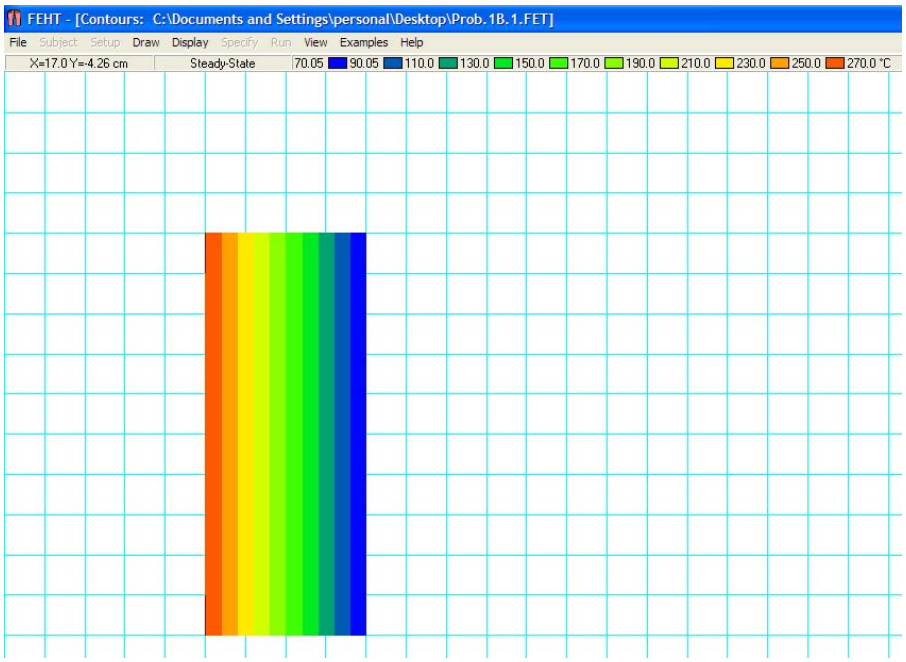
Temp. contour: This is obtained by clicking Temp contour from the View menu:



It also shows the color scheme on top of the screen.

Next, calculate Temperatures on RHS for different values of h:

This is obtained in a straight forward manner by changing the value of h in 'Boundary conditions' in the Specify menu, for the RHS:

We get:

h (W/m^2.K)	T_0 (deg.C)	Q (W)
20	170	3002
40	127	4289
60	103	5005
80	88.2	5460
100	77.7	5775
120	70	6007
140	64.2	6183
160	59.5	6323
180	55.8	6436
200	52.6	6529

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4 About MS EXCEL Spreadsheet

EXCEL is the most popular spreadsheet software that comes bundled with MS Office.

Note the following points in connection with EXCEL:

1. EXCEL is a very popular spreadsheet which is available in practically every Personal Computer (PC), since, generally, every PC comes with MS Office pre-installed in it.
2. EXCEL, though perceived as a Chartered Accountant's tool, is very good for mathematical calculations and producing publication-quality graphs, required for scientific works.
3. EXCEL has a cell structure, made of rows and columns; so, it is particularly suited for calculations of ***numerical methods in heat transfer***, where each cell is considered as a 'Node'.
4. EXCEL spreadsheet is 'live', i.e. change of one cell immediately affects calculations in other cells which are related to the changed cell. This fact helps to visually 'observe' the results of parametric analysis.
5. EXCEL has a large number of built-in functions to perform calculations in the areas of Finance, Mathematics, Trigonometry, Statistics, Database… etc.
6. Graphing in EXCEL is very easy. Formatting of graphs is also very easy.

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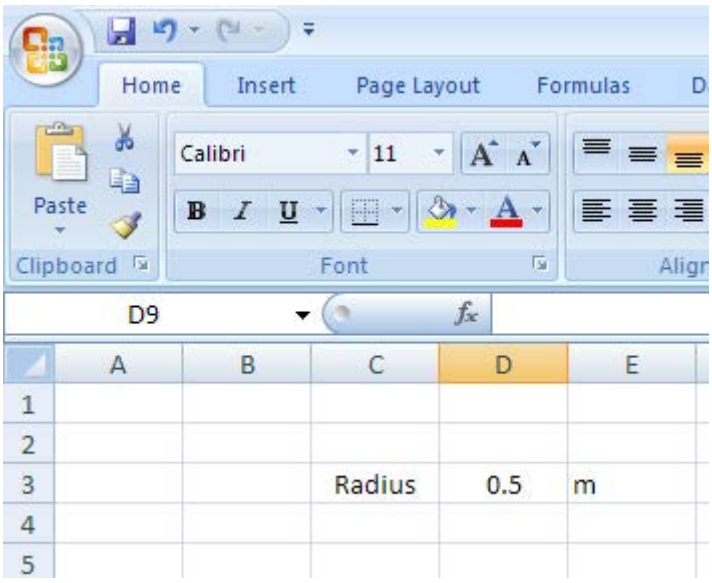
7. In EXCEL, there is facility to record and execute Macros, i.e. oft-used commands in the required sequence can be recorded and then used as many times as needed.
8. EXCEL has a very simple and powerful programming language called **'Visual Basic for Applications' (i.e. VBA, in short)** running in the background. By writing programs in this language, EXCEL can be made to perform very complex calculations. ***Thus, in fact, EXCEL can make any calculations performed by other, more sophisticated and dedicated softwares.***
9. One ***draw-back*** of EXCEL is that the formulas used in calculations are not readily visible; so, tracing the errors is a bit tedious. However, this can be alleviated by **'naming' the cells** used in equations. Also comments can be included to make the calculation procedures clear.

It is assumed that the student is familiar with EXCEL since EXCEL is introduced in high school level itself. For detailed instructions, one may refer to the very good help system available in EXCEL or to many specialized, illustrated books on working with EXCEL.

However, we give below a few important tips that may be helpful while solving heat transfer problems with EXCEL:

1. **Start EXCEL, and enter the data, and name the cells:**

While entering data, have the variable, its numerical value and the units in adjacent columns. For, example, let us say that we wish to find out the volume and surface area of a sphere when its radius is given:



Cell D3 gives value of radius (=0.5 m). Now, volume of sphere is (4/3) * PI * D3^3. And, surface area is 4 * PI * D3^2. However, if we name the cell D3 as Radius it is very convenient to enter the formulas.

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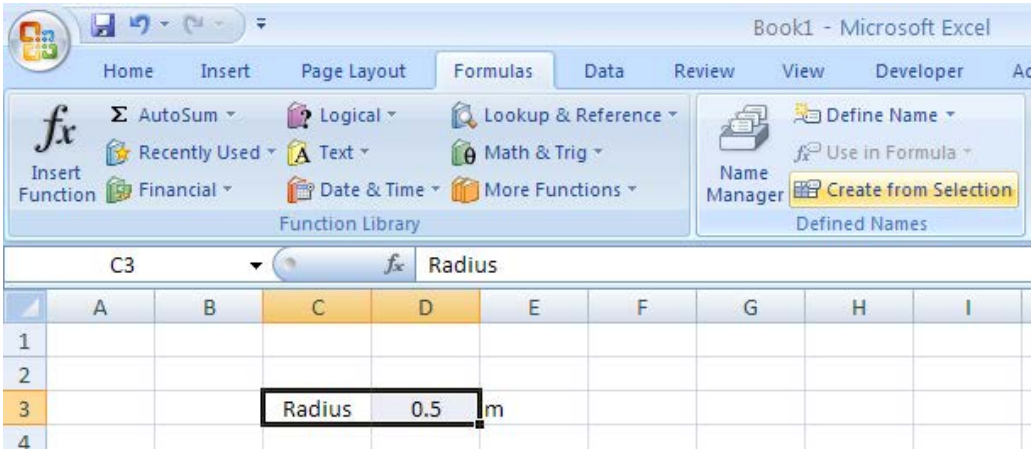
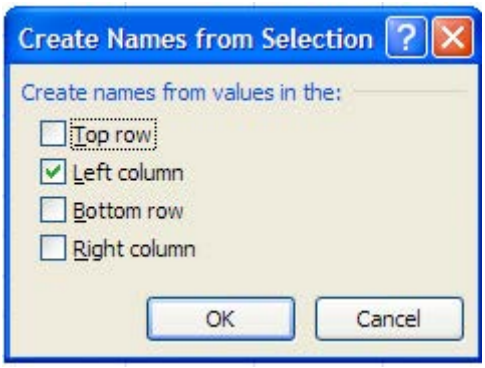
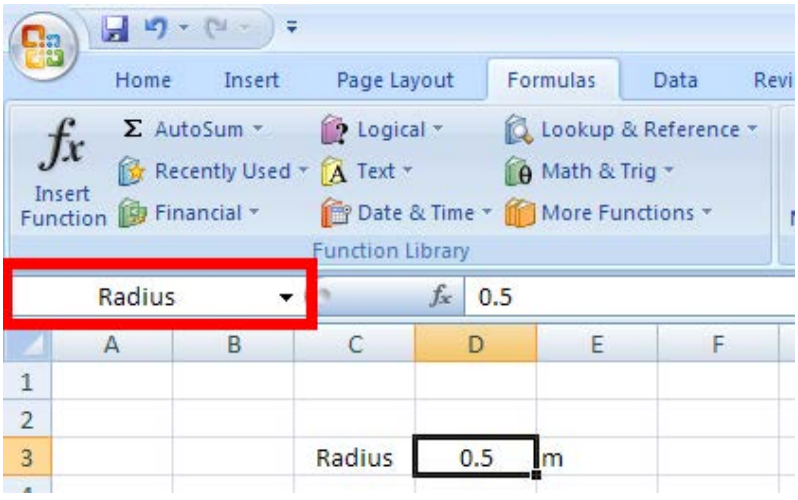
Procedure to name the cell is as follows: select cells C3 and D3 and click on Formulas tab:



And, click on 'create from selection: We get the pop up:



Clicking OK will name the cell D3 with whatever is entered in the left column in cell C3, i.e. Radius. Click OK. Now, if you select D3, you will see in the Formula bar the name of that cell:



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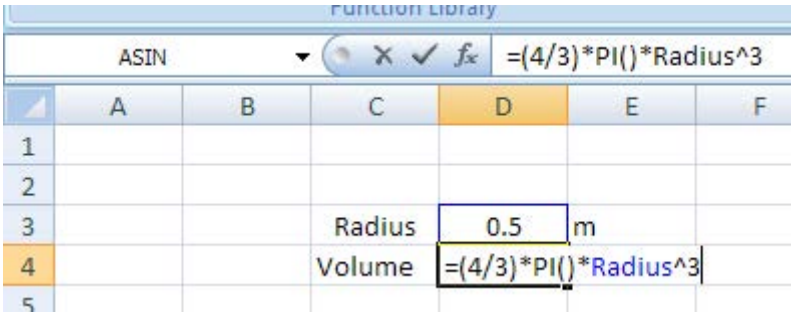
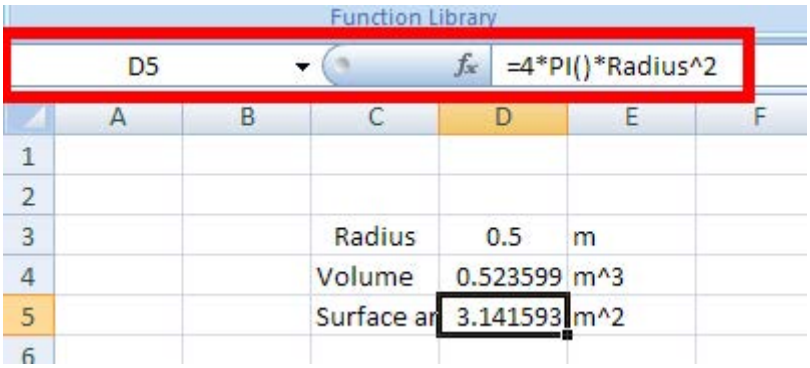
2. **Next, enter the formulas for Volume and Surface area in cells:**



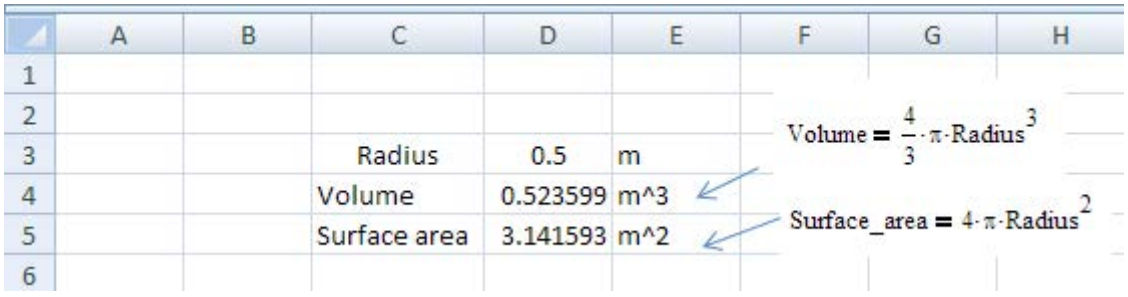
Note that we have used 'Radius' in the formula, instead of D3.

Similarly for Surface area:



Naming the cells *will help us in entering the formulas without errors easily, particularly when the formulas are complicated or too long.*

3. **It is preferable to show the formulas hidden behind the cells, if possible, as shown below. (Here, we have pasted the eqn used in cells D4 and D5):**



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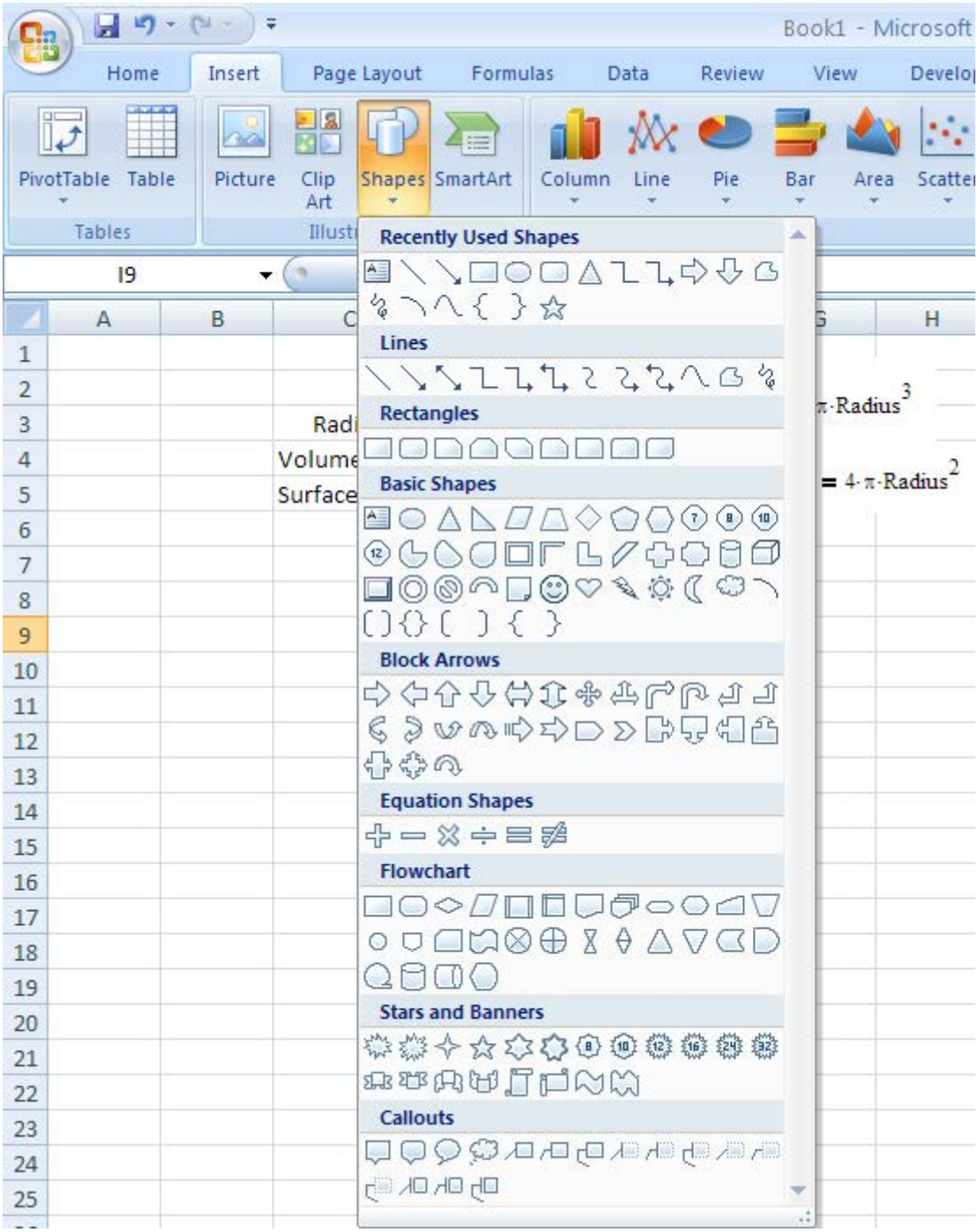
Arrows were inserted by going to: Insert-Shapes as shown below:



Note that we can insert lines, shapes and several objects of different shapes.

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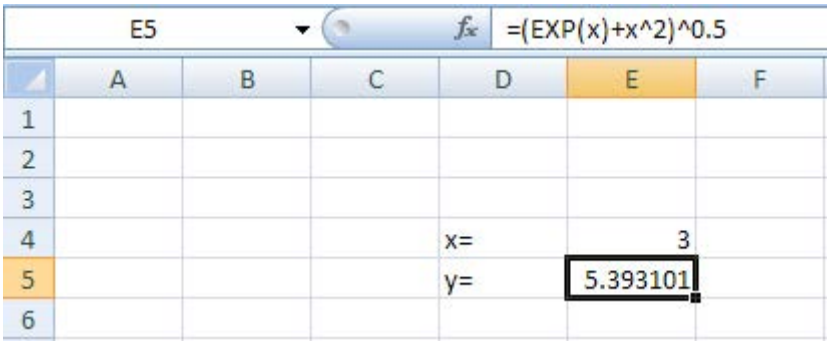
4. **Use of Goal Seek in EXCEL:** This is an important use of EXCEL, where we can change the value of the Target cell to the desired value by changing a connected cell by iteration. The procedure is explained with an example:

Consider the function y = (exp(x) + x^2)$^{0.5}$.

Set up an EXCEL worksheet as follows:



Note the formula used for y in cell E5 in the Formula bar.

We see that when x = 3, value of y is 5.393101.

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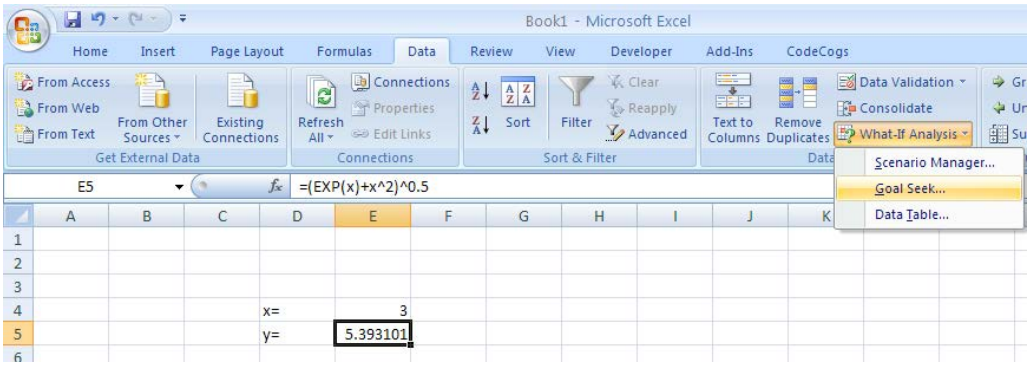
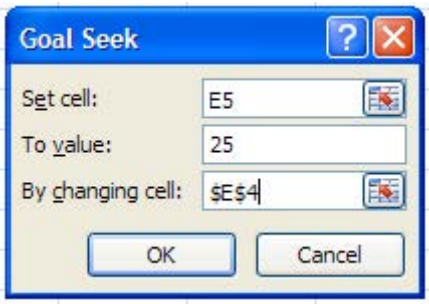
Now, let us say, we want to find out the value of x to make y = 25.

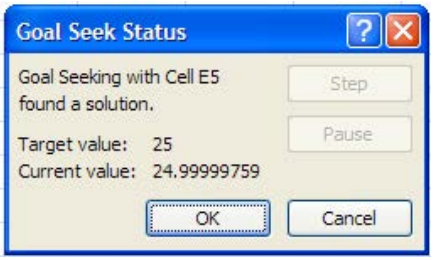
We use Goal Seek. Go to Data – What-If Analysis-Goal Seek.



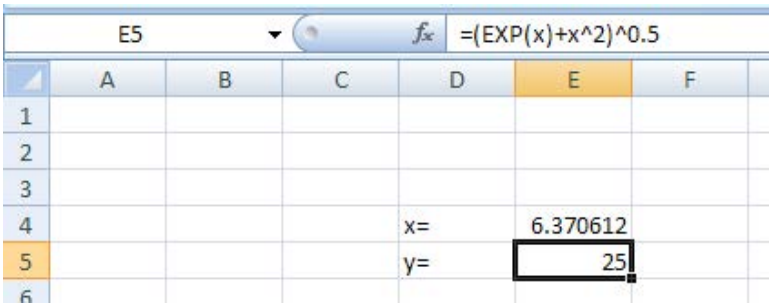
We get:



Set cell is E5, To value is 25, By changing cell: E4. Click OK, and we get:



And the solution for x appears as:



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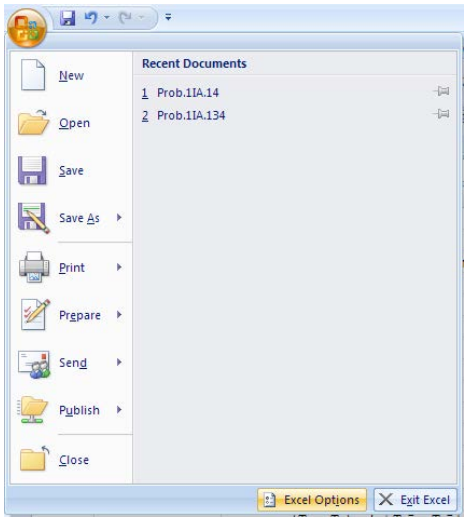
Goal Seek is conveniently applied when a single is to be changed to get desired value in a Target cell. Of course, the cell to be changed should be connected to Target cell by a Formula.

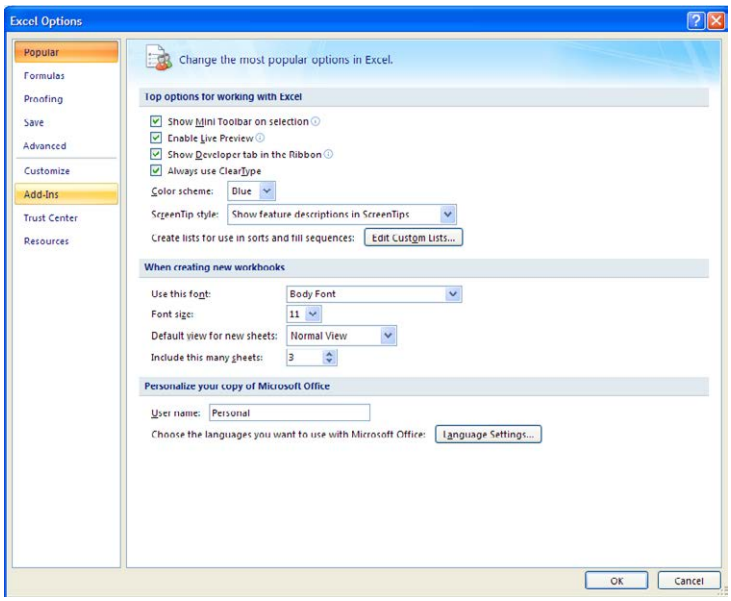
5. **Use of Solver in EXCEL:** Solver is used when the Target cell is to get a desired value by changing multiple no. of cells. This is conveniently used to solve a set of linear or non-linear algebraic equations.

First, **enable solver**, if it is not already done. To do this:

Click on Office button and press Excel Options:



We get:



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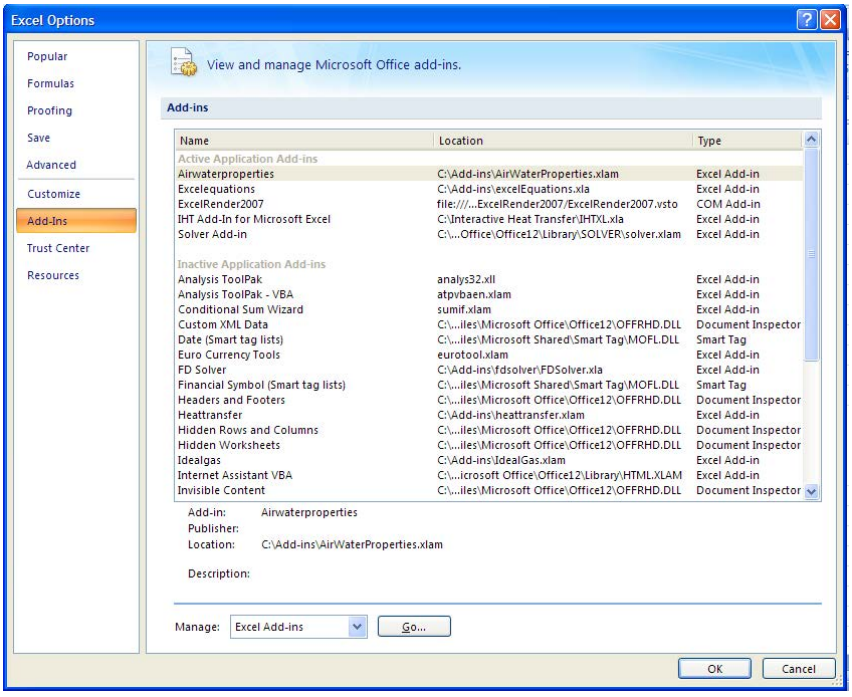
Press AddIns:

We get:



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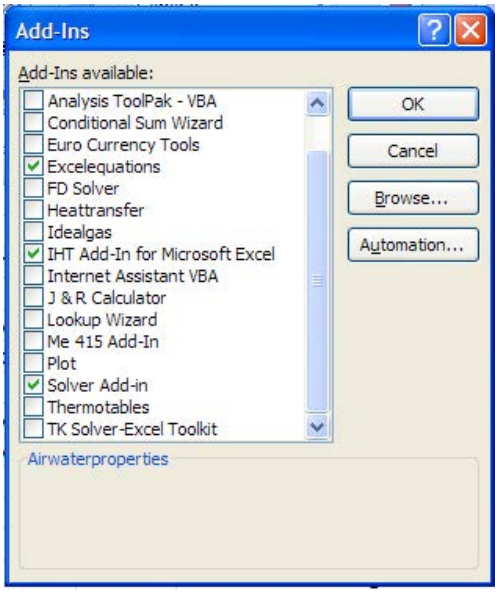
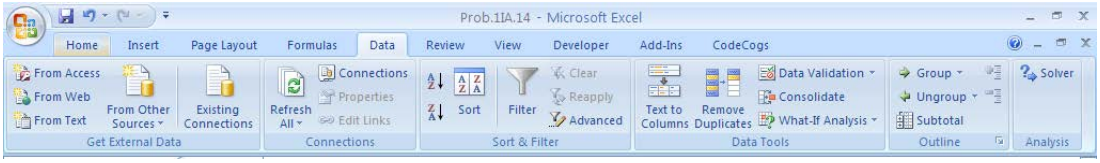
Press Go. We get:

Put check mark on Solver Add-In and press OK.



Now, the solver is enabled.

This can be verified in EXCEL by clicking on Data tab, and on extreme right on top row, you see 'Solver':



---

a) **Consider an example of a solving a set of linear equations:**

$$3 \cdot x_1 - x_2 + 3 \cdot x_3 = 0$$

$$-x_1 + 2 \cdot x_2 + x_3 - 3 = 0$$

$$2 \cdot x_1 - x_2 - x_3 - 2 = 0$$

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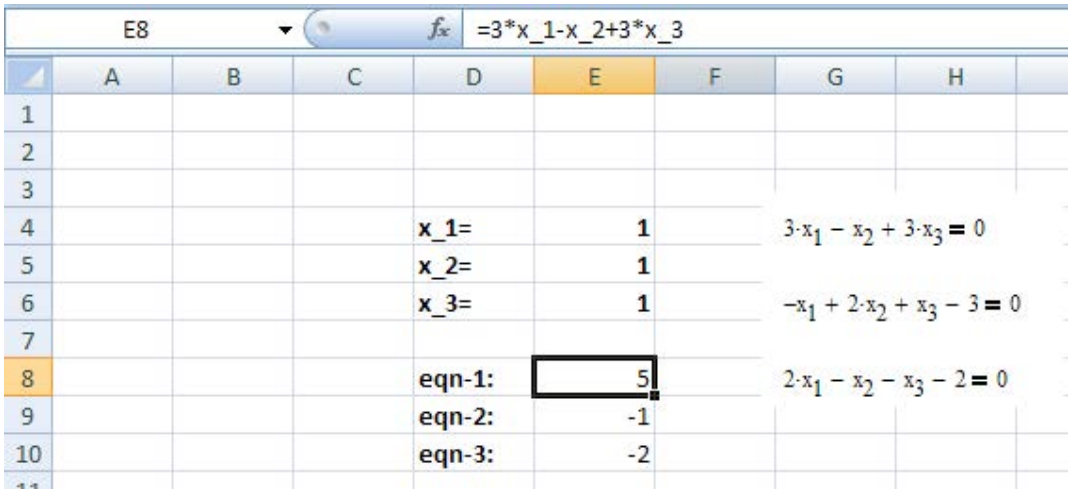
We have to find out x1, x2 and x3, satisfying these equations:

Set up the EXCEL Worksheet as follows:



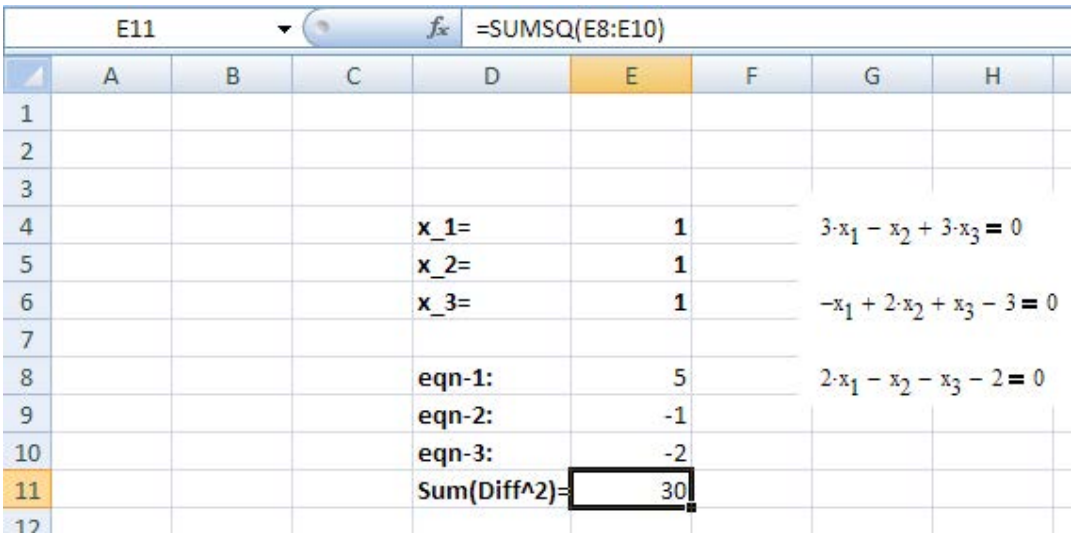
Here x_1, x_2 and x_3 are allocated with trial values of 1 each. Also, these are named cells.

Then, eqns 1, 2 and 3 are entered in cells E8, E9 and E10 respectively.

Now, ideally, each of these cells should be equal to zero, if the trial values satisfy the eqns. Obviously, it is not so. And, we see the 'residual values' in cells E8, E9 and E10.

Our aim is to make these cells have values equal to zero.

So, we have another cell, E11, where we calculate Sum of the squares of the residuals, i.e SUM(E8^2,+E9^2 + E10^2):



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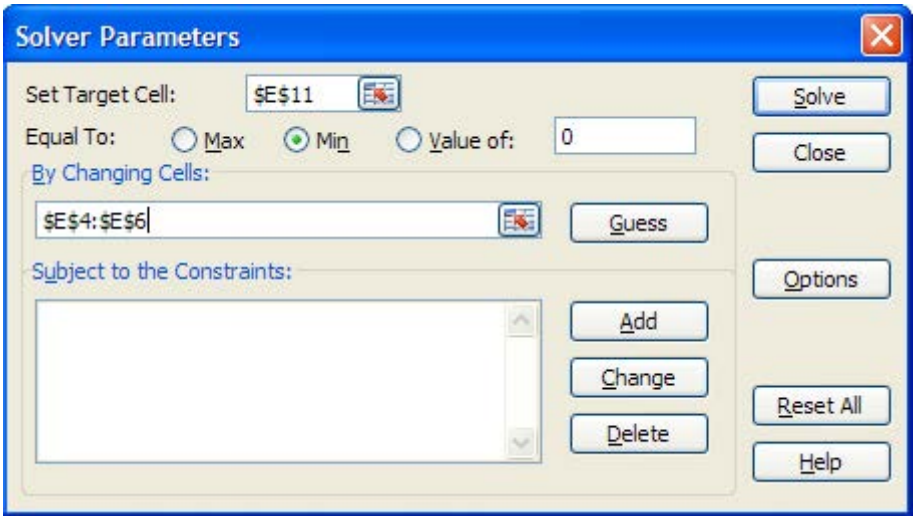
We see that E11 is 30.

Now, we apply Solver.

Click on Data-Solver. We get:



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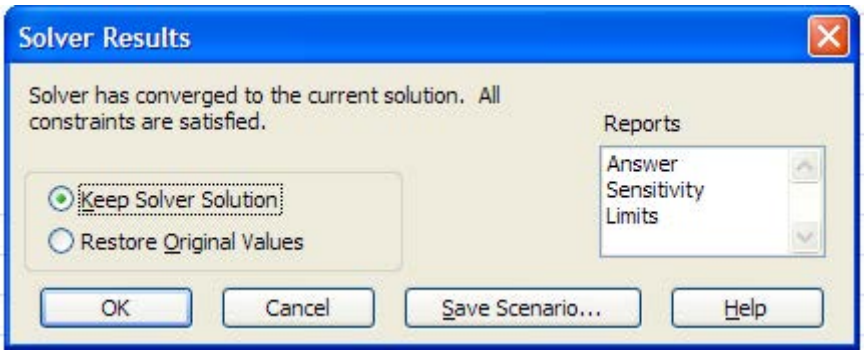
Target cell is E11.

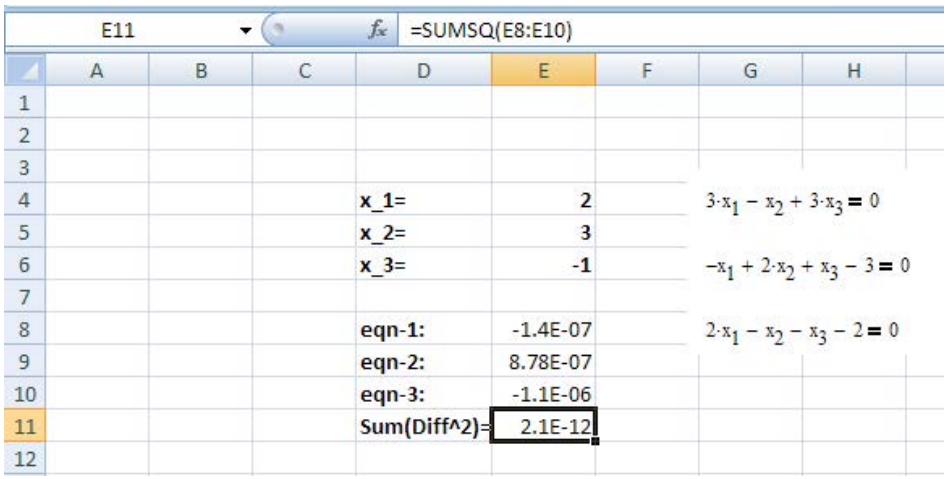
Equal to: Click on Min.i.e. Target cell will be minimized by:

By changing cells: E4:E6, i.e. x_1, x_2 and x_3 to be found out.

Click Solve. We get the window:



Click OK to keep the solution. We see:



i.e. the solution is: x_1 = 2, x_2 = 3 and x_3 = -1.

Note that SUM(Diff^2) is almost equal to zero. Also, E8, E9 and E10 are also almost equal to zero, as required.

Note: Matrix methods can also be used o solve a set of linear algebraic equations, such as the above. It will involve finding out the Inverse of the coeff. matrix, and then, matrix multiplication.

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b) **Consider another example of a solving a *set of non-linear equations*, given below:**

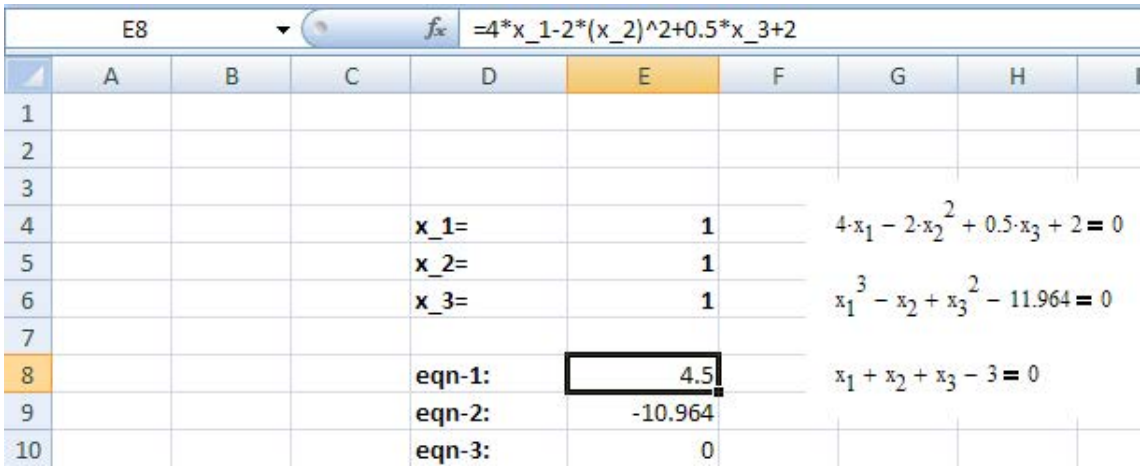
$$4 \cdot x_1 - 2 \cdot x_2^{\,2} + 0.5 \cdot x_3 + 2 = 0$$

$$x_1^{\,3} - x_2 + x_3^{\,2} - 11.964 = 0$$

$$x_1 + x_2 + x_3 - 3 = 0$$

We have to find out x1, x2 and x3, satisfying these equations:

Set up the EXCEL Worksheet as follows:



Here x_1, x_2 and x_3 are allocated with *trial values* of 1 each. Also, these are named cells.

Then, eqns 1, 2 and 3 are entered in cells E8, E9 and E10 respectively. Equation entered in cell E8 can be seen in the Formula bar, in the above Fig.

Now, ideally, each of these cells should be equal to zero, if the trial values satisfy the eqns. Obviously, it is not so. And, we see the 'residual values' in cells E8, E9 and E10.

Our aim is to make these cells have values equal to zero.

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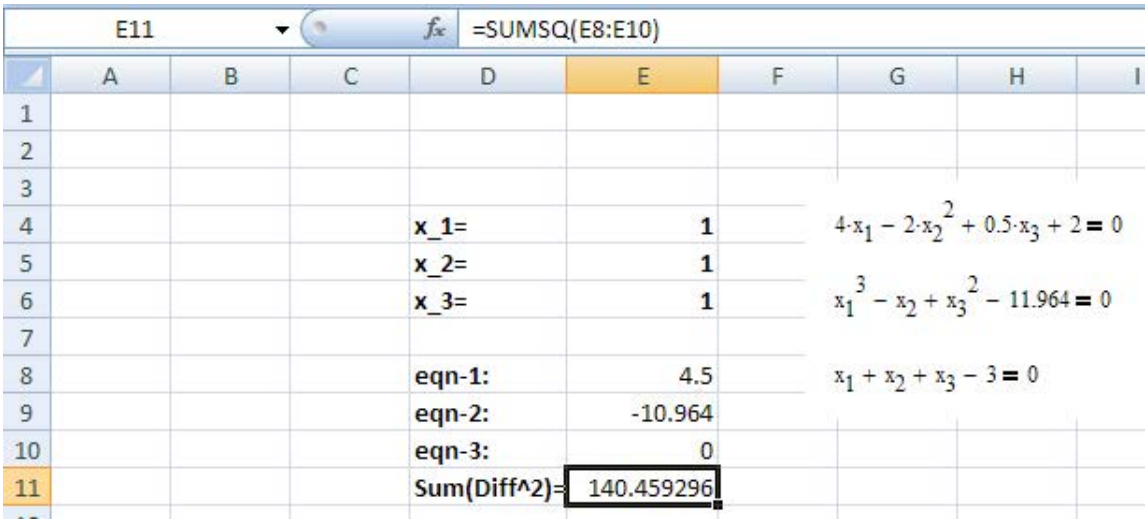
So, we have another cell, E11, where we calculate ***Sum of the squares of the residuals,*** i.e SUM(E8^2,+E9^2 + E10^2):



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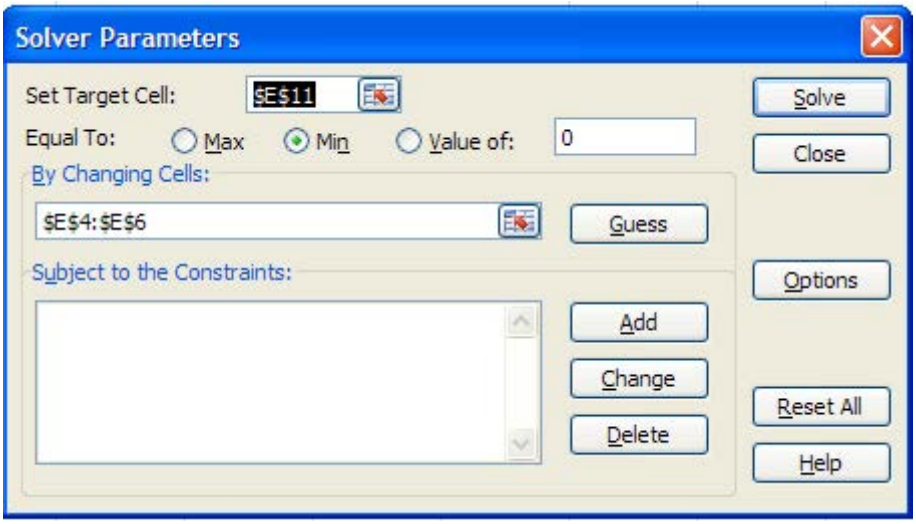
We see that E11 is 140.459296.

Now, we apply Solver.

Click on Data-Solver. We get:

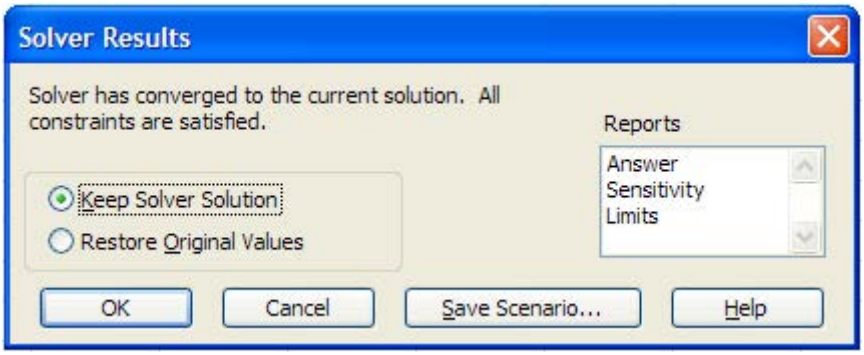


Target cell is E11.

Equal to: Click on Min.i.e. Target cell will be minimized by:

By changing cells: E4:E6, i.e. x_1, x_2 and x_3 to be found out.

Click Solve. We get the window:



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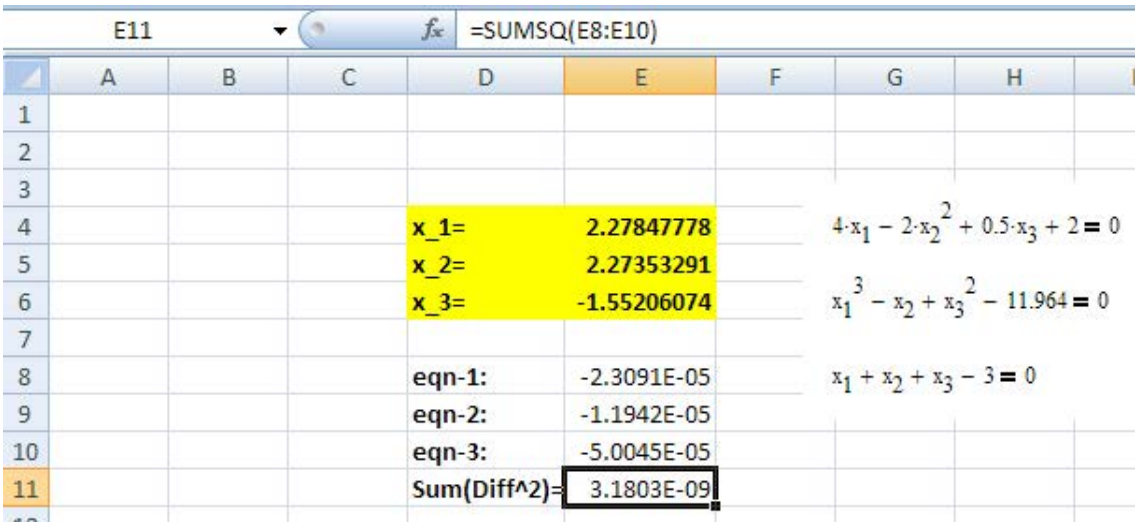
Click OK to keep the solution. We see:



i.e. the solution is: x_1 = 2.2785, x_2 = 2.27353 and x_3 = -1.55206.

Note that SUM(Diff^2) is almost equal to zero. Also, E8, E9 and E10 are also almost equal to zero, as required.

6. **Differentiation in EXCEL:** This is important in heat transfer calculations. If the temperature profile (T vs x) is given by an equation, we can find the derivative at a given x by simply finding dT for a very small dx.

This is shown in the following example:

Temp profile in a slab 0.3 m thick, thermal conductivity k = 45 W/m.C is given by the equation:

$$T(x) = 100 + 200\text{-}x - 500\text{-}x^2$$

where x is in meters. Find the heat flux at the LHS and RHS i.e. at x = 0 and art x = 0.3 m.

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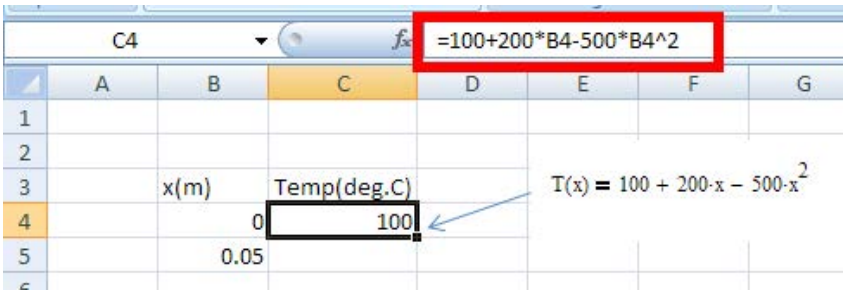
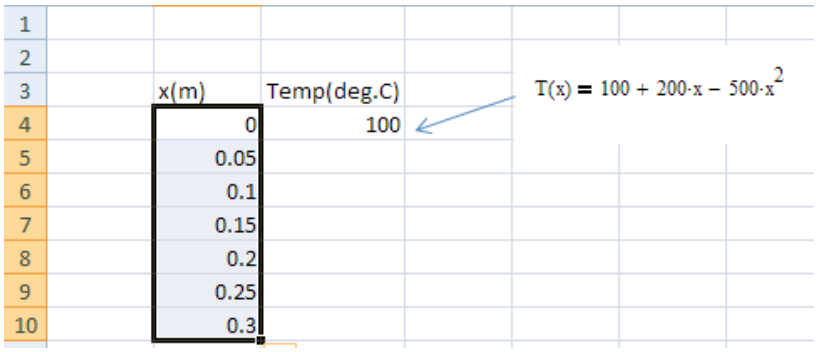
To do this numerically, in EXCEL,

a) Set up the worksheet:



b) Now, complete the column B upto x = 0.3



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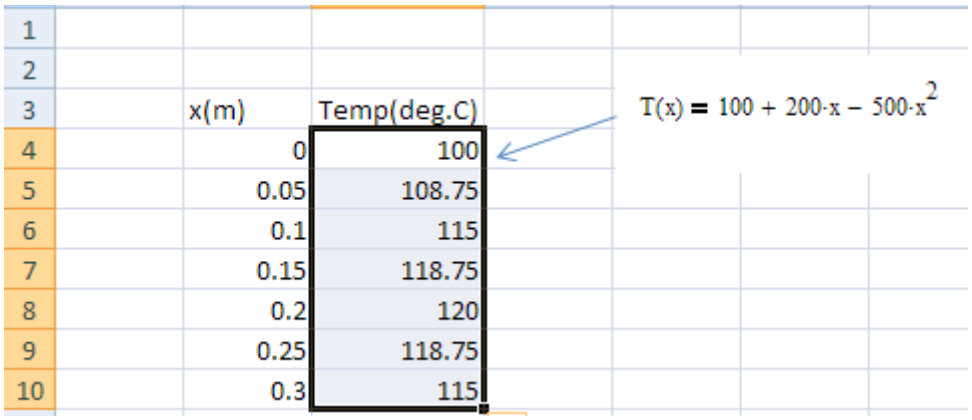
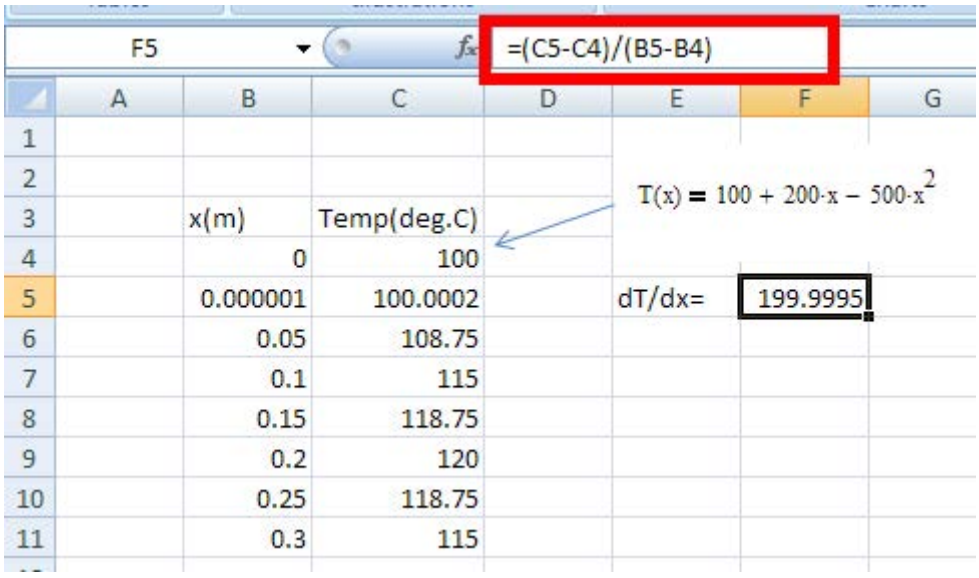
c) And, then copy-drag C4 to complete the calculations:



		x(m)	Temp(deg.C)
1			
2			
3		x(m)	Temp(deg.C)
4		0	100
5		0.05	108.75
6		0.1	115
7		0.15	118.75
8		0.2	120
9		0.25	118.75
10		0.3	115

d) **Now, we need dT/dx at x = 0. To get this:**

At x = 0, i.e. between rows 4 and 5, insert another row, and put a *very small increment* in x.(say, 0.000001 m); calculate the corresponding T, which is very easy in EXCEL (just drag copy C4 to C5), and calculate dT/dx as shown below:



	A	B	C	D	E	F	G
1							
2							
3		x(m)	Temp(deg.C)				
4		0	100				
5		0.000001	100.0002		dT/dx=	199.9995	
6		0.05	108.75				
7		0.1	115				
8		0.15	118.75				
9		0.2	120				
10		0.25	118.75				
11		0.3	115				

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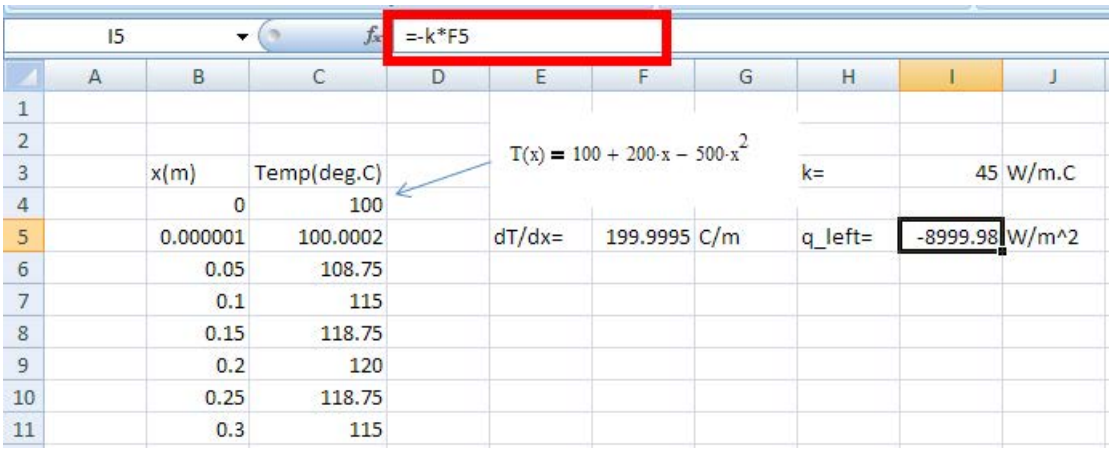
e) And, then, heat flux, q_left = -k * dT/dx. This is calculated as:



i.e. q_left = -9000 W/m^2 ..(appprox.). Note that q_left *has negative sign*, indicating heat flow from right to left.

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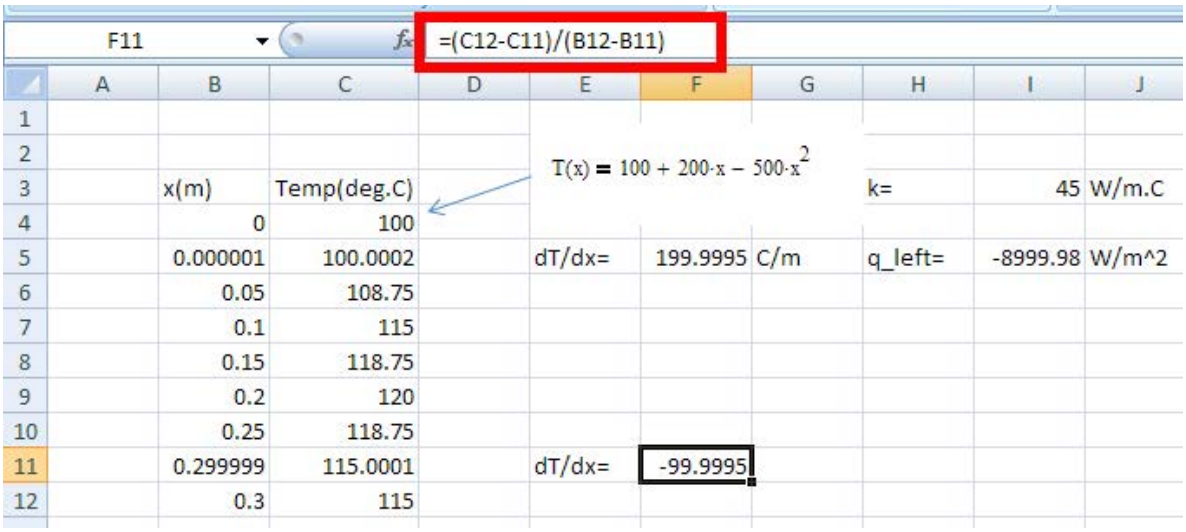
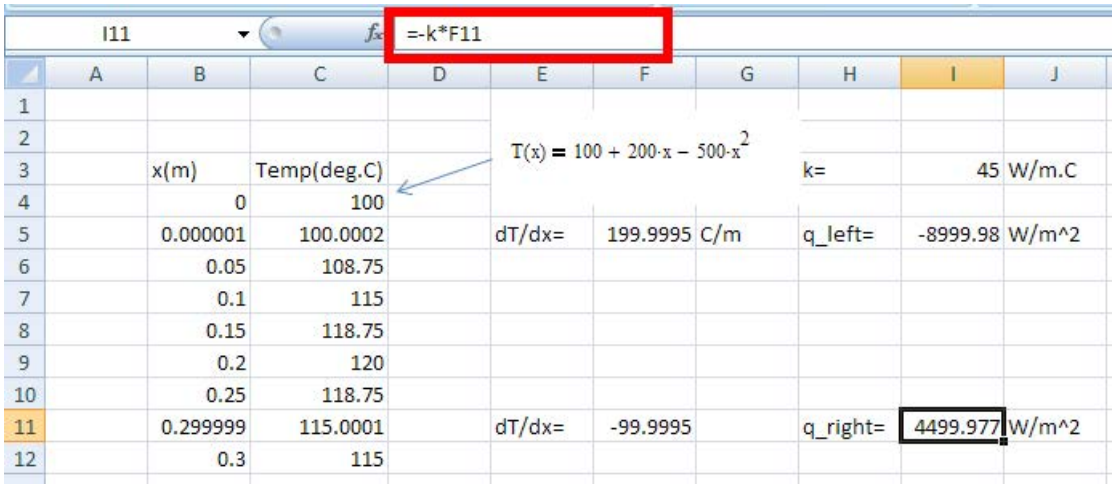
Similarly, find dT/dx at RHS, by finding dT at x = 0.3 for a very small dx:



	A	B	C	D	E	F	G	H	I	J
1										
2										
3		x(m)	Temp(deg.C)					k=	45	W/m.C
4		0	100							
5		0.000001	100.0002		dT/dx=	199.9995	C/m	q_left=	-8999.98	W/m^2
6		0.05	108.75							
7		0.1	115							
8		0.15	118.75							
9		0.2	120							
10		0.25	118.75							
11		0.299999	115.0001		dT/dx=	-99.9995				
12		0.3	115							

f) And, then find q_right = -k * dT/dx at RHS:



	A	B	C	D	E	F	G	H	I	J
1										
2										
3		x(m)	Temp(deg.C)					k=	45	W/m.C
4		0	100							
5		0.000001	100.0002		dT/dx=	199.9995	C/m	q_left=	-8999.98	W/m^2
6		0.05	108.75							
7		0.1	115							
8		0.15	118.75							
9		0.2	120							
10		0.25	118.75							
11		0.299999	115.0001		dT/dx=	-99.9995		q_right=	4499.977	W/m^2
12		0.3	115							

i.e. q_right = 4500 W/m^2 (approx.). This is +ve, i.e. flowing from left to right.

g) In the above case, an equation was given for T vs x. Instead , if a Table of T vs x was supplied, we could find an eqn to fit those values by curve-fit.

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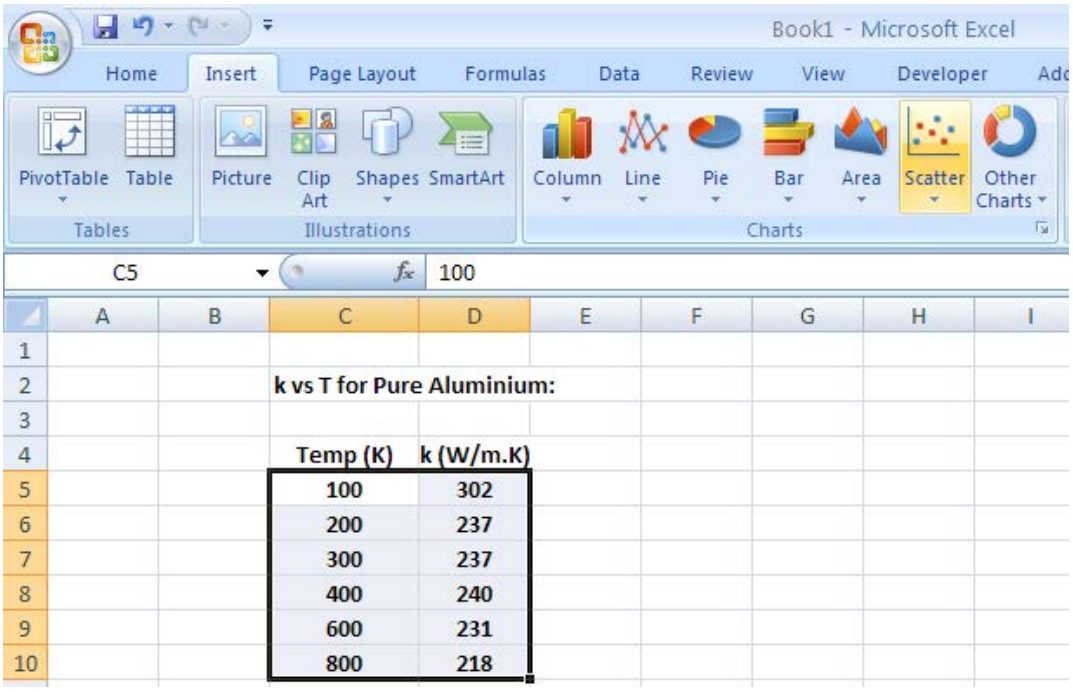
7. **Curve fitting in EXCEL:**

Consider a Table of Thermal conductivity (k) vs Temp for pure Aluminium. It is entered in EXCEL:

	A	B	C	D	E
1					
2			**k vs T for Pure Aluminium:**		
3					
4			**Temp (K)**	**k (W/m.K)**	
5			**100**	**302**	
6			**200**	**237**	
7			**300**	**237**	
8			**400**	**240**	
9			**600**	**231**	
10			**800**	**218**	

Now, first draw the plot of k vs T. To do this, select C5 to D9 and click on Insert-Scatter:



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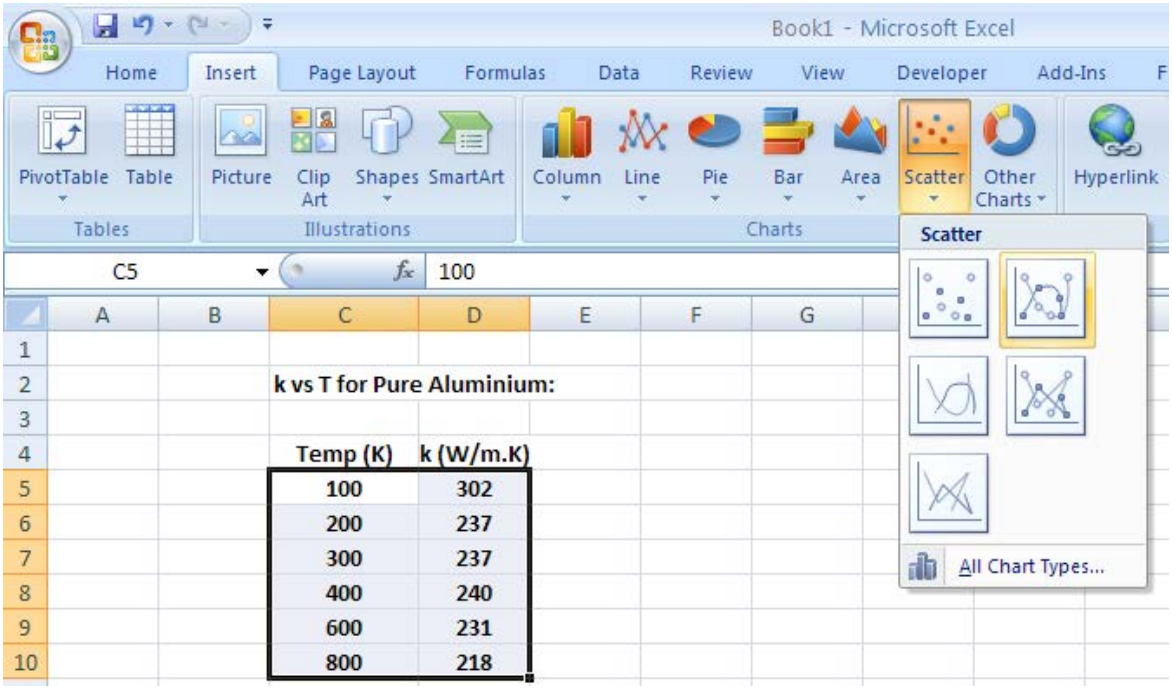
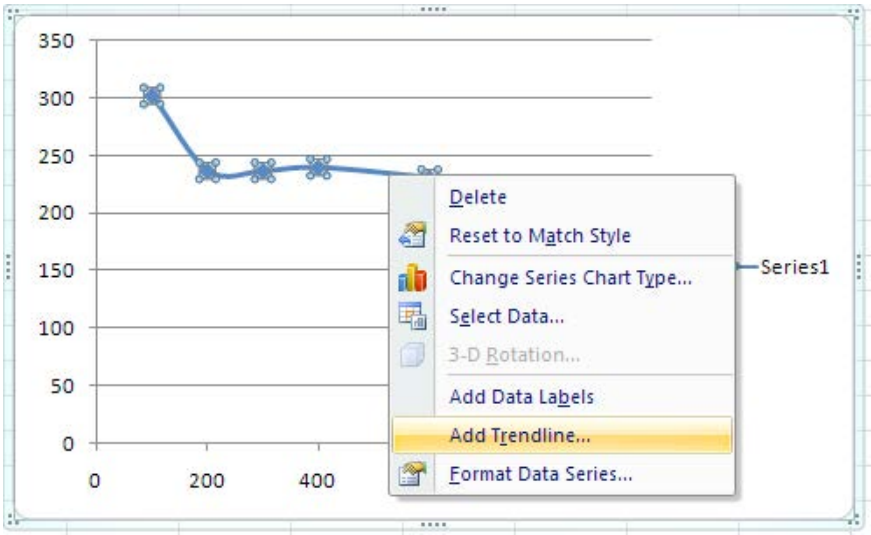
We get:



Select Scatter with markers, i.e. top-right item:

Immediately, we get the plot. Select the line and right click on mouse, w get:



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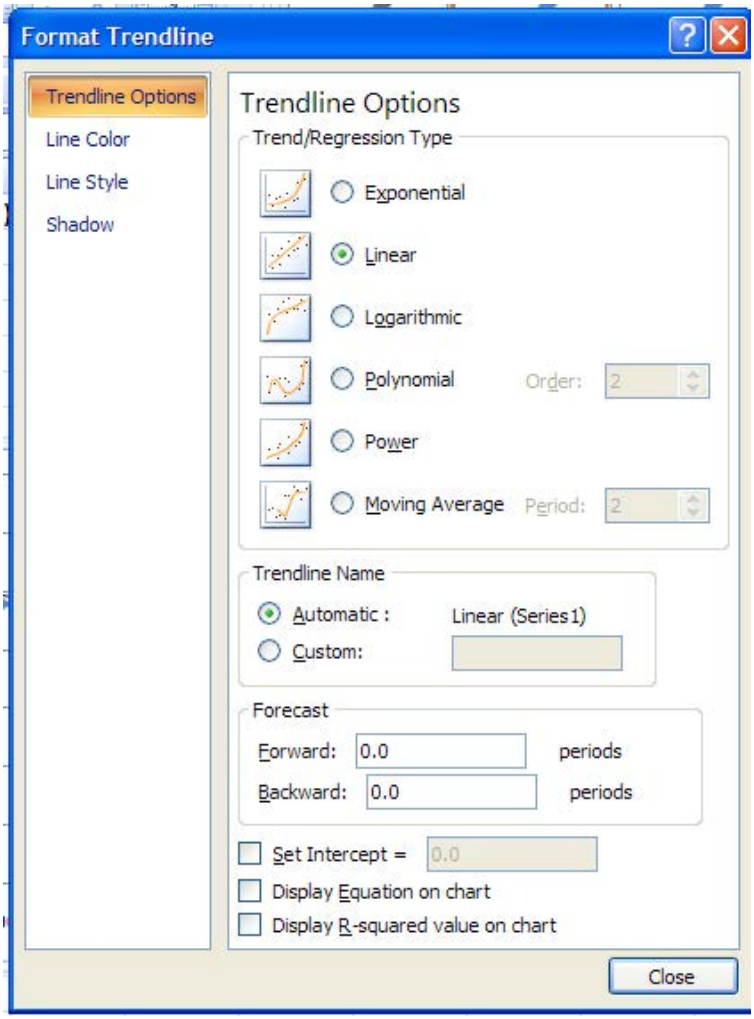
Click on Add Trendline: We get:



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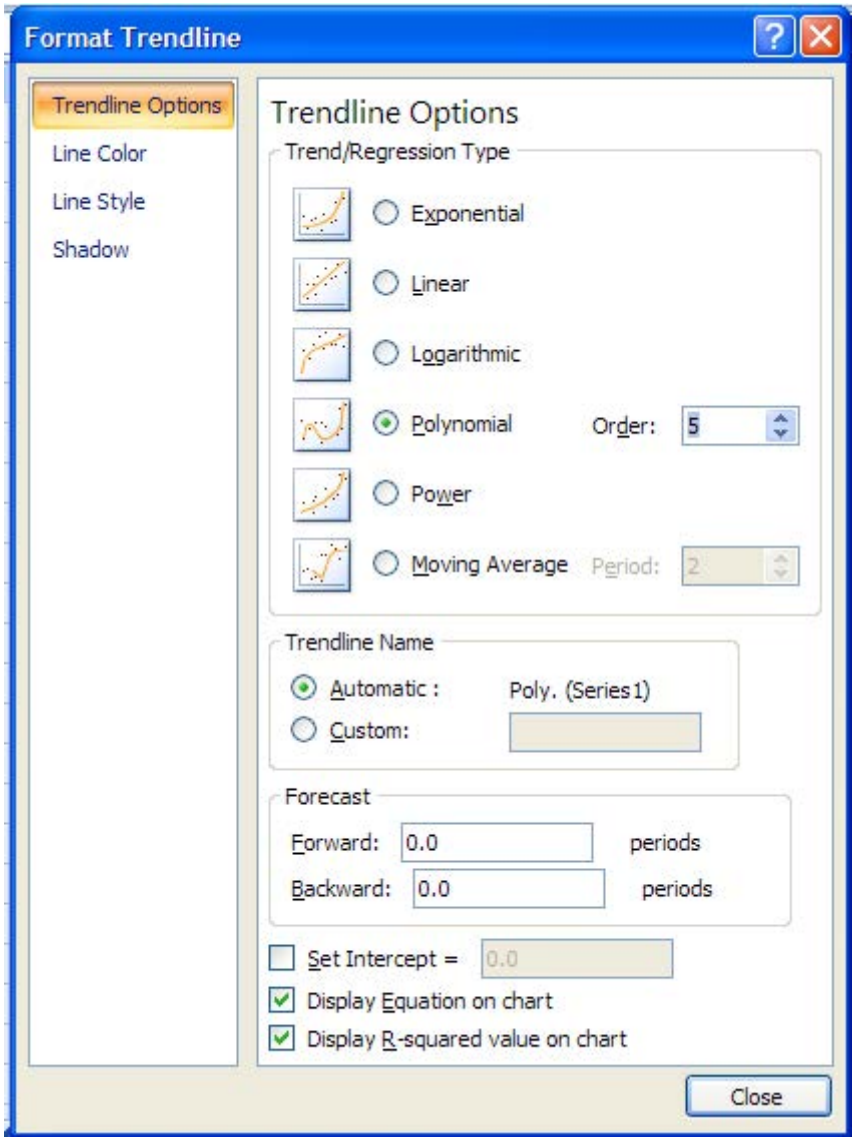
There are several options for curve fit; Select polynomial, order 5:



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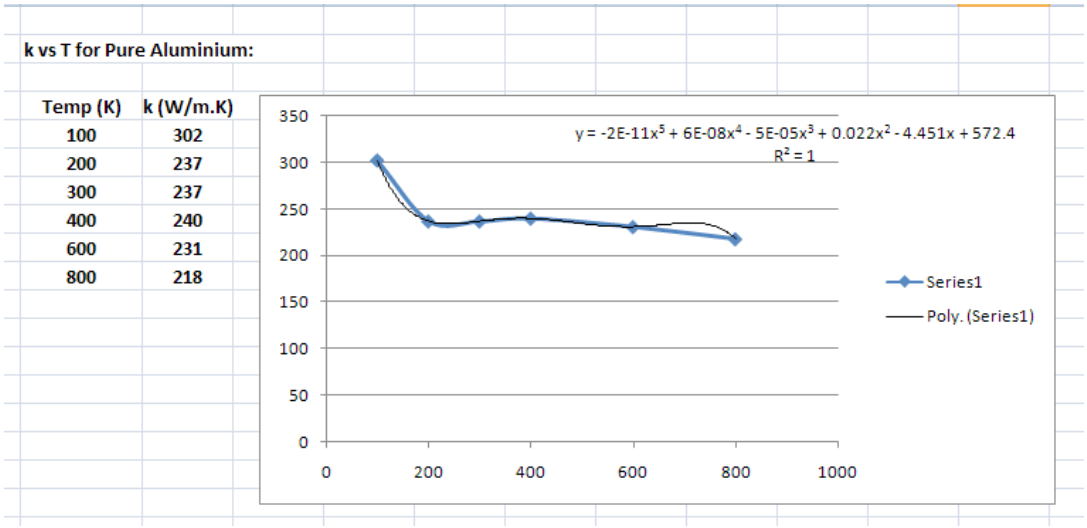
Also, note that we have chosen to display the cirve-fit eqn on the chart and the R_squared value. R_squared value should be as near to 1 as possible, indicating the best fit:

We get:



Note that curve-fit eqn and R_squared value appear on the plot. Also, the curve fit eqn is plotted automatically, and one can compare the plot with the original data plot.

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8. **Integration in EXCEL:**

If y = f(x) is plotted, area under the curve is obtained by integration. Numerical integration is adopted when the function to be integrated is complicated or difficult to integrate analytically.

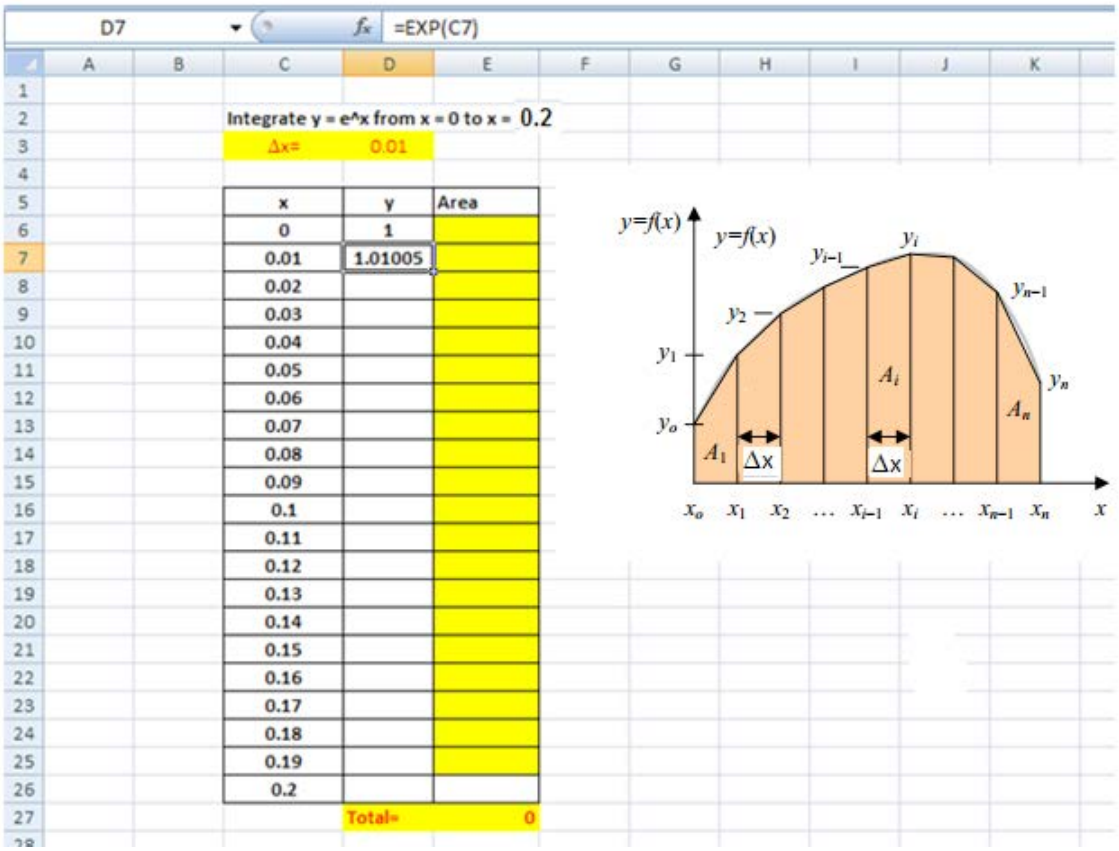
We adopt Trapezoidal method to integrate numerically, since it is the easiest to apply. Here, the area is divided into large no. of trapezoids and area of each trapezoid is calculated as: average height x its width. Then, areas of all trapezoids are summed up.

Let us take an example of integrating $y = e^x$ from x = 0 to x = 0.2:

Set up the EXCEL worksheet as follows:

The interval x = 0 to 0.2 is divided into 20 equal divisions. So, Δx = 0.01 m.

Enter formula for y = e^x in cells D6 and D7 . See the formula entered in cell D7 in the formula bar:



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Now, drag-copy to calculate all values of y, i.e. upto cell D26:

	A	B	C	D	E
1					
2			Integrate y = e^x from x = 0 to x = 0.2		
3			Δx=	0.01	
4					
5			x	y	Area
6			0	1	
7			0.01	1.01005	
8			0.02	1.0202	
9			0.03	1.03045	
10			0.04	1.04081	
11			0.05	1.05127	
12			0.06	1.06184	
13			0.07	1.07251	
14			0.08	1.08329	
15			0.09	1.09417	
16			0.1	1.10517	
17			0.11	1.11628	
18			0.12	1.1275	
19			0.13	1.13883	
20			0.14	1.15027	
21			0.15	1.16183	
22			0.16	1.17351	
23			0.17	1.1853	
24			0.18	1.19722	
25			0.19	1.20925	
26			0.2	1.2214	
27				Total=	0

Now, find out the area of first trapezoid: A1 = (y1 + y0)/2)* Δx, as shown below:

E7 f_x =((D7+D6)/2)*0.01

	A	B	C	D	E	F
1						
2			Integrate y = e^x from x = 0 to x = 0.2			
3			Δx=	0.01		
4						
5			x	y	Area	
6			0	1		
7			0.01	1.01005	0.0100503	
8			0.02	1.0202		
9			0.03	1.03045		
10			0.04	1.04081		

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See the formula for A1 (i.e. cell E7) in formula bar.

Now, drag-copy to complete all calculations for areas, and also the summation of all areas:

E27 =SUM(E6:E25)

	A	B	C	D	E	F
1						
2			Integrate y = e^x from x = 0 to x =		0.2	
3			Δx=	0.01		
4						
5			x	y	Area	
6			0	1		
7			0.01	1.01005	0.0100503	
8			0.02	1.0202	0.0101513	
9			0.03	1.03045	0.0102533	
10			0.04	1.04081	0.0103563	
11			0.05	1.05127	0.0104604	
12			0.06	1.06184	0.0105655	
13			0.07	1.07251	0.0106717	
14			0.08	1.08329	0.010779	
15			0.09	1.09417	0.0108873	
16			0.1	1.10517	0.0109967	
17			0.11	1.11628	0.0111072	
18			0.12	1.1275	0.0112189	
19			0.13	1.13883	0.0113316	
20			0.14	1.15027	0.0114455	
21			0.15	1.16183	0.0115605	
22			0.16	1.17351	0.0116767	
23			0.17	1.1853	0.0117941	
24			0.18	1.19722	0.0119126	
25			0.19	1.20925	0.0120323	
26			0.2	1.2214	0.0121533	
27				Total=	0.2092513	

Thus: the value of integral is: 0.2092513.

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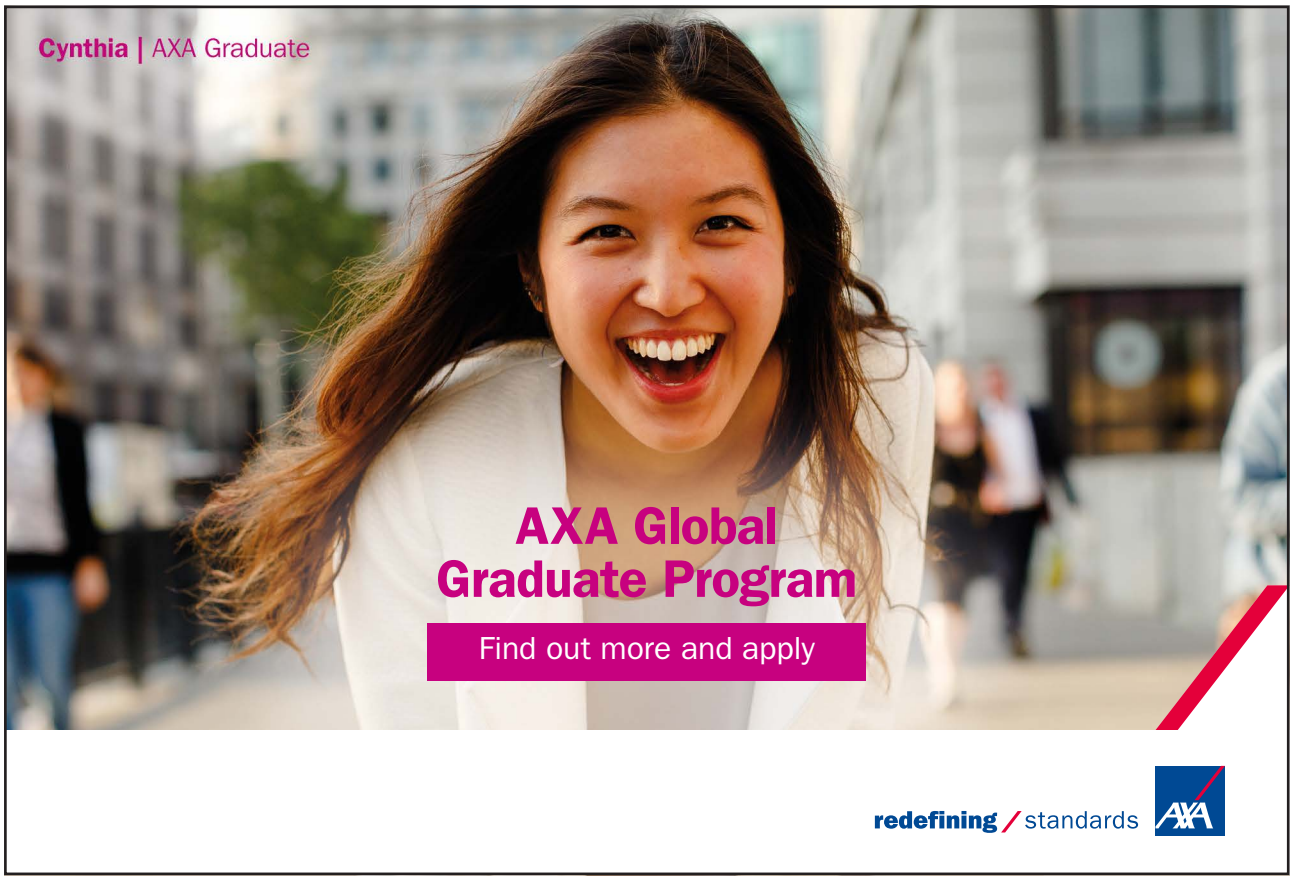
However, *if we have more subdivisions*, accuracy will be better. For example, let there be 40 subdivisions between 0 and 0.2; i.e. $\Delta x = 0.005$. Then, we get:

	A	B	C	D	E	F
1						
2			Integrate y = e^x from x = 0 to x = 0.2:			
3			Δx=	0.005		
4						
5			x	y	Area	
6			0	1		
7			0.005	1.005013	0.00501253	
8			0.01	1.01005	0.00503766	
9			0.015	1.015113	0.00506291	
10			0.02	1.020201	0.00508829	
11			0.025	1.025315	0.00511379	
12			0.03	1.030455	0.00513942	
13			0.035	1.03562	0.00516519	
14			0.04	1.040811	0.00519108	
15			0.045	1.046028	0.0052171	
16			0.05	1.051271	0.00524325	
17			0.055	1.056541	0.00526953	
18			0.06	1.061837	0.00529594	
19			0.065	1.067159	0.00532249	
20			0.07	1.072508	0.00534917	
21			0.075	1.077884	0.00537598	
22			0.08	1.083287	0.00540293	
23			0.085	1.088717	0.00543001	
24			0.09	1.094174	0.00545723	
25			0.095	1.099659	0.00548458	



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	A	B	C	D	E
26			0.1	1.105171	0.00551207
27			0.105	1.110711	0.0055397
28			0.11	1.116278	0.00556747
29			0.115	1.121873	0.00559538
30			0.12	1.127497	0.00562343
31			0.125	1.133148	0.00565161
32			0.13	1.138828	0.00567994
33			0.135	1.144537	0.00570841
34			0.14	1.150274	0.00573703
35			0.145	1.15604	0.00576578
36			0.15	1.161834	0.00579468
37			0.155	1.167658	0.00582373
38			0.16	1.173511	0.00585292
39			0.165	1.179393	0.00588226
40			0.17	1.185305	0.00591174
41			0.175	1.191246	0.00594138
42			0.18	1.197217	0.00597116
43			0.185	1.203218	0.00600109
44			0.19	1.20925	0.00603117
45			0.195	1.215311	0.0060614
46			0.2	1.221403	0.00609178
47				Sum=	0.22140322

Thus the value of the integral is: 0.22140322.

And, an alternative result (from Mathcad) is:

$$\int_0^{0.2} \exp(x)\,dx = 0.221$$

Note: It should be mentioned that there are other more accurate methods of integration, and functions can be written in Visual Basic for Applications (VBA) programming language to do the calculations. However, Trapezoidal method is straight forward and easy to implement in EXCEL.

9. **Graphing in EXCEL:**

Producing publication quality plots in EXCEL is very easy.

We will describe an example of drawing a scatter plot from a Table of two columns. (You can draw many other types of graphs too; however, scatter plot is required more often, in practice).

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Consider the following Table which gives thermal conductivity of Air at various temperatures:

	A	B	C	D
1		Properties of dry air at 1atm:		
2		T(K)	k (W/m.K)*10^3	
3		100	9.469	
4		120	11.38	
5		140	13.24	
6		160	15.05	
7		180	16.8	
8		200	18.5	
9		220	20.16	
10		240	21.77	
11		260	23.35	
12		280	24.88	
13		300	26.38	
14		320	27.85	
15		340	29.29	
16		360	30.71	
17		380	32.09	
18		400	33.45	
19		420	34.79	
20		440	36.11	
21		460	37.41	
22		480	38.68	
23		500	39.94	
24		520	41.19	
25		540	42.42	
26		560	43.63	
27		580	44.83	
28		600	46.01	
29		620	47.18	
30		640	48.34	
31		660	49.49	
32		680	50.63	
33		700	51.76	
34		720	52.87	
35		740	53.98	
36		760	55.08	
37		780	56.17	
38		800	57.25	
39		820	58.32	
40		840	59.39	
41		860	60.45	
42		880	61.5	
43		900	62.54	

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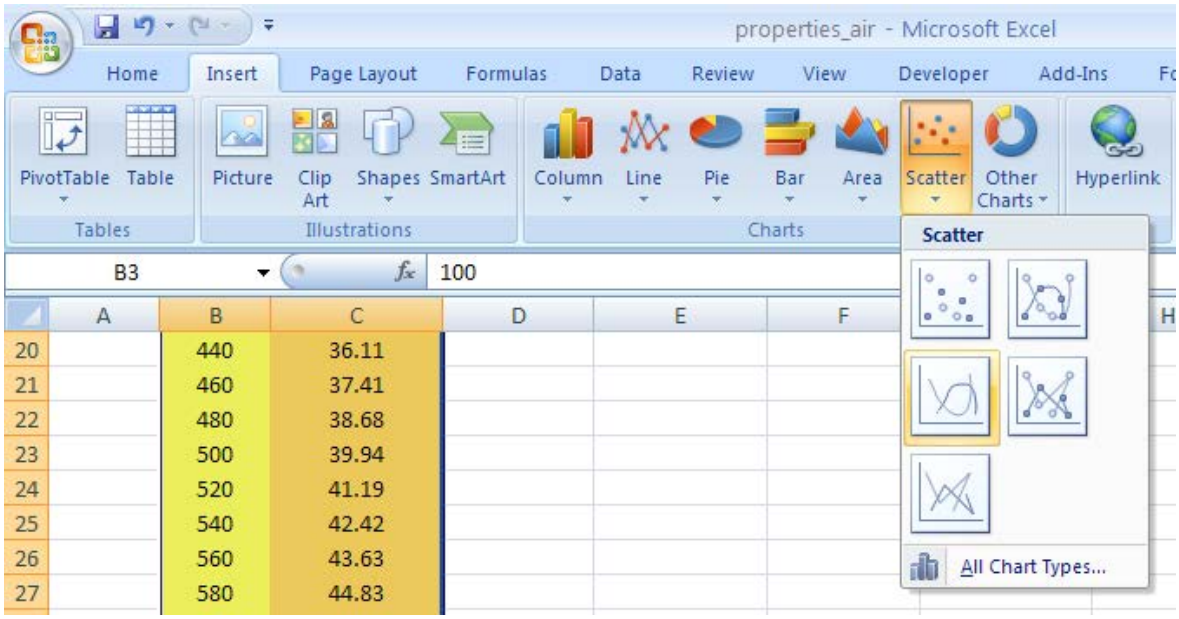
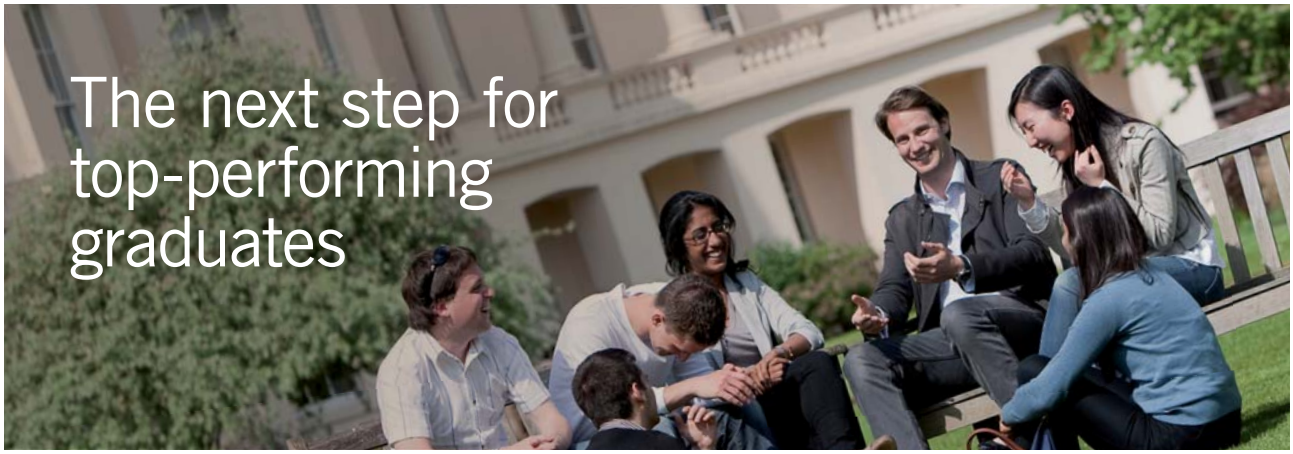
To draw the plot:

a) First, select both the columns (without the captions, i.e. from cell B3:B43 and C3:C43)

b) Then, click Insert-Scatter (since we wish to create a scatter plot). We get:





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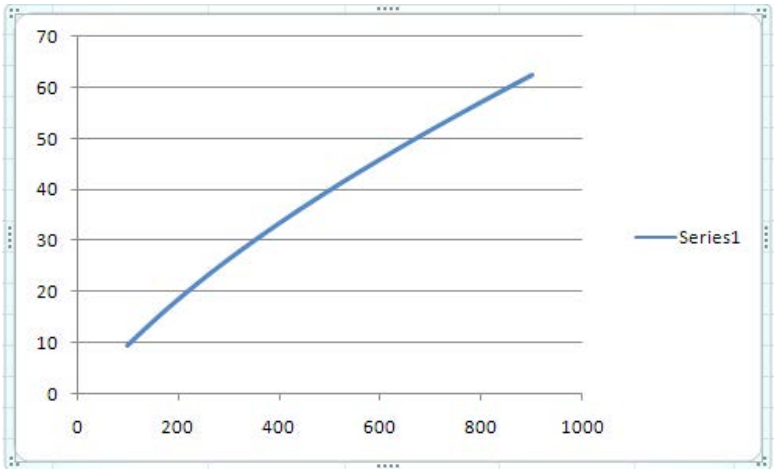
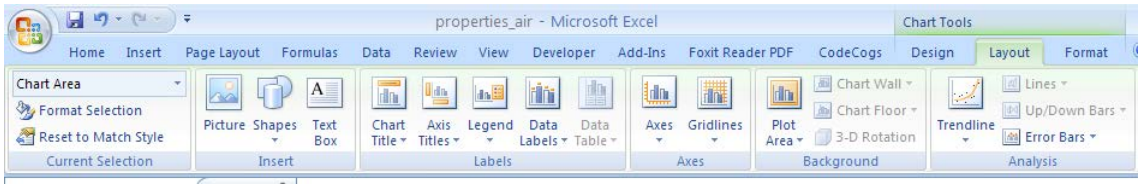
c) Click on *Scatter with smooth lines*, i.e. 2nd button from top in the left column under Scatter, shown highlighted in the above fig.). We get:



d) Now, we have to Format this graph. To do so, select the plot, and go to Chart Tools – Layout:



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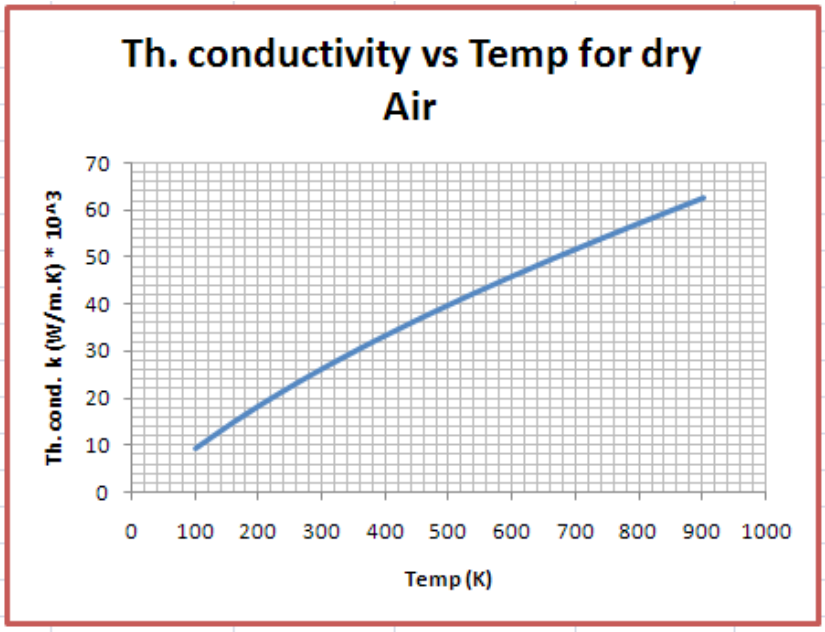
In the above Fig. you see that there are buttons to perform a variety of formatting: Gridlines, Axes Titles, Chart Title, etc. *Experiment with them to gain practice*. The formatted graph is shown below:



EXCEL has many, many more capabilities. What we have explained is just sufficient information required to do heat transfer calculations. The student is advised to read the built-in HELP in EXCEL or some specialized books on EXCEL, to get deeper understanding of EXCEL.

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To the Student

Dear Student:

I would like to remind you that Heat Transfer is an important subject useful in many branches of engineering.It is also a subject in which you can score high marks in the examinations, since the question paper generally consists of derivations and numerical problems, almost in the ratio 50:50. Therefore, it requires that:

1. you are thorough with the derivations, and
2. skillful in solving numerical problems.

To be thorough with derivations, you should refer to well known, standard Text books on the subject of Heat Transfer (See References at the end of this book). **And, to develop your skill in solving problems… well, that is where I think that this book will help you.**

This book contains solutions to problems on heat transfer using four popular softwares, viz. Mathcad, Engineering Equation Solver (EES), Finite Element Heat Transfer (FEHT), and EXCEL spreadsheet. Trial versions of Mathcad, EES and FEHT can be downloaded from the websites indicated. EXCEL, which is a part of MS OFFICE, is generally pre-installed in most of the Personal Computers. Problems are chosen from the University question papers and standard heat transfer Text books.

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I hope that you too will enjoy as much as I did in solving these problems and get benefitted.

Good Luck!

Author

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Vol. 1
Conduction

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1A Fourier's Law and Heat conduction equation, multimode heat transfer:

Learning objectives:

1. In this section, we will work out problems using the Fourier's Law, which is the basic governing 'rate equation' for conduction. In fact, Fourier's Law is the foundation on which rest of the material in this chapter stands.
2. We will also apply the one-dimensional (1-D) heat conduction equation in Cartesian coo-ordinates, cylindrical and spherical coordinates to rectangular, cylindrical and spherical geometries, respectively. For example: 1D-heat conduction eqn in rectangular coordinates is used in solving problems of rectangular shapes (such as slabs, furnace walls, building wall-insulations etc.). 1D-heat conduction eqn in cylindrical coordinates is used in solving problems of cylindrical shapes (such as electric cables, pipes, cylindrical heaters, containers etc.). And, 1D-heat conduction eqn in spherical coordinates is used in solving problems of spherical shapes (such as balls, spherical reactors or containers etc.).
3. We will also consider problems where heat transfer occurs not only by conduction, but includes convection and or radiation too.

Formulas:

Sl. No.	Equation	Remarks
1	$\frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial T}{\partial z}) + q_g = \rho\, c_p \frac{\partial T}{\partial \tau}$	Three dimensional, time dependent heat conduction eqn with heat generation and temp. dependent k, in cartesian coords.
2	$(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) + \frac{q_g}{k} = \frac{\rho c_p}{k}\frac{\partial T}{\partial \tau} = \frac{1}{\alpha}\frac{\partial T}{\partial \tau}$	Three dimensional, time dependent heat conduction eqn with heat gen. and const. k, in cartesian coords.
3	$(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) + \frac{q_g}{k} = 0$	**'Poisson equation' i.e.** three dimensional, steady state heat conduction eqn. with heat generation and constant k, in cartesian coordinates.
4	$(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) = \frac{1}{\alpha}\frac{\partial T}{\partial \tau}$	**'Diffusion equation' i.e.** three dimensional, time dependent heat conduction eqn. with no heat generation and constant k, in cartesian coordinates.

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5	$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=0$	**"Laplace equation"** i.e. three dimensional, steady state heat conduction eqn. with no heat generation and with constant k, in cartesian coordinates.
6	$\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T}{\partial r})+\frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}+\frac{\partial^2 T}{\partial z^2}+\frac{q_g}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial \tau}$	Three dimensional, time dependent heat conduction eqn with heat gen. and const. k, in cylindrical coords.
7	$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\frac{\partial T}{\partial r})+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}(\sin\theta\frac{\partial T}{\partial \theta})+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 T}{\partial \phi^2}+\frac{q_g}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial \tau}$	Three dimensional, time dependent heat conduction eqn with heat gen. and const. k, in spherical coords
8	$\frac{\partial}{\partial x}(k\frac{\partial T}{\partial x})+q_g=\rho c_p\frac{\partial T}{\partial \tau}$	One dimensional, time dependent heat conduction eqn with heat gen. and temp. dependent k, in cartesian coords
9	$\frac{1}{r}\frac{\partial}{\partial r}(rk\frac{\partial T}{\partial r})+q_g=\rho c_p\frac{\partial T}{\partial \tau}$	One dimensional, time dependent heat conduction eqn with heat gen. and temp. dependent k, in cylindrical coords
10	$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2k\frac{\partial T}{\partial r})+q_g=\rho c_p\frac{\partial T}{\partial \tau}$	One dimensional, time dependent heat conduction eqn with heat gen. and temp. dependent k, in spherical cords
11	Equations 8, 9, 10 are compactly written as: $\frac{1}{r^n}\frac{\partial}{\partial r}(r^nk\frac{\partial T}{\partial r})+q_g=\rho c_p\frac{\partial T}{\partial \tau}$ where n = 0 for Cartesian coords., use x as variable instead of r n = 1 for cylindrical coords. n = 2 for spherical coords.	Compact form of one dimensional, **time dependent**, heat conduction equation with heat gen. and **temp. dependent k**
12	$\frac{1}{r^n}\frac{\partial}{\partial r}(r^n\frac{\partial T}{\partial r})+\frac{q_g}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial \tau}$ where n = 0 for Cartesian coords. use x as variable instead of r n = 1 for cylindrical coords. n = 2 for spherical coords.	Compact form of one dimensional, **time dependent,** heat conduction equation with heat gen. and **constant k**
13	$\frac{1}{r^n}\frac{\partial}{\partial r}(r^n\frac{\partial T}{\partial r})+\frac{q_g}{k}=0$ where n = 0 for Cartesian coords. use x as variable instead of r n = 1 for cylindrical coords. n = 2 for spherical coords.	Compact form of one dimensional, **steady state,** heat conduction equation with heat gen. and **constant k**
14	$\frac{d^2T}{dx^2}+\frac{q_g}{k}=0$	Alternate form of one dimensional, **steady state,** heat conduction equation with heat gen. and **constant k, in Cartesian coords.**

Table 1A.1

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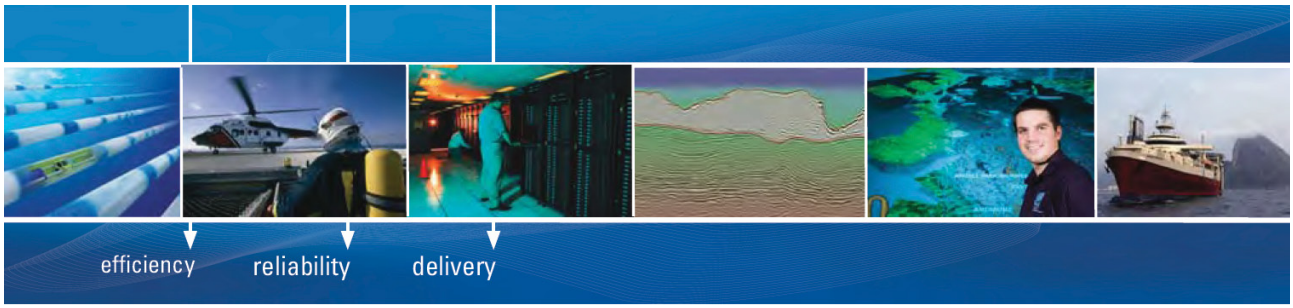
Relations for steady state, one dimensional conduction with no internal heat generation, and constant k

Relation	Plane wall	Cylindrical shell	Spherical shell
Governing diff. Eqn.	$\frac{d^2T}{dx^2}=0$	$\frac{1}{r}\cdot\frac{d}{dr}\left(r\cdot\frac{dT}{dr}\right)=0$	$\frac{1}{r^2}\cdot\frac{d}{dr}\left(r^2\cdot\frac{dT}{dr}\right)=0$
Temp. distribution	$\frac{T(x)-T1}{T2-T1}=\frac{x}{L}$	$\frac{T(r)-T_i}{T_o-T_i}=\frac{\ln\left(\frac{r}{r_i}\right)}{\ln\left(\frac{r_o}{r_i}\right)}$	$\frac{T(r)-T_i}{T_o-T_i}=\frac{\frac{1}{r}-\frac{1}{r_i}}{\frac{1}{r_o}-\frac{1}{r_i}}$
Heat transfer rate, Q, (W)	$\frac{k\cdot A\cdot(T1-T2)}{L}$	$\frac{2\cdot\pi\cdot k\cdot L\cdot(T_i-T_o)}{\ln\left(\frac{r_o}{r_i}\right)}$	$\frac{4\cdot\pi\cdot k\cdot r_i\cdot r_o\cdot(T_i-T_o)}{r_o-r_i}$
Thermal resistance, R, (C/W)	$\frac{L}{k\cdot A}$	$\frac{\ln\left(\frac{r_0}{r_i}\right)}{2\cdot\pi\cdot k\cdot L}$	$\frac{r_o-r_i}{4\cdot\pi\cdot k\cdot r_i\cdot r_o}$
Critical radius, r_c, (m)	----	$\frac{k}{h}$	$\frac{2\cdot k}{h}$

Table 1A.2



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Relations for steady state, one dimensional conduction with no internal heat generation and k varying linearly with temperature as: $k(T) = k_o (1 + \beta T)$

$k_m = k_o (1 + \beta T_m)$; $T_m = (T1 + T2)/2$

Relation	Plane wall
Governing diff. Eqn.	$\frac{d}{dx}\left(k(T)\cdot\frac{dT}{dx}\right)=0$
Temp. distribution, T(x)	$\frac{-1}{\beta}+\sqrt{\left(\frac{1}{\beta}+T1\right)^2-\frac{2}{\beta}\cdot\frac{x}{L}\cdot(T1-T2)\cdot\left(1+\beta\cdot T_m\right)}$
Heat transfer rate, Q, (W)	$\frac{k_m\cdot A\cdot(T1-T2)}{L}$
Thermal resistance, R, (C/W)	$\frac{L}{k_m\cdot A}$

Table 1A.3

Relations for steady state, one dimensional conduction with no internal heat generation, and k varying linearly with temperature as: $k(T) = k_o (1 + \beta T)$

$k_m = k_o (1 + \beta T_m)$; $T_m = (T_i + T_o)/2$

Relation	Cylindrical shell
Governing diff. Eqn.	$\frac{d}{dr}\left(r\cdot k(T)\cdot\frac{dT}{dr}\right)=0$
Temp. distribution, T(r)	$\frac{-1}{\beta}+\sqrt{\left(\frac{1}{\beta}+T_i\right)^2-\frac{2}{\beta}\cdot\frac{\ln\left(\frac{r}{r_i}\right)}{\ln\left(\frac{r_o}{r_i}\right)}\cdot\left(T_i-T_o\right)\cdot\left(1+\beta\cdot T_m\right)}$
Heat transfer rate, Q, (W)	$\frac{2\cdot\pi\cdot k_m\cdot L\cdot\left(T_i-T_o\right)}{\ln\left(\frac{r_o}{r_i}\right)}$
Thermal resistance, R, (C/W)	$\frac{\ln\left(\frac{r_o}{r_i}\right)}{2\cdot\pi\cdot k_m\cdot L}$

Table 1A.4

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Relations for steady state, one dimensional conduction with no internal heat generation, and k varying linearly with temperature as: $k(T) = k_o (1 + \beta T)$

$k_m = k_o (1 + \beta T_m)$; $T_m = (T_i + T_o)/2$

Relation	Spherical shell
Governing diff. Eqn.	$\frac{d}{dr}\left(r^2 \cdot k(T) \cdot \frac{dT}{dr}\right) = 0$
Temp. distribution, T(r)	$\frac{-1}{\beta} + \sqrt{\left(\frac{1}{\beta} + T_i\right)^2 - \frac{2}{\beta} \cdot \frac{r_o}{r} \cdot \left[\frac{(r - r_i)}{(r_o - r_i)} \cdot (T_i - T_o) \cdot (1 + \beta \cdot T_m)\right]}$
Heat transfer rate, Q, (W)	$\frac{4 \cdot \pi \cdot k_m \cdot r_i \cdot r_o \cdot (T_i - T_o)}{r_o - r_i}$
Thermal resistance, R, (C/W)	$\frac{r_o - r_i}{4 \cdot \pi \cdot k_m \cdot r_i \cdot r_o}$

Table 1A.5

Prob. 1A.1. The temperature distribution across a large concrete slab 50 cm thick, heated from one side, as measured by thermocouples approximates to the relation: $T(x) = 60 - 50\,x + 12\,x^2 + 20\,x^3 - 15\,x^4$, where T is in deg.C and x is in metres. Considering an area of 5 m^2, compute:

a) heat entering and leaving the slab in unit time
b) heat energy stored in unit time

For concrete, take k = 1.2 W/(m.K) [VTU-6th Sem-B.E.- Jan/Feb.2003]

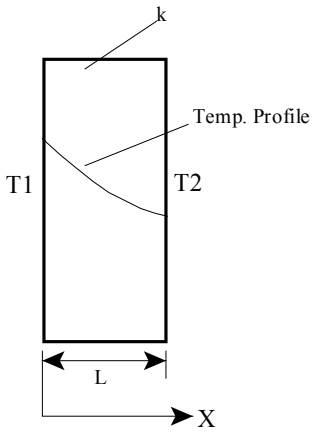

Fig. Prob.1A.1.

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Mathcad Solution:

Data:

$L := 0.5$ m

$k := 1.2$ W/m.C

$T(x) := 60 - 50 \cdot x + 12 \cdot x^2 + 20 \cdot x^3 - 15 \cdot x^4$ .... Define T(x)...i.e. temp. as a function of x

Temp. at left face: i.e. at x = 0: $T(0) = 60$ C....**Ans.**

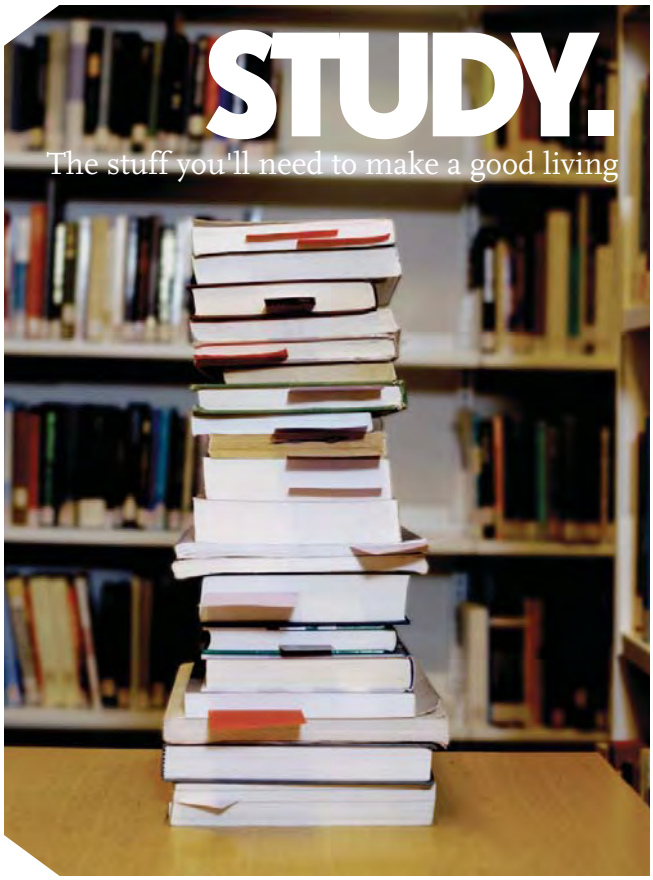
Temp. at right face: i.e. at x = 0.5 m: $T(0.5) = 39.563$ C....**Ans.**

Temp. profile in the slab:

$x := 0, 0.01 .. 0.5$ Define the range variable x i.e. x to vary from 0 to 0.5 m in steps of 0.01 m

To draw the graph:

Select the x-y plot from pallete, plug in x and T(x) in the place holders:
Click anywhere outside the graph region; immediately the graph appears.



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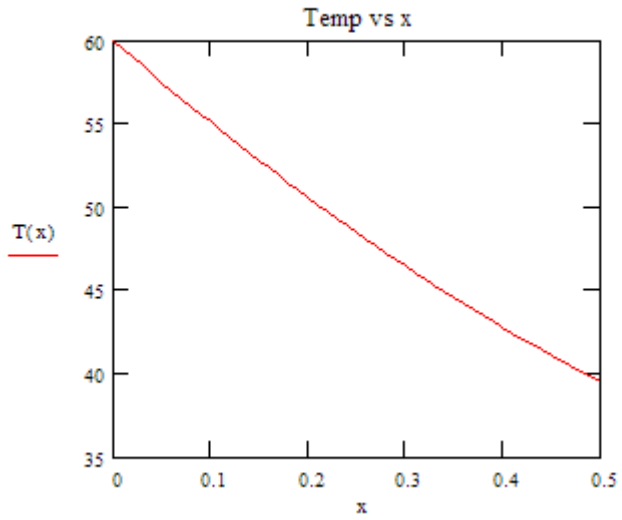

x in meters, T(x) in deg.C

Define the first derivative of T(x): $T'(x) := \frac{d}{dx} T(x)$

To calculate the heat fluxes at the left and right faces:

Apply the Fourier's Law at x = 0 and at x = 0.5 m, remembering that temp. gradient is given by T'(x), aready defined.

$q_{left} := -k \cdot T'(0)$ ..applying Fourier's Law at left face i.e. at x = 0

$q_{left} = 60$ ...**Heat flux at the left face (W/m^2)**; note that +ve sign indicates heat flowing from left to right

$q_{right} := -k \cdot T'(0.5)$ ..applying Fourier's Law at right face i.e. at x = 0.5 m

$q_{right} = 36.6$ ...**Heat flux at the right face (W/m^2)**; note that +ve sign indicates heat flowing from left to right.

$q_{stored} := q_{left} - q_{right}$ .. heat stored per m^2 of surface

$q_{stored} = 23.4$ **W/m^2...heat stored/m^2...Ans.**

Therefore, for 5 m^2 area: $Q_{stored} := q_{stored} \cdot 5$

i.e. $Q_{stored} = 117$ **W...heat energy stored in unit time...Ans.**

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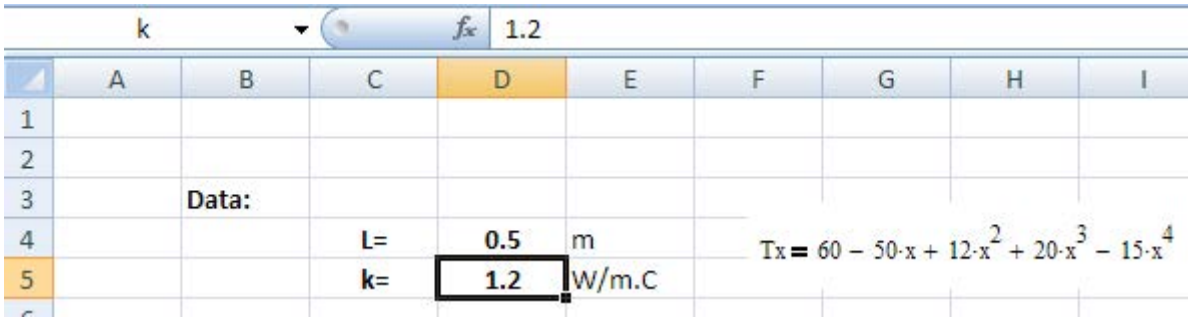
Solve the above problem with EXCEL:

Following are the steps:

1. Set up the EXCEL worksheet as shown below. Enter the data, with the variable, its numerical value and the units in three adjacent columns. Also, name the cells as explained in the Introduction to EXCEL, since it will make entering formulas without errors easier.



2. Now, calculate temperatures at various x's. Take increment in x as 0.05 m, varying from 0 to 0.5 m:

	A	B	C	D	E	F	G	H	I
1									
2									
3		Data:							
4			L=	0.5	m				
5			k=	1.2	W/m.C				
6									
7			x(m)	Tx (deg.C)					
8			0						
9			0.05						
10			0.1						
11			0.15						
12			0.2						
13			0.25						
14			0.3						
15			0.35						
16			0.4						
17			0.45						
18			0.5						

$$Tx = 60 - 50 \cdot x + 12 \cdot x^2 + 20 \cdot x^3 - 15 \cdot x^4$$

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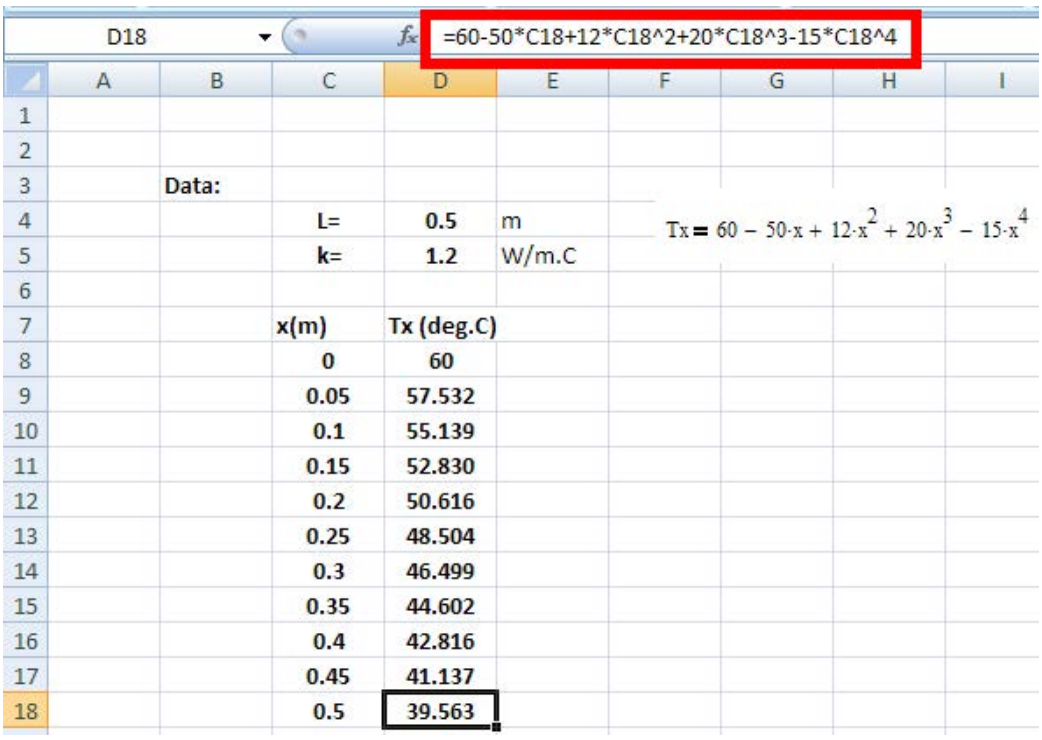
3. Now, enter the equation for Tx in cell D8, and then drag-copy it up to cell D18. Immediately, the values of Tx are calculated:



D18 | =60-50*C18+12*C18^2+20*C18^3-15*C18^4

	A	B	C	D	E	F	G	H	I
1									
2									
3		Data:							
4			L=	0.5	m				
5			k=	1.2	W/m.C				
6									
7			x(m)	Tx (deg.C)					
8			0	60					
9			0.05	57.532					
10			0.1	55.139					
11			0.15	52.830					
12			0.2	50.616					
13			0.25	48.504					
14			0.3	46.499					
15			0.35	44.602					
16			0.4	42.816					
17			0.45	41.137					
18			0.5	39.563					

$$Tx = 60 - 50 \cdot x + 12 \cdot x^2 + 20 \cdot x^3 - 15 \cdot x^4$$

Note that formula for Tx in cellD18 can be seen in the Formula bar.

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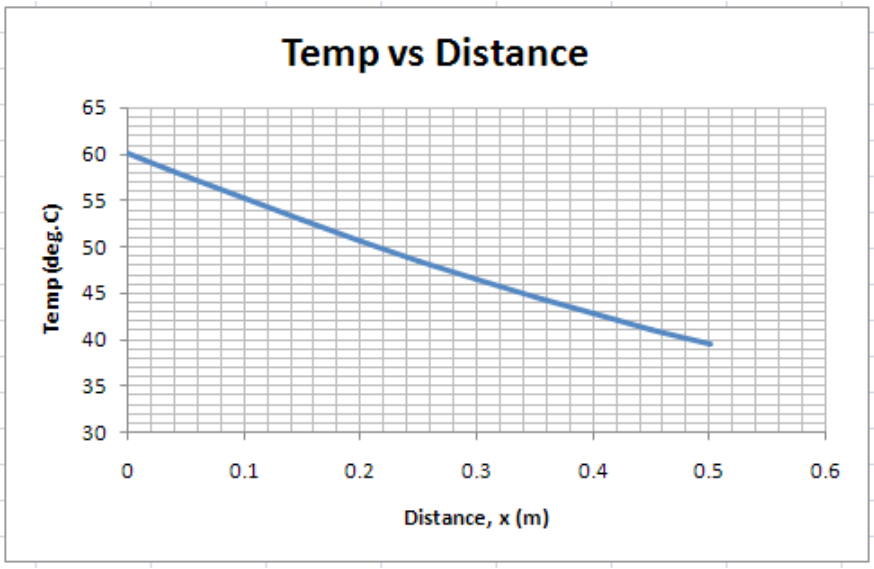
Thus: Temp at x = 0 is 60 deg.C and Temp at x = 0.5 is 39.563 deg.C.

Same values were obtained with Mathcad earlier.

4. Now draw and format the graph of Tx vs x: (See Introduction to EXCEL for the procedure)



5. To calculate heat fluxes at Left and Right faces:

We have: q = – k * (dT/dx). So, dT/dx has to be calculated at x = 0 and x = 0.5.

For this use the simple procedure explained earlier. i.e. take a very small dx and calculate dx and calculate dT/dx. At x = 0, introduce one more row, take dx = 0.000001 and find new Tx, and then dT/dx, and q at x= 0:

F8 =(D9-D8)/(C9-C8)

	A	B	C	D	E	F	G	H	I
4			L=	0.5	m	Tx = 60 – 50·x + 12·x^2 + 20·x^3 – 15·x^4			
5			k=	1.2	W/m.C				
6									
7			x(m)	Tx (deg.C)					
8			0	60	dT/dx=	-50	C/m		
9			0.000001	59.99995	q=	59.99999	W/m^2		
10			0.05	57.532					
11			0.1	55.139					
12			0.15	52.830					
13			0.2	50.616					
14			0.25	48.504					
15			0.3	46.499					
16			0.35	44.602					
17			0.4	42.816					
18			0.45	41.137					
19			0.5	39.563					

In the above Fig. formula for dT/dx entered in cell F8 can be seen in the Formula bar.

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Thus: q_{left} = 59.9999 W/m^2 … same as obtained earlier.

6. Similarly, find out heat flux q_{right}:

F19 =(D20-D19)/(C20-C19)

	A	B	C	D	E	F	G
7			x(m)	Tx (deg.C)			
8			0	60	dT/dx=	-50	C/m
9			0.000001	59.99995	q=	59.99999	W/m^2
10			0.05	57.532			
11			0.1	55.139			
12			0.15	52.830			
13			0.2	50.616			
14			0.25	48.504			
15			0.3	46.499			
16			0.35	44.602			
17			0.4	42.816			
18			0.45	41.137			
19			0.499999	39.563	dT/dx=	-30.5	C/m
20			0.5	39.563	q=	36.60002	W/m^2

Thus: q_{right} = 36.6 W/m^2 .. same as obtained earlier with Mathcad.

7. **And, $q_{stored} = q_{left} - q_{right}$ = 23.4 W/m^2**

Prob. 1A.2. The steady state temperature distribution in a wall of thermal conductivity 50 W/m.K and thickness 50 mm is observed to be: $T(x) = a + b.x^2$ where a = 200 C and b = 2000 C/m^2 and x is in metres.

What is the heat dissipation rate in the wall?

Determine the heat fluxes at the two wall faces.

In what manner are these heat fluxes related to the heat generation rate? [VTU-6th Sem-B.E.- July/Aug.2004]

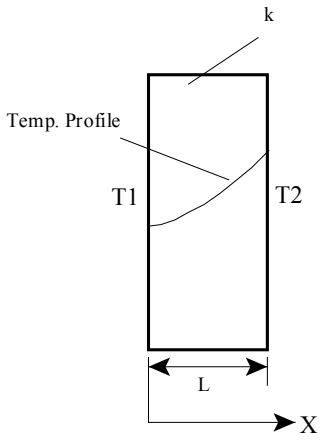

Fig. Prob.1A.2

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Mathcad Solution:

Data:

$L := 0.05$ m

$k := 50$ W/m.C

$A := 1$ m^2

$T(x) := 200 + 2000 \cdot x^2$ ... Define T(x)...i.e. temp. as a function of x

Temp. at left face: i.e. at x = 0: $T(0) = 200$ C....**Ans**.

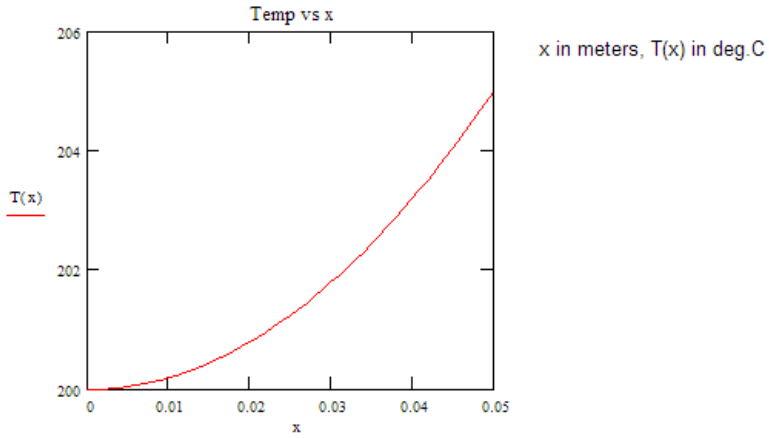
Temp. at right face: i.e. at x = 0.05 m: $T(0.05) = 205$ C....**Ans**.

Temp. profile in the slab:

$x := 0, 0.001 .. 0.05$ Define the range variable x i.e. x to vary from 0 to 0.05 m in steps of 0.001 m

To draw the graph:

Just select the x-y plot from pallete, plug in x and T(x) in the place holders:
Click anywhere outside the graph region; immediately the graph appears.



Define the first derivative of T(x): $T'(x) := \frac{d}{dx} T(x)$

To calculate the heat fluxes at the left and right faces:

Apply the Fourier's Law at x = 0 and at x = 0.05 m, remembering that temp. gradient is

given by T'(x), aready defined.

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$q_{left} := -k \cdot T'(0)$ ..applying Fourier's Law at left face i.e. at x = 0

$q_{left} = 0$ ...**Heat flux at the left face (W/m^2)**

$q_{right} := -k \cdot T'(0.05)$ ..applying Fourier's Law at right face i.e. at x = 0.5 m

$q_{right} = -1 \cdot 10^4$ ...**Heat flux at the right face (W/m^2)**; note that -ve sign indicates heat flowing from right to left.

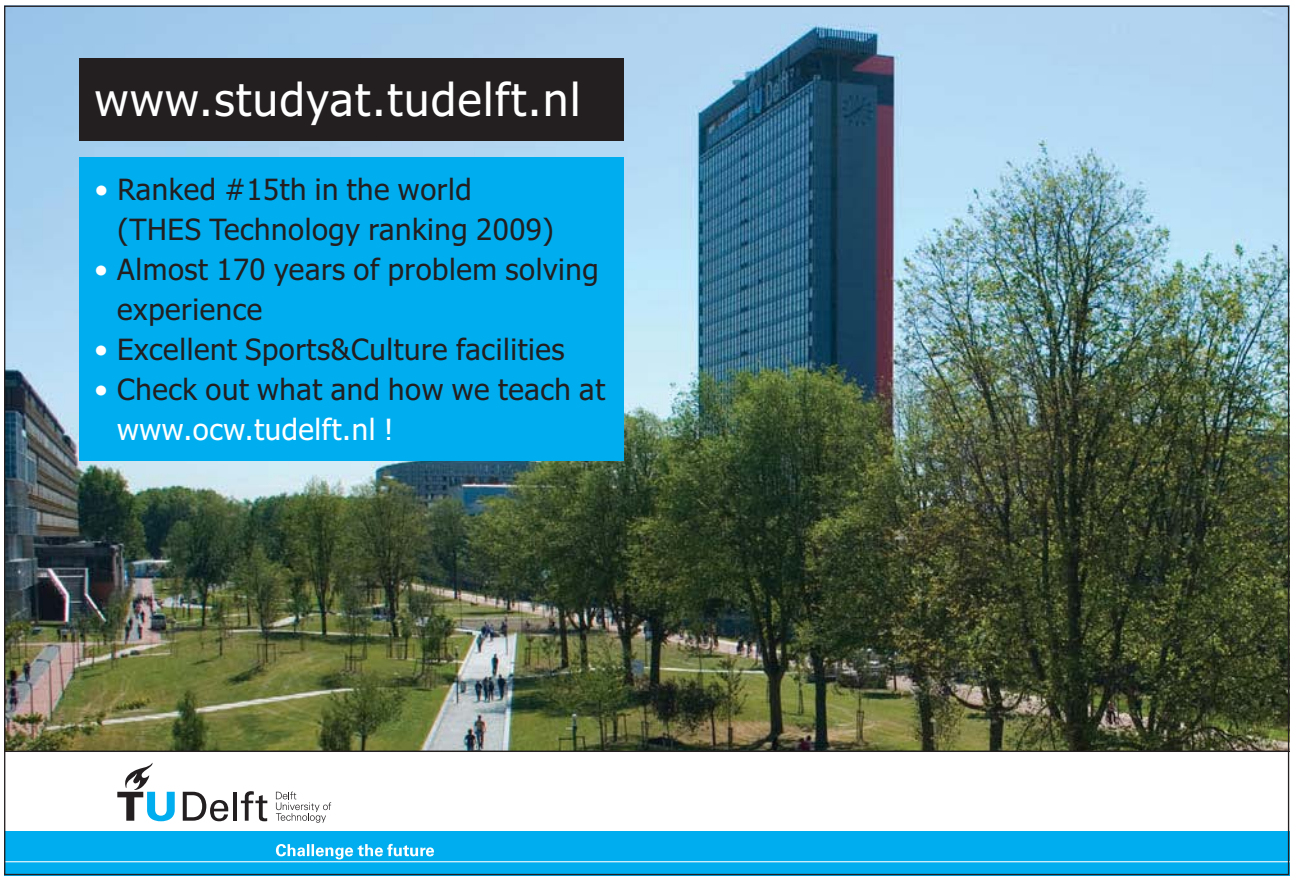
$q_{stored} := q_{left} - q_{right}$ .. heat stored per m^2 of surface

$q_{stored} = 1 \cdot 10^4$ **W/m^2...heat stored/m^2**

Heat energy stored per unit volume:

$q_g := \frac{q_{stored}}{A \cdot L}$ i.e. $q_g = 2 \cdot 10^5$ **W/m^3.....Ans.**

Note: In steady state, heat stored is equal to (heat going in - heat going out)



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Prob. 1A.3. A 5 cm dia. cylindrical rod (k = 15 W/(m.C)), with an uniform heat generation rate of q_g (W/m^3) inside it, has a radial temperature distribution given by:

$T(r) = 315 - 2.1\times10^4\ r^2$ where T is in deg.C, r in metres. Determine:

1. Max. temperature in the rod
2. Volumetric rate of heat generation
3. Average temperature of the cylinder

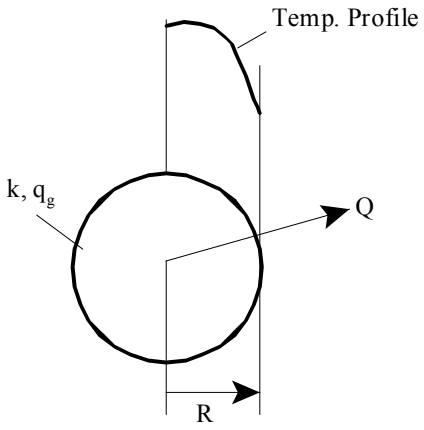

Fig. Prob.1A.3.

Mathcad Solution:

Data:

$R := 0.025$ m

$k := 15$ W/m.C

$L := 1$ m

$T(r) := 315 - 2.1\cdot10^4\cdot r^2$ ...Define T(r)...i.e. temp. as a function of r

Therefore:

$T(0) = 315$ C....temp at r = 0, i.e. at the centre

$T(R) = 301.875$ C....temp at r = R, i.e. at the surface

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Solution:

$T'(r) := \frac{d}{dr} T(r)$ ...Define first derivative of T(r)

$T''(r) := \frac{d}{dr} T'(r)$ .....Define second derivative of T(r)

(i) **Tmax occurs at r = 0, i.e. at the centre. Therefore:**

Tmax = 315 C.....Ans.

$T'(R) = -1.05 \cdot 10^3$ C/m.....dT/dr at the surface i.e. at r = R

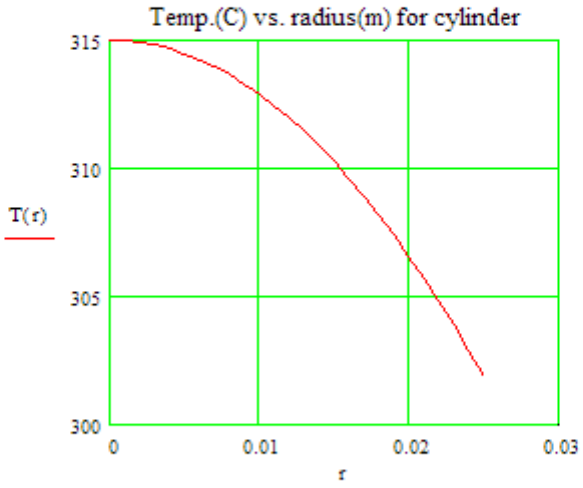
$Q_{surface} := -k \cdot (2 \cdot \pi \cdot R \cdot L) \cdot T'(R)$ ..heat tr. rate at the surface is obtained by applying Fourier's Law at the surface i.e. at r = R; T'(R) is the temp. gradient at r = R

$Q_{surface} = 2.474 \cdot 10^3$ ....**W/metre length...heat tr. at the surface...Ans**.

Temperature distribution:

$r := 0, 0.001 .. 0.025$ ....define a range variable. i.e. r varies from 0 to 0.025 m in steps of 0.001 m

Then, select the x-y graph from pallete and fill in the place holders in both the axes. On x - axis, fill in r and on y-axis, fill in T(r). Click anywhere outside the graph region and immediately, the graph appears.



Note from the graph that max. temp. occurs at the centre (r = 0); slope of the temp. curve (dT/dr) tends to zero (i.e. the curve becomes almost horizontal) as it aproaches the y - axis at r = 0

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(ii) Volumetric Heat generation rate, q_g:

We have the one dimensional, time dependent differential equation, with constant k, for heat conduction in cylindrical coordinates:

$$\frac{d^2T}{dr^2}+\frac{1}{r}\frac{dT}{dr}+\frac{q_g}{k}=\frac{1}{\alpha}\frac{dT}{d\tau}$$

In steady state, RHS of above eqn is zero.

Then:

$$q_g = k\cdot\left(-\frac{d^2}{dr^2}T(r)-\frac{1}{r}\cdot\frac{d}{dr}T(r)\right)$$

i.e. $$q_g := k\cdot\left(-T''(R)-\frac{1}{R}\cdot T'(R)\right)$$

i.e. $q_g = 1.26\cdot 10^6$ **W/m^3....Vol. heat gen. rate.....Ans.**

Average temp. of the cylinder:

For a differential element of thickness dr, amount of heat energy contained in the element is equal to $2\pi r.dr.L.\rho.cp.T(r)$. Total amount of energy in the cylinder is obtained by integrating this from r = 0 to r = R. Now, if the average temp. of cylinder is Tavg, amount of energy in the cylinder can also be written as: $\rho.\pi.R^2.L.cp.Tavg$. Equating these two expressions:
we get:

$$T_{avg} := \frac{2}{R^2}\cdot\int_0^R T(r)\,r\,dr$$ ...Mathcad easily does the integration of T(r) within the limits specified

$T_{avg} = 308.438$ **C....Avg. temp. of the cylinder....Ans**

Note that Mathcad directly gives the value of the integral within the limits specified; there is no need to expand the integral and write down as you do in hand calculations.

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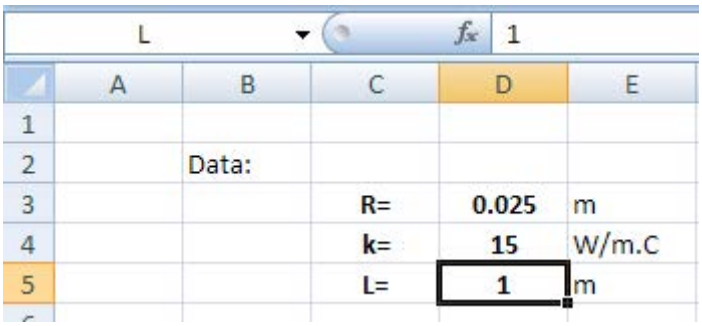
Solve the above Problem with EXCEL:

Following are the steps:

1. Enter the data, and name the cells:



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2. Calculate temperatures at various r's:

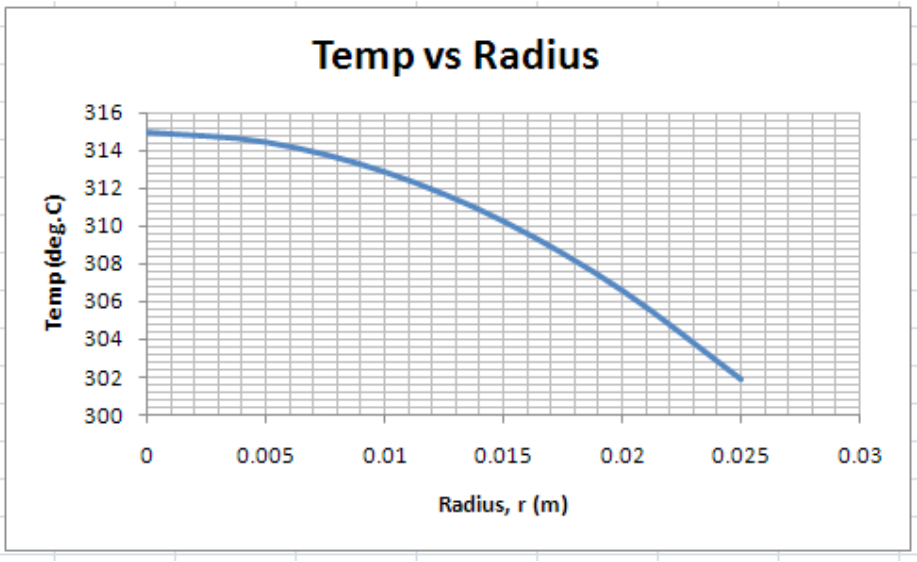
D8 =315-21000*C8^2

	A	B	C	D	E	F	G	H
1								
2		Data:						
3			R=	0.025	m			
4			k=	15	W/m.C		$T(r) := (315 - 2.1 \cdot 10^4 \cdot r^2)$	
5			L=	1	m			
6								
7			r (m)	Tr (deg.C)				
8			0	315	Temp at centre = Tmax.			
9			0.005	314.475				
10			0.01	312.9				
11			0.015	310.275				
12			0.02	306.6				
13			0.025	301.875	Temp. at surface			

Note the eqn entered at cell D8 in the Formula bar.

Also note that max. temp (i.e. temp at r = 0) is = 315 deg. C ans thw temp at the surface (i.e. at r = 0.025 m) is = 301.875 deg.C.

3. Now, draw the temp. profile:



4. Heat transfer from the surface = $-k * (2 * \pi * R) * (dT/dr)_{r=R}$

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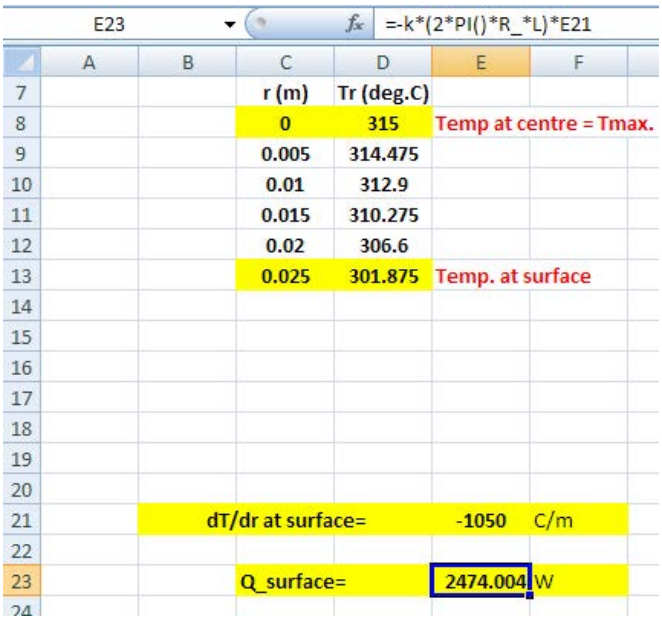
5. To calculate Q_surface: Temp gradient at the surface is easily calculated as:
   dT/dr at R = -2*2.1E04*R , and Q = -k *Area * dT/dr at r = R.
   The part of EXCEL worksheet for this calculation is shown below:



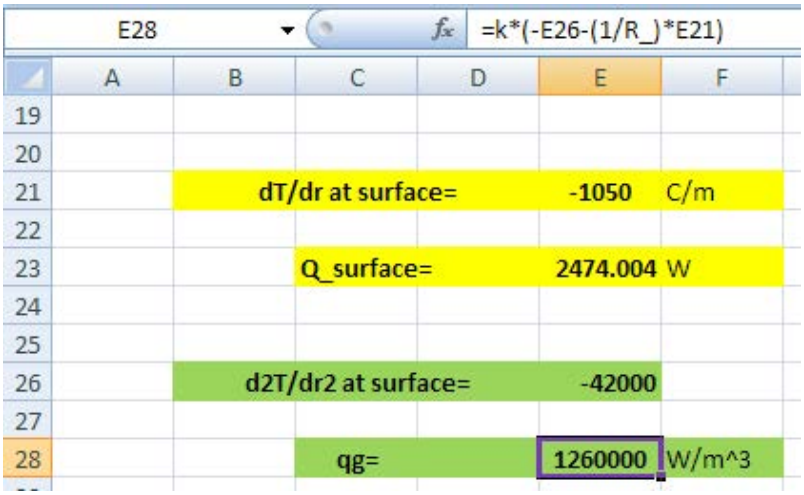
	A	B	C	D	E	F
E23					=-k*(2*PI()*R_*L)*E21	
7			r (m)	Tr (deg.C)		
8			0	315	Temp at centre = Tmax.	
9			0.005	314.475		
10			0.01	312.9		
11			0.015	310.275		
12			0.02	306.6		
13			0.025	301.875	Temp. at surface	
21		dT/dr at surface=			-1050	C/m
23			Q_surface=		2474.004	W

   I the above Fig, Formula bar shows the eqn for Q_surface in cell E23.

6. To find heat gen. rate, qg: Refer to the formula for qg worked out while solving with Mathcad. We have:

$$q_g = k \cdot \left(-\frac{d^2T}{dr^2} - \frac{1}{R} \cdot \frac{dT}{dr} \right) \quad \text{at } r = R$$

This is implemented in EXCEL:



	A	B	C	D	E	F
E28					=k*(-E26-(1/R_)*E21)	
19						
20						
21		dT/dr at surface=			-1050	C/m
22						
23			Q_surface=		2474.004	W
24						
25						
26		d2T/dr2 at surface=			-42000	
27						
28			qg=		1260000	W/m^3

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Here formula entered for qg can be seen in the formula bar.

Thus, qg = 1.26 x 10^4 W/m^3, … same as obtained earlier with Mathcad.

7. Average temp of cylinder is obtained as:

$$T_{avg} = \frac{2}{R^2} \cdot \int_0^R T(r) \cdot r \, dr$$

So, in EXCEL, we find out the integral first, and then T_{avg}.

Procedure of numerical integration is already explained in Introduction.

Following is the worksheet for this calculation:

Since the integral contains Tr * r, we have three columns: In column E r is entered from 0 to 0.025, with an increment of 0.001. In column F, (Tr * r) is calculated. The formula entered in cell F63 can be seen in the Formula bar.

F63 | fx | =(315-21000*E63^2)*E63

$$T(r) := \left(315 - 2.1 \cdot 10^4 \cdot r^2\right)$$

$$T_{avg} = \frac{2}{R^2} \cdot \int_0^R T(r) \cdot r \, dr$$

r	Tr * r	A1 = area of Trapezoid
0	0	
0.001	0.314979	
0.002	0.629832	
0.003	0.944433	
0.004	1.258656	
0.005	1.572375	
0.006	1.885464	
0.007	2.197797	
0.008	2.509248	

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And, in column G, areas of Trapezoids are calculated:

G64 =((F64+F63)/2)*0.001

$$T(r) := \left(315 - 2.1 \cdot 10^{4} \cdot r^{2}\right)$$

$$T_{avg} = \frac{2}{R^{2}} \cdot \int_{0}^{R} T(r) \cdot r \, dr$$

	r	Tr * r	A1 = area of Trapezoid
63	0	0	
64	0.001	0.314979	0.00015749
65	0.002	0.629832	0.000472406
66	0.003	0.944433	0.000787133
67	0.004	1.258656	0.001101545
68	0.005	1.572375	0.001415516
69	0.006	1.885464	0.00172892
70	0.007	2.197797	0.002041631
71	0.008	2.509248	0.002353523
72	0.009	2.819691	0.00266447
73	0.01	3.129	0.002974346
74	0.011	3.437049	0.003283025
75	0.012	3.743712	0.003590381
76	0.013	4.048863	0.003896288
77	0.014	4.352376	0.00420062
78	0.015	4.654125	0.004503251

In the above Fig. area of the first Trapezoid is calculated in cell G64; the formula used can be seen in the Formula bar.

Then, sum up all the areas to get the value of the integral:

G89 =SUM(G64:G88)

79				0.016	4.953984	0.004804055
80				0.017	5.251827	0.005102906
81				0.018	5.547528	0.005399678
82				0.019	5.840961	0.005694245
83				0.02	6.132	0.005986481
84				0.021	6.420519	0.00627626
85				0.022	6.706392	0.006563456
86				0.023	6.989493	0.006847943
87				0.024	7.269696	0.007129595
88				0.025	7.546875	0.007408286
89					Sum=	0.096383438

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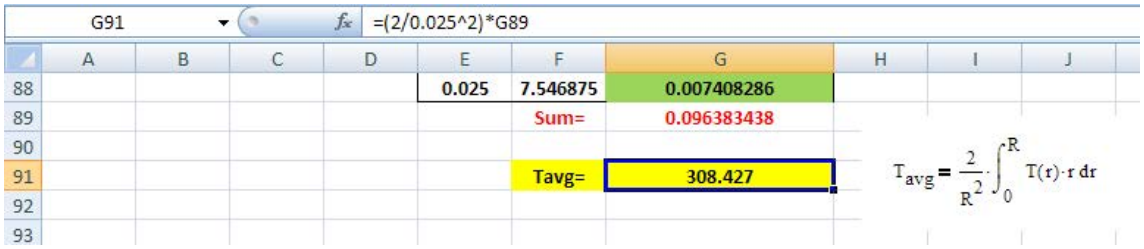
And the average temp of cylinder is calculated as:



i.e. T_{avg} = 308.427 deg.C. (See the formula in cell G91 in the Formula bar).

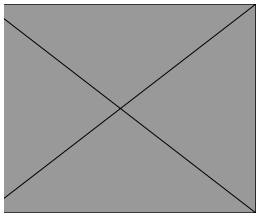
Compare this with the value obtained with Mathcad, i.e. 308.438 deg.C.

Prob. 1A.4. The steady state radial temperature profile in a 10 cm dia solid sphere is given by:

$T(r) = 101.4 - 1390\ r^2$, where T is in deg.C and r, in metres. Its k = 10 W/(m.C). The sphere is placed in an ambient of 30 C.

a) What is the max. temp. in the sphere?
b) Is there heat generation in the sphere? If yes, at what rate?
c) Calculate the convection coeff. at the outer surface.

Mathcad Solution:



$T_a := 30$ C...ambient temp.

$T(r) := 101.4 - 1390 \cdot r^2$ ...Define T(r)...i.e. temp. as a function of r, by data

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Solution:

(i) Max. temp.:

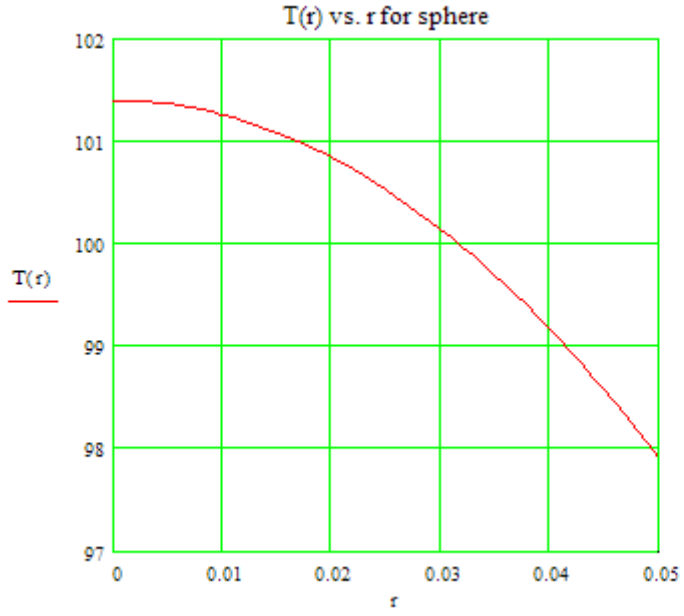
$T(0) = 101.4$ C...**Max. temp. occurs at the centre, i.e. at r = 0...Ans**

$T(R) = 97.925$ C... **temp. at the surface**

Temp. profile:

$r := 0, 0.001 .. 0.05$ ....define a range variable. i.e. r varies from 0 to 0.05 m in steps of 0.001 m

Then, select the x-y graph from pallete and fill in the place holders in both the axes. On x - axis, fill in r and on y-axis, fill in T(r). Click anywhere outside the graph region and immediately, the graph appears.



T(r)....in Celsius

r...in metres

Note from the graph that max. temp. occurs at the centre (r = 0); slope of the temp. curve (dT/dr) tends to zero (i.e. the curve becomes almost horizontal) as it aproaches the y - axis at r = 0

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(ii) Heat generation rate in the sphere:

Find out the heat transfer at the surface:

$T'(r) := \frac{d}{dr} T(r)$ ...Define derivative of T(r)

$Q(R) := -k \cdot \left(4 \cdot \pi \cdot R^2\right) \cdot T'(R)$ ...Q(R) is the heat tr. rate at radius R, by Fourier's Law

$Q(R) = 43.668$ **W..heat tr. rate at the surface i.e. at r = R = 0.05 m...Ans.**

This must be equal to heat generated inside the sphere in steady state, Q_{gen}.

Volumetric heat generation rate q_g is, therefore, given by:

$$q_g := \frac{Q(R)}{\frac{4}{3} \cdot \pi \cdot R^3} \quad \text{i.e.} \quad q_g = 8.34 \cdot 10^4$$ **W/m^3.....Ans.**

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(iii) Convection coeff. at the outer surface:

Obviously, the heat generated in the sphere is transferred to the ambient by convection. Writing the heat balance:

$$h \cdot \left(4 \cdot \pi \cdot R^2\right) \cdot \left(T(R) - T_a\right) = 43.668$$

i.e. $$h \cdot \left(4 \cdot \pi \cdot R^2\right) \cdot (97.925 - 30) = 43.668$$

i.e. $$h := \frac{43.668}{\left[\left(4 \cdot \pi \cdot R^2\right) \cdot (97.925 - 30)\right]}$$

i.e. $h = 20.464$ **W/m^2.C.....Ans.**

==========

"**Prob. 1A.5.** A plane wall is 0.05 m thick and has a thermal conductivity of 1.2 W/m.C. Left face of the wall is maintained at 300 K and the right face has an emissivity of 0.85, and the solar absorptivity of 0.25. The right surface is exposed to solar radiation incident at a rate of 850 W/m^2. This surface also loses heat by radiation to deep space, assumed to be at 0 K. Determine the temperature of the right face of the wall in steady state, and also the heat transfer rate."

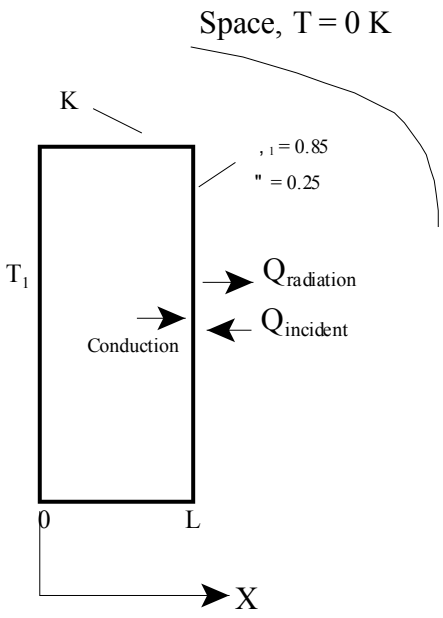

Fig. Prob.1A.5

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EES Solution:

"Data:"

L = 0.05 [m]
k = 1.2 [W/m-C]
A = 1[m^2]
epsilon = 0.85
sigma = 5.67e-08 [W/m^2-K^4] "… Stefan-Boltzmann constant"
alpha = 0.25
T_1 = 300 "K …. temp of left face of the wall"
q_solar = 850 "W/m^2"
T_space = 0 "K"

"Calculations:"

R_slab = L/(k*A) "[C/W] … thermal resistance of the plane wall"

"Write the heat balance on the right face of the wall:

i.e. Since there is no heat generated at the surface, rate of energy into the surface should be equal to the rate of energy leaving the surface:

i.e. heat flow ***to*** right face from left face by conduction + heat flow ***into*** the right face by absorption of incident solar flux = heat ***leaving*** the surface to deep space by radiation:"

Q_conduction = (T_1 – T_2) / R_slab "[W/m^2]… heat flow rate from left face of wall to the right face, by Fourier's law"
Q_solar = q_solar * alpha "[W/m^2] … incident solar energy which is absorbed"
Q_radiation = sigma * epsilon * A * (T_2^4 – T_space^4) "[W/m^2] …. Energy that is radiated from the surface to deep space"

Q_conduction + Q_solar = Q_radiation "heat balance … finds the temp of right face, T_2"

"Note that the resulting eqn is highly non-linear because of the radiation term and would generally require a trial and error solution. However, EES solves such equations with ease."

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Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]

$\varepsilon = 0.85$ [-]

$L = 0.05$ [m]

$Q_{conduction} = 147$ [W/m^2]

$q_{solar} = 850$ [W/m^2]

$\sigma = 5.670E\text{-}08$ [$W/m^2\text{-}K^4$]

$T_2 = 293.9$ [K]

$\alpha = 0.25$ [-]

$k = 1.2$ [W/m-K]

$Q_{absorbed} = 212.5$ [W/m^2]

$Q_{radiation} = 359.5$ [W/m^2]

$R_{slab} = 0.04167$ [K/W]

$T_1 = 300$ [K]

$T_{space} = 0$ [K]

Thus:

T_ 2 = 293.9 K….. Ans.

Q_conduction = 147 W/m^2…..Ans.

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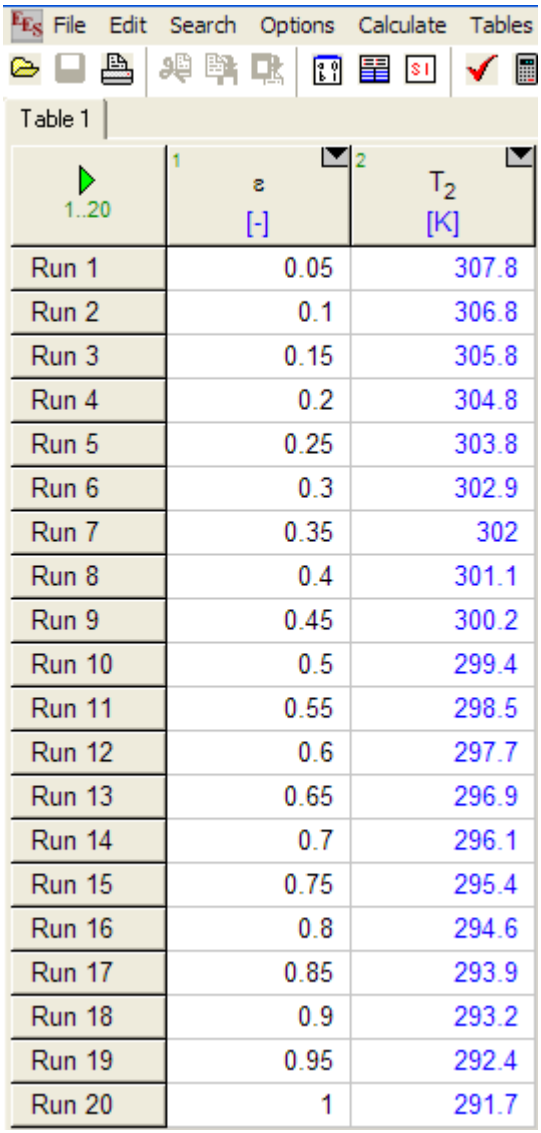
In addition, draw the variation of steady state temp T_2 as emissivity varies from 0.05 to 1:

With EES, this is very easy. Construct a parametric table with epsilon varying from 0.05 to 1. Then, click on New Plot tab, select epsilon on x-axis and T_2 on y-axis and complete the plot. The parametric table and the plot are shown below:



1..20	1 ε [-]	2 T_2 [K]
Run 1	0.05	307.8
Run 2	0.1	306.8
Run 3	0.15	305.8
Run 4	0.2	304.8
Run 5	0.25	303.8
Run 6	0.3	302.9
Run 7	0.35	302
Run 8	0.4	301.1
Run 9	0.45	300.2
Run 10	0.5	299.4
Run 11	0.55	298.5
Run 12	0.6	297.7
Run 13	0.65	296.9
Run 14	0.7	296.1
Run 15	0.75	295.4
Run 16	0.8	294.6
Run 17	0.85	293.9
Run 18	0.9	293.2
Run 19	0.95	292.4
Run 20	1	291.7

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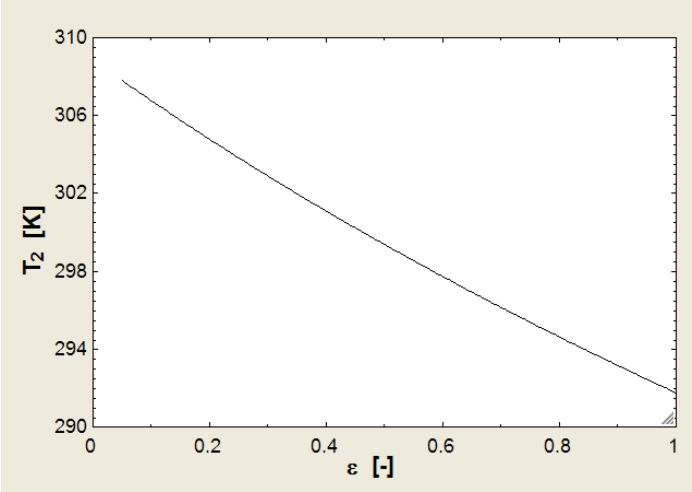

==========

Solve the above Problem with EXCEL:

Following are the steps:

1. Set up the EXCEL worksheet as shown below. Enter the data, and name the cells:

	A	C	D	E	F	G
1						
2						
3		Data:				
4			L	0.05	m	
5			k	1.2	W/m.K	
6			A	1	m^2	
7			epsilon	0.85		
8		Stefan-Boltzmann const. =	sigma	5.67E-08	W/m^2.K^4	
9			alpha	0.25		
10			T_1	300	K	
11			q_solar	850	W/m^2	
12			T_space	0	K	
13			T_2	200	K....Trial value	

In the above fig. note that a trial value of 200 K has been assumed for temp T_2. It is important to start with a trial (or guess) value when we solve the heat balance eqn later by iteration using 'Goal Seek' in EXCEL.

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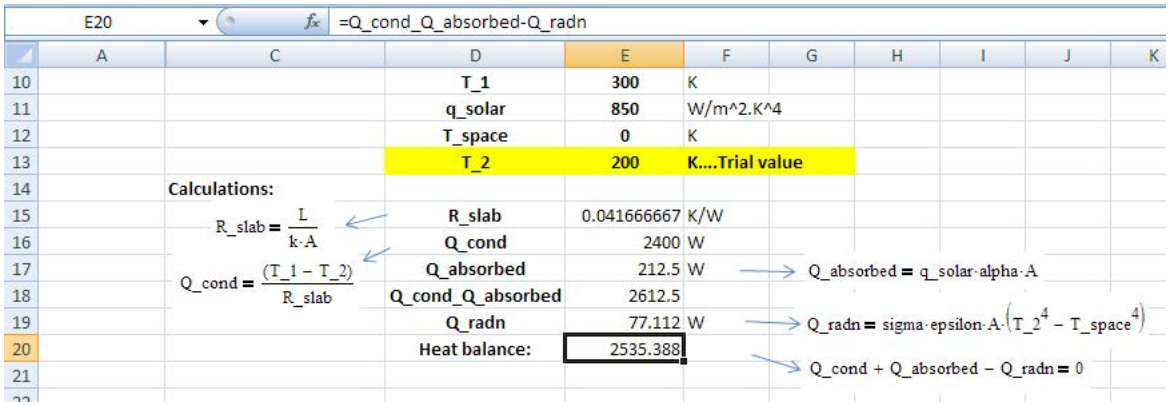
2. Do the preliminary calculations as sown; again name these new cells:



Note in the above fig. that the formulas used in calculations are shown separately. Heat balance eqn can be seen in the Formula bar.

We know that in equilibrium condition of T_2, the heat balance eqn in cell E20 should be zero. However, since we started with a guess value, cell E20 is not equal to zero, but is some other value (=2535.388).

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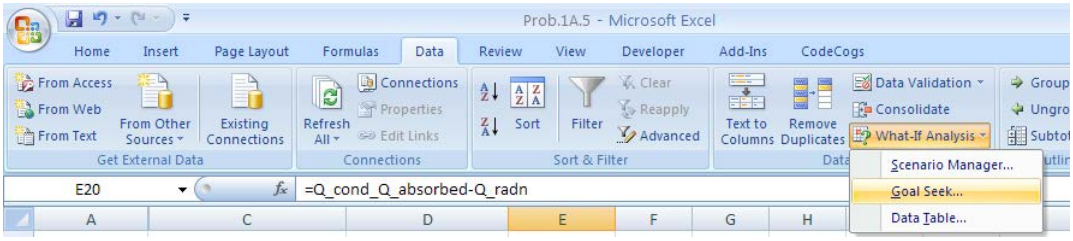
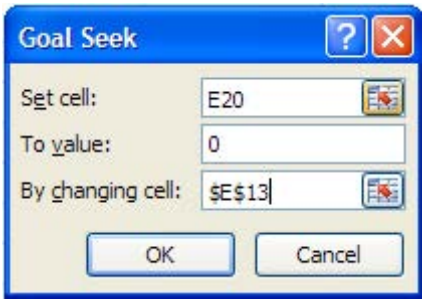
3. So, now, we seek the value of T_2 such that value in cell E29 is equal to zero. For this, we use 'Goal Seek' in EXCEL:

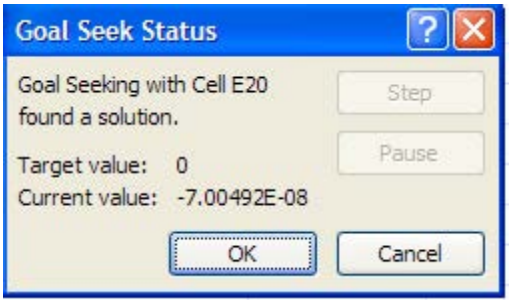
Go to Data-What If Analysis – Goal Seek:



Click on Goal Seek. We get the pop up:



In the above pop up, we fill up: Set cell: E20,
To value: zero
By changing cell: E13 (i.e. T_2).
Click OK. We get a message saying that Goal Seek has found a solution:



And the worksheet cell E13 (i.e. T_2) has changed to 293.876 and all other related cells also have been re-calculated. *This value of T_2 matches with value obtained with EES earlier.*

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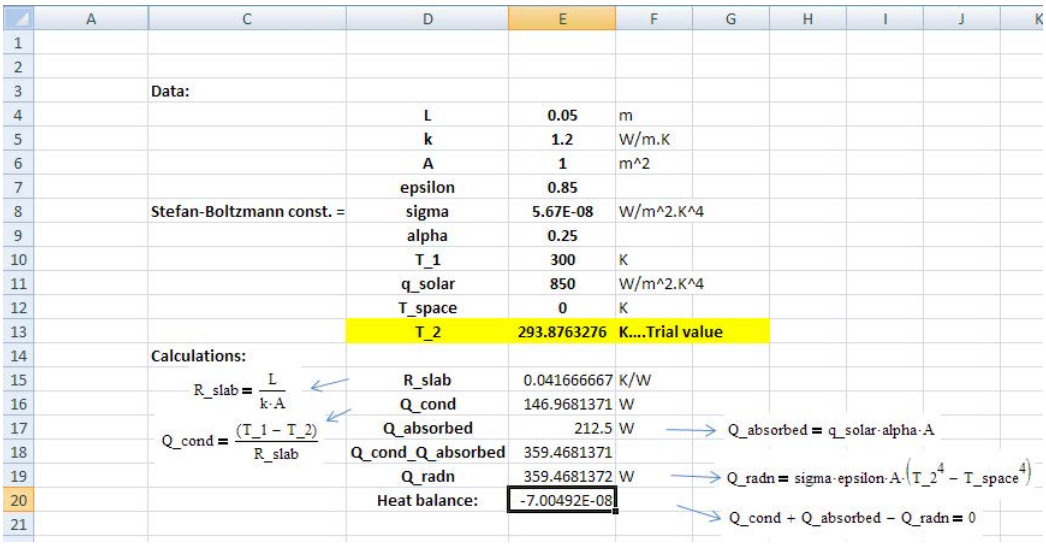
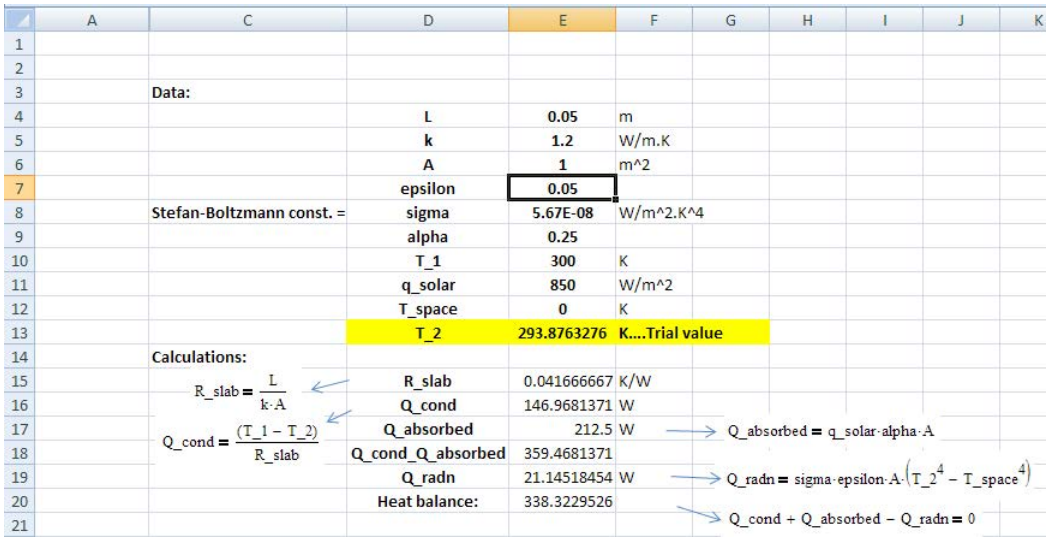


Note that cell E20 is not 'exactly equal to zero', but has converged to -7.00492E-08, almost equal to zero; it is good enough.

4. Now, we would like to get values of T_2 for a range of values of epsilon. This will involve epsilon, i.e. cell E7 for different value and applying Goal Seek repeatedly. **To apply Goal Seek repeatedly, we can write a Macro.** Following is the procedure:

   a) Change cell E7 to 0.05. Immediately, connected values will change and cell E20 for heat balance is no more equal to zero. See the following screen shot:



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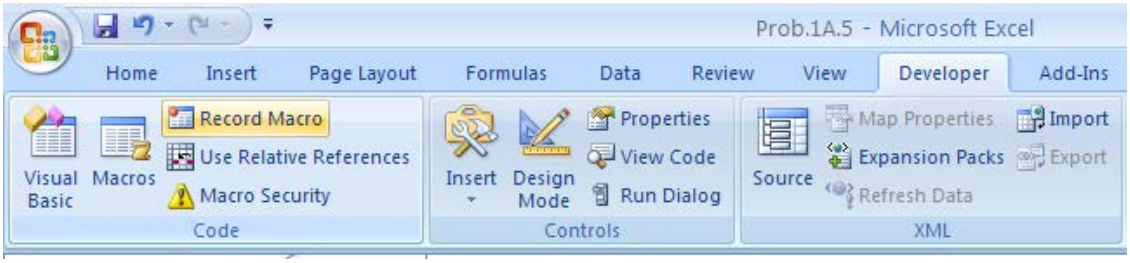
b) Now, go to Developer – Record Macro:



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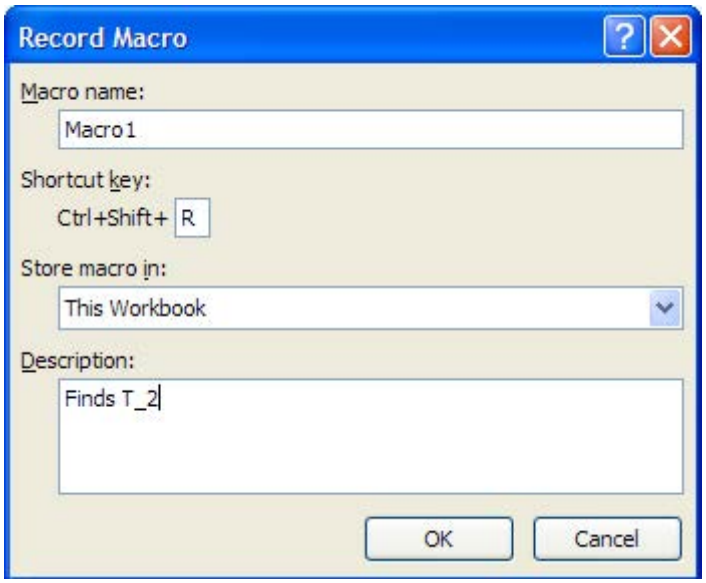
c) Click on Record Macro. We get:



In the above, Macro Name: we have left the default value viz. Macro1
Short cut key: WE have chosen Ctrl+Shift+R
Store macro in: This Workbook (default), and
Description: we have written briefly: Finds T_2.
Press OK. Immediately, recording starts, and 'Record Macro' button changes to 'Stop Recording':

Now, go through the steps of using Goal Seek to make cell E20 equal to zero by changing cell E13. Whatever value is there presently in cell E13 becomes the guess value for this process. After the goal seek gets a new value for T_2, close goal seek window by pressing OK and stop the recording by clicking on 'Stop Recording' button. We get:

	A	C	D	E	F	G	H	I	J	K
1										
2										
3		Data:								
4			L	0.05	m					
5			k	1.2	W/m.K					
6			A	1	m^2					
7			epsilon	0.05						
8		Stefan-Boltzmann const. =	sigma	5.67E-08	W/m^2.K^4					
9			alpha	0.25						
10			T_1	300	K					
11			q_solar	850	W/m^2					
12			T_space	0	K					
13			T_2	307.7939733	K....Trial value					
14		Calculations:								
15		$R_slab = \frac{L}{k \cdot A}$	R_slab	0.041666667	K/W					
16			Q_cond	-187.0553581	W					
17		$Q_cond = \frac{(T_1 - T_2)}{R_slab}$	Q_absorbed	212.5	W	→ Q_absorbed = q_solar·alpha·A				
18			Q_cond_Q_absorbed	25.44464189						
19			Q_radn	25.44447596	W	→ $Q_radn = sigma \cdot epsilon \cdot A \cdot (T_2^4 - T_space^4)$				
20			Heat balance:	0.000165931		→ Q_cond + Q_absorbed − Q_radn = 0				
21										

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Note that T_2 is 307.79397 when epsilon is 0.05.

d) Now, change epsilon to 0.1 and simply run the Macro1 by pressing Ctrl+Shift+R. Immediately, we get:

	A	C	D	E	F	G	H	I	J
1									
2									
3		Data:							
4			L	0.05	m				
5			k	1.2	W/m.K				
6			A	1	m^2				
7			epsilon	0.1					
8		Stefan-Boltzmann const. =	sigma	5.67E-08	W/m^2.K^4				
9			alpha	0.25					
10			T_1	300	K				
11			q_solar	850	W/m^2				
12			T_space	0	K				
13			T_2	306.7620855	K....Trial value				
14		Calculations:							
15		$R_{slab} = \frac{L}{k \cdot A}$	R_slab	0.041666667	K/W				
16			Q_cond	-162.2900522	W				
17		$Q_{cond} = \frac{(T_1 - T_2)}{R_{slab}}$	Q_absorbed	212.5	W	→ Q_absorbed = q_solar·alpha·A			
18			Q_cond_Q_absorbed	50.20994782					
19			Q_radn	50.2099496	W	→ Q_radn = sigma·epsilon·A·$(T_2^4 - T_{space}^4)$			
20			Heat balance:	-1.78453E-06		→ Q_cond + Q_absorbed − Q_radn = 0			
21									

We see that for epsilon = 0.1, T_2 has converged to 306.762 K. *Again, this value matches with the value obtained with EES earlier.*

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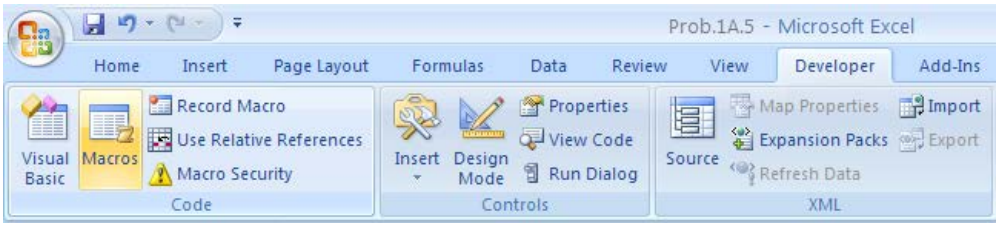
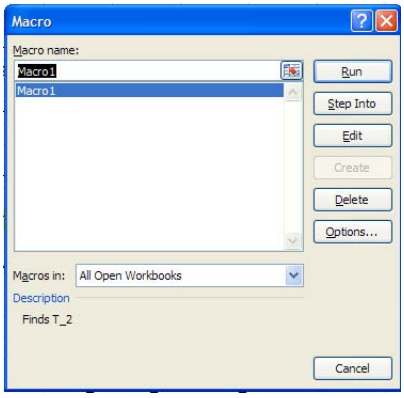
Thus, we can run the macro for different values of epsilon and create a Table, and then, a plot.

e) Still, this is a tedious process, if there are a large no. of values to be considered for epsilon. ***So, we will look at the recorded Macro1 and modify it to calculate T_2 using Goal Seek for different values of epsilon, and then enter those values in a Table.*** Procedure is as follows:

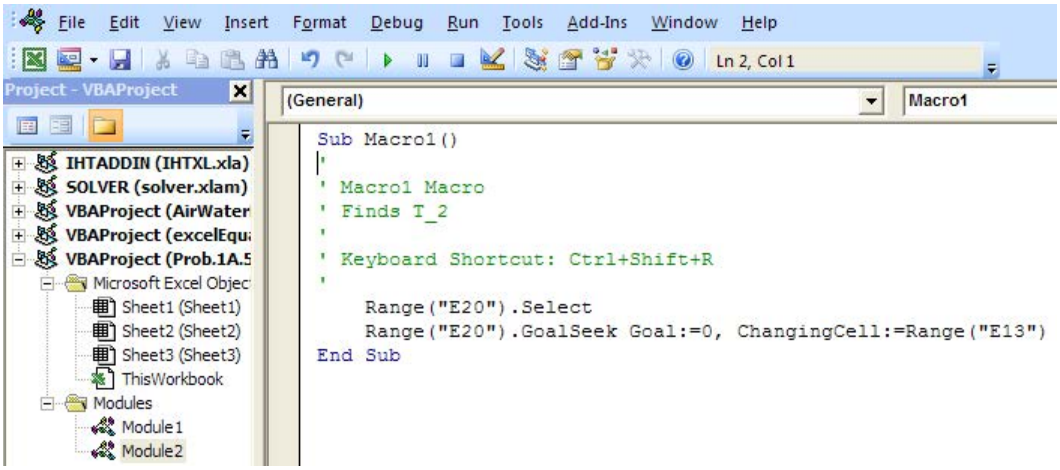
f) Go to: Developer-Macros:



g) Click on Macros. We get:



Click on Edit. We get:



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What we see in the above Fig. is the VBA code written in the background when we recorded the Macro.

h) **Now, we will modify this code to get values of T_2 for different values of epsilon (i.e. cell E7):**

First, prepare a Table of epsilon and T_2 as shown below:

	A	B	C	D
22				
23			To calculate vatiation of T_2 with epsilon:	
24				
25			epsilon	T_2 (K)
26			0.05	
27			0.1	
28			0.15	
29			0.2	
30			0.25	
31			0.3	
32			0.35	
33			0.4	
34			0.45	
35			0.5	
36			0.55	
37			0.6	
38			0.65	
39			0.7	
40			0.75	
41			0.8	
42			0.85	
43			0.9	
44			0.95	
45			1	

i) Now, the modified code, shown below, will put different values of epsilon in cell E7 and apply Goal Seek to get different values of T_2 and then put those T_2 values in the respective rows:

(General) Macro1

```
Sub Macro1()
'
' Macro1 Macro
' Finds T_2
'
' Keyboard Shortcut: Ctrl+Shift+R
'

Dim i As Integer

 For i = 0 To 19

Range("E7") = Range("C26") + i * 0.05


    Range("E20").Select
    Range("E20").GoalSeek Goal:=0, ChangingCell:=Range("E13")

    Cells(26 + i, 4) = Range("E13")

    Next i
End Sub
```


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Variable 'i' is the counter for looping. It is an integer, from 0 to 19.

For … Next loop varies values in E7, applies Goal Seek repeatedly for these values to get corresponding values of cell E13 (i.e. temp T_2); then value in E13 is copied to cells in Row 26, 27 …45 in column D (i.e. column 4).

j) Now, press the key board short-cut (Ctrl+Shift+R) and immediately the Table is completed:

	A	B	C	D
21				
22				
23			To calculate vatiation of T_2 with epsilon:	
24				
25			epsilon	T_2 (K)
26			0.05	307.794
27			0.1	306.762
28			0.15	305.757
29			0.2	304.777
30			0.25	303.822
31			0.3	302.889
32			0.35	301.978
33			0.4	301.088
34			0.45	300.218
35			0.5	299.367
36			0.55	298.534
37			0.6	297.718
38			0.65	296.919
39			0.7	296.136
40			0.75	295.368
41			0.8	294.615
42			0.85	293.876
43			0.9	293.151
44			0.95	292.439
45			1	291.740

Comparing these values with those obtained with EES we see that they match very well.

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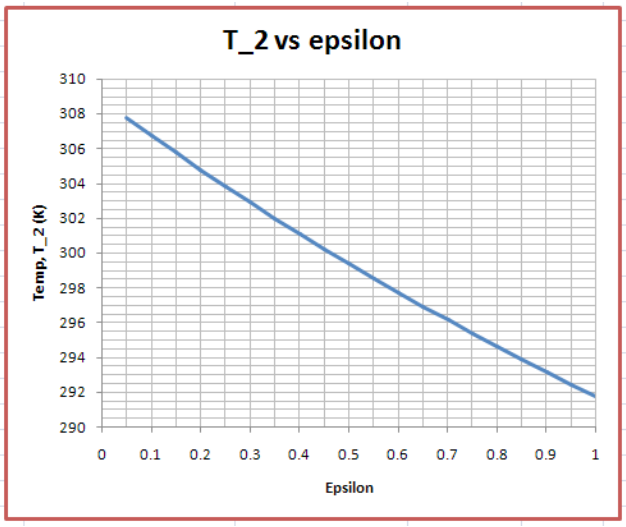
k) Now, we can prepare a plot of T_2 vs epsilon, in EXCEL:



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"**Prob. 1A.6.** Roof of a car is exposed to solar radiation of 850 W/m^2 and its surface emissivity is 0.8. Underside of the roof is perfectly insulated. The surface also loses heat by convection to ambient air at a temperature of 27 C with a convection heat transfer coeff. of 20 W/m^2.C. Determine:

1. the temperature of the roof in steady state conditions.
2. Convection coeff. increases with increasing wind speed. Draw the variation of the roof temperature as the convection coeff. varies from 5 to 200 W/m^2.C for three different values of emissivities, viz. epsilon = 0.1, 0.5 and 0.8."

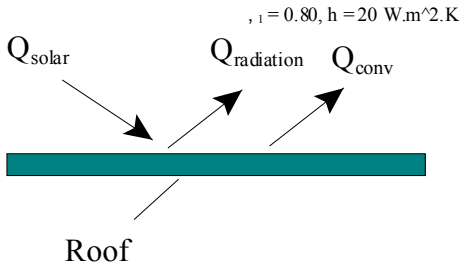

Fig.Prob.1A.6

Mathcad Solution:

Solution:

Data:

$T_{amb} := 27 + 273$ K $h := 20$ W/m^2.C

$\varepsilon := 0.8$ $q_{rad} := 850$ W/m^2 $A := 1$ m^2....area of 1 m^2 for calculation.

$\sigma := 5.67 \cdot 10^{-8}$ ...W/m^2.K^4...Stefan - Boltzmann constant

Let the roof temp. in steady state be T_{roof} (K)

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Calculations:

Making an energy balance on the roof surface, under steady state conditions:

Energy received by the roof = Energy lost by radiation + Energy lost by convection

i.e. $Q_{solar} = Q_{rad} + Q_{conv}$

$Q_{solar} := q_{rad} \cdot A$ W...heat received through solar radiation

$Q_{rad} = \sigma \cdot \varepsilon \cdot A \cdot \left(T_{roof}^4 - T_{amb}^4\right)$ W....energ lost froof by radiation

$Q_{conv} = h \cdot A \cdot \left(T_{roof} - T_{amb}\right)$ W....energ lost froof by convection

Now, use the Solve Block of Mathcad to solve the energy balance eqn:

First assume a guess value for T_{roof}. Then use Solve Block:

$T_{roof} := 310$ K.....guess value

Given

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$$q_{rad} \cdot A = \sigma \cdot \varepsilon \cdot A \cdot \left(T_{roof}^{4} - T_{amb}^{4}\right) + h \cdot A \cdot \left(T_{roof} - T_{amb}\right)$$

$T_{roof}(\varepsilon, h) := \text{Find}(T_{roof})$ ....define T_{roof} as a function of epsilon and h, since we wish to draw a graph of T_{roof} vs h for different values of epsilon

$T_{roof}(\varepsilon, h) = 332.987$ K.....equilibrium temp T_{roof} in steady state for $\varepsilon = 0.8$, h = 20....Ans.

Table of values of T_roof for various values of h when ε = 0.8:

$\varepsilon := 0.8$ ....fix the value of ε as 0.8

$h := 5, 10 .. 105$ ..vary h from 5 to 105 with an increment of 5

h	$T_{roof}(\varepsilon, h)$
5	371.215
10	352.058
15	340.508
20	332.987
25	327.758
30	323.932
35	321.02
40	318.732
45	316.889
50	315.374
55	314.107
60	313.031
65	312.108
70	311.306
75	310.603
80	309.983
85	309.43
90	308.936
95	308.491
100	308.087
105	307.721

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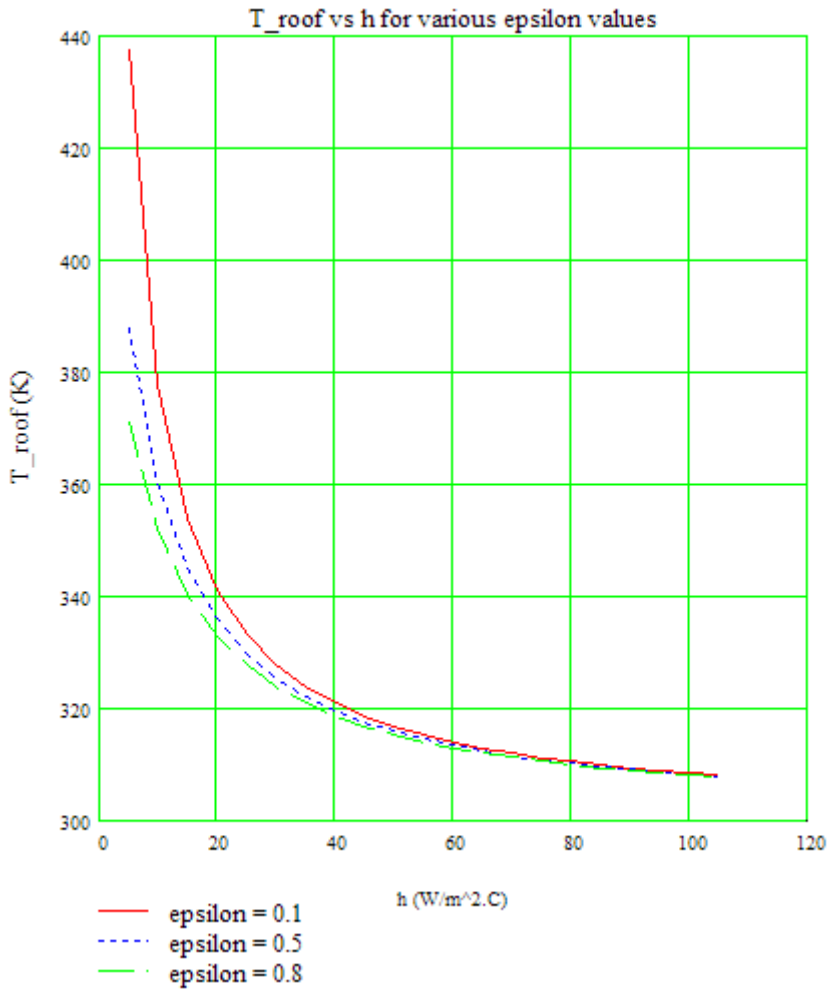
To draw a plot of T_{roof} vs h for various values of epsilon:

h := 5, 10.. 105 ....define a range variable h from 5 to 105 with an increment of 5

Then, select the x-y graph from pallete and fill in the place holders in both the axes. On x - axis, fill in ε and on y-axis, fill in $T_{root}(\varepsilon,h)$. Fill in the value of ε as desired i.e. 0.1 or 0.5 or 0.8. Click anywhere outside the graph region and immediately, the graph appears.



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"**Prob. 1A.7.** An IR detector is cooled by keeping it on the top of a cryocooler rod 5 mm in diameter and 70 mm long. The lower end is kept at a temperature of 77 K by immersing it in liquid nitrogen. At the upper end the detector temperature is controlled by inserting a thin electric heater in between the detector and the cryocooler surface. Emissivity of upper surface of the detector, exposed to vacuum, is 0.9. The surroundings of vacuum is at 300 K. Determine:

1) the steady state temp of the detector when no power is supplied to the heater
2) heater power required to maintain the detector temp at 190 K, and
3) plot the heater power required to maintain the detector temp at 190 K for different values of thermal conductivity (k = 0.1 to 400 W/m.K) of the cryocooler rod"

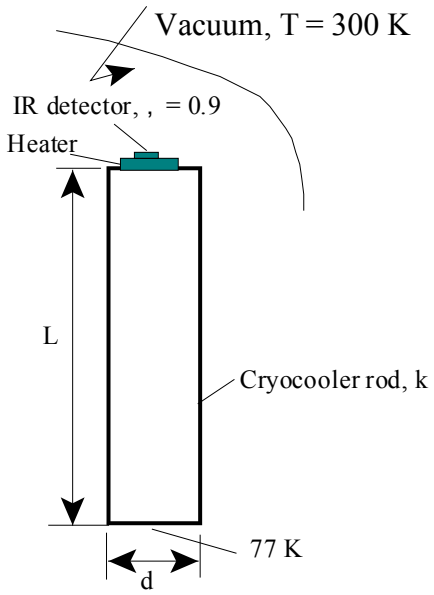

Fig.Prob.1A.7

EES Solution:

"Data:"

d = 0.005 [m]
L = 0.05 [m]
T_L = 77 [K]
k = 10 [W/m-K]
epsilon = 0.9
T_amb = 300 [K]
sigma = 5.67e-08 [W/m^2-K^4] "…Stefan-Boltzmann const."

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"Case 1: When no power is supplied to heater:"

"Let the detector temp be T_det1 (K)"

"Heat balance at the detector:
Heat received by detector from ambient by radiation is dissipated by conduction through the rod to liquid nitrogen"

"Calculations:"

A = (pi * d^2 / 4) "[m^2]… area of top of the rod"

Q_rad = sigma * epsilon * A * (T_amb^4 – T_det1^4) "[W]… heat transfer by radiation from surroundings to the detector on the cryocooler rod top surface"

R_cond = L/(k * A) "[C/W]… conductive resistance of the rod"

Q_cond = (T_det1 – T_L)/ R_cond "[W]…. Heat transfer by conduction from the top of the rod to liquid nitrogen at the bottom"

Q_rad = Q_cond "…finds T_det1 (K) …by heat balance"

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"Case 2 : What is the heater power required to maintain detector temp at 190 K?"

T_det2 = 190[K]

"Let the heater power required be Q_heater (W):"

"Then, by heat balance:

Heat received by detector from ambient by radiation + heat received from heater = heat loss by conduction through the rod to liquid nitrogen"

Q_rad2 = sigma * epsilon * A * (T_amb^4 – T_det2^4) "[W]… heat received by the detector from surroundings by radiation"
Q_cond2 = (T_det2 – T_L)/ R_cond "[W]… heat transferred by conduction from the detector to liquid nitrogen"
Q_rad2 + Q_heater = Q_cond2 "…finds Q_heater (W)…. By heat balance"

"Results:"

Unit Settings: SI K Pa J mass deg

$A = 0.00001963$ [m^2]	$d = 0.005$ [m]	$\varepsilon = 0.9$ [-]
$k = 10$ [W/m-K]	$L = 0.05$ [m]	$Q_{cond} = 0.008077$ [W]
$Q_{cond2} = 0.4437$ [W]	$Q_{heater} = 0.4369$ [W]	$Q_{rad} = 0.008077$ [W]
$Q_{rad2} = 0.00681$ [W]	$R_{cond} = 254.6$ [C/W]	$\sigma = 5.670E\text{-}08$ [$W/m^2\text{-}K^4$]
$T_{amb} = 300$ [K]	$T_{det1} = 79.06$ [K]	$T_{det2} = 190$ [K]
$T_L = 77$ [K]		

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"To plot Q_heater vs. k of the cryocooler rod for a detector temp of 190 K:"

First construct a parametric Table as shown below:

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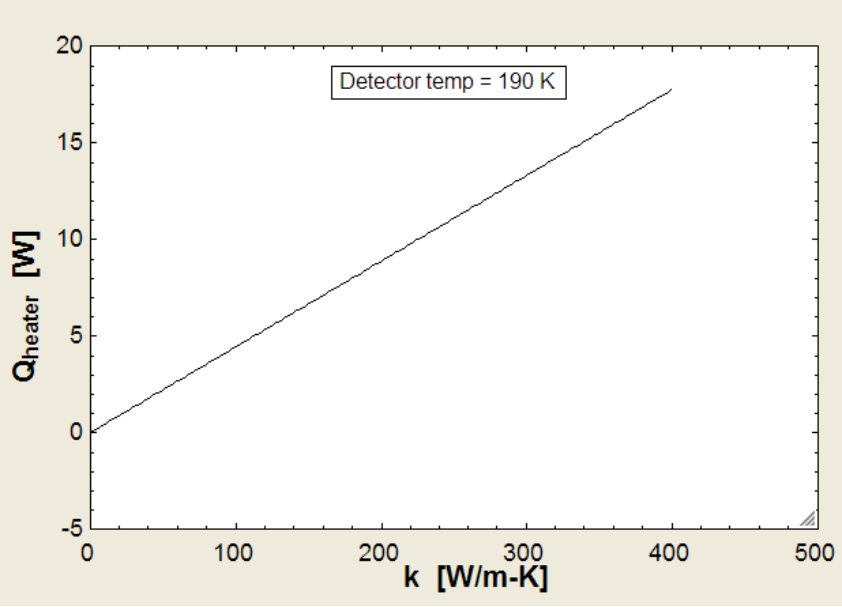
Table 1

1..20	1 T_{det2} [K]	2 k [W/m-K]	3 Q_{heater} [W]
Run 1	190	0.1	-0.002373
Run 2	190	21.15	0.9316
Run 3	190	42.19	1.866
Run 4	190	63.24	2.8
Run 5	190	84.29	3.734
Run 6	190	105.3	4.668
Run 7	190	126.4	5.601
Run 8	190	147.4	6.535
Run 9	190	168.5	7.469
Run 10	190	189.5	8.403
Run 11	190	210.6	9.337
Run 12	190	231.6	10.27
Run 13	190	252.7	11.21
Run 14	190	273.7	12.14
Run 15	190	294.8	13.07
Run 16	190	315.8	14.01
Run 17	190	336.9	14.94
Run 18	190	357.9	15.88
Run 19	190	379	16.81
Run 20	190	400	17.74

Then, the plot is produced:



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Prob. 1A.8. A furnace wall is made of diatomaceous silica brick (k = 0.3 W/m.K) and emissivity of outer surface of wall is 0.8. Inside surface is exposed to hot gases at 1300 C with a convection heat transfer coeff. h1 = 50 W/m^2.K. Ambient air is at 25 C. Outside convection coeff is h2 = 10 W/m^2.K.

1. Plot the inner and outer surface temperatures T1 and T2 as a function of wall thickness L, with L varying from 0.02 m to 0.5 m.
2. Also, for a wall thickness L = 0.15 m, plot T1 and T2 as a function of h2, with h2 varying from 2 to 50 W/m^2.K

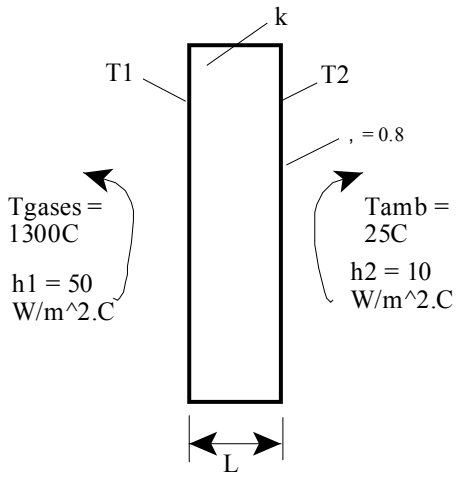

Fig.Prob.1A.8

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Mathcad Solution:

Solution:

Data:

$L := 0.15$ m $k := 0.3$ W/m.K $\varepsilon := 0.8$ $T_{gases} := 1300$C $\sigma := 5.67 \cdot 10^{-8}$ W/m^2.K^4

$h1 := 50$ W/m^2.K $h2 := 10$ W/m^2.K $T_amb := 25$ C $A := 1$ m^2....assumed

Calculations:

$$R_{cond}(L) := \frac{L}{k \cdot A} \quad R_{cond}(L) = 0.5 \quad C/W$$

$$R_{conv1} := \frac{1}{h1 \cdot A} \quad R_{conv1} = 0.02 \quad C/W$$

$$R_{conv2} := \frac{1}{h2 \cdot A} \quad R_{conv2} = 0.1 \quad C/W$$

Making a heat balance on the outer surface of the wall:

heat reaching the outer surface = heat lost from the outer surface by convection + heat lost to ambient by radiation. Use the Solve Block of Mathcad to get T2:

$T2 := 320$ C....guess value

Given

$$\frac{\langle T_{gases} - T2 \rangle}{R_{conv1} + R_{cond}(L)} = h2 \cdot A \cdot (T2 - T_amb) + \sigma \cdot \varepsilon \cdot A \cdot \left[(T2 + 273)^4 - (T_amb + 273)^4 \right]$$

$T2(L, h2) := \text{Find}(T2)$ ..define T2 as a function of L and h2, since we have to draw plot T2 as a function of L and h2

$T2(L, h2) = 144.765$ **C....temp of right face of the wall for a wall thickness of L = 0.15 m and h2 = 10 W/m^2.K**

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To find T1: Use the fact that in steady state, Q is the same through each layer:
Define T1 also as a function of L and h2, to easily draw the plot of T1 vs.L

i.e.

$$\frac{T1(L,h2) - T2(L,h2)}{R_{cond}(L)} = \left[\frac{\left(T_{gases} - T2(L,h2)\right)}{R_{conv1} + R_{cond}(L)}\right]$$

Then, $$T1(L,h2) := \left[\frac{\left(T_{gases} - T2(L,h2)\right)}{R_{conv1} + R_{cond}(L)}\right] \cdot R_{cond}(L) + T2(L,h2)$$

$T1(L,h2) = 1.256 \cdot 10^{3}$ **C....temp of left face of wall for wall thickness L = 0.15 m**

To plot T1 and T2 against L for h2 = 10 W/m^2.K:

h2 := 10 W/m^2.K

L := 0.02, 0.03.. 0.5 m....define the range variable L from 0.02 m to 0.5 m, with an increment of 0.01 m

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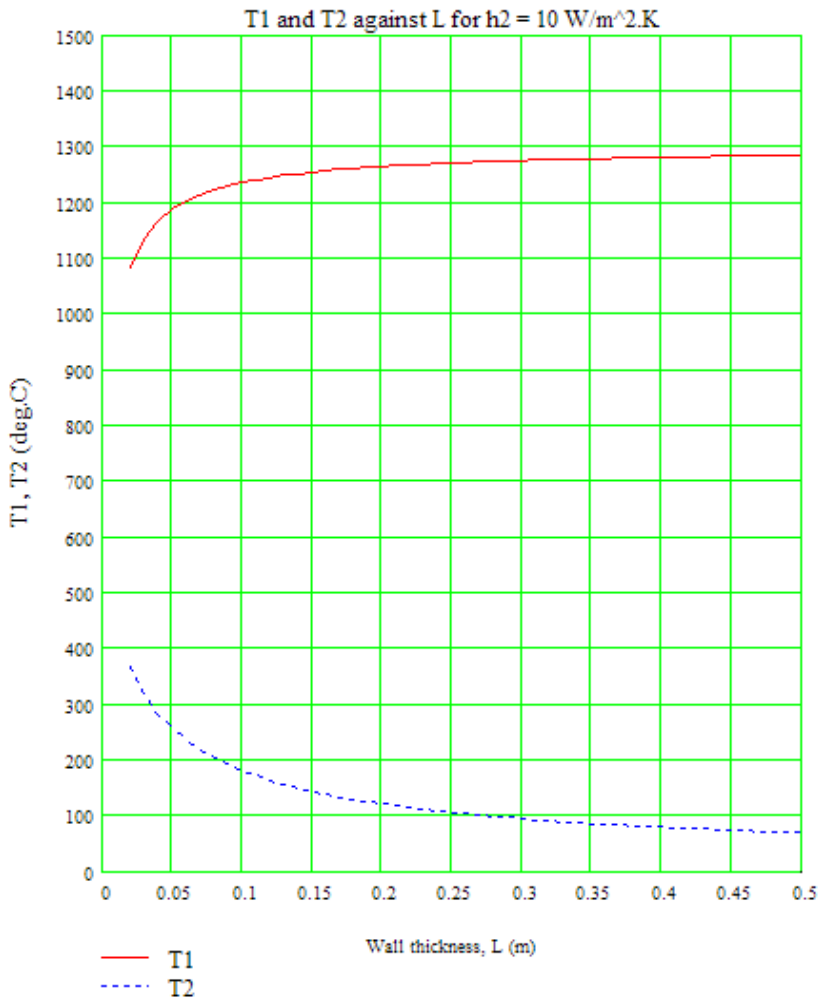
Plot of T1 and T2 against L for h2 = 10 W/m^2.K:



To plot T1 and T2 against h2 for L = 0.15 m:

L := 0.15 m

h2 := 2, 4.. 50 W/m^2.K....define the range variable h2 from 2 to 50 W/m^2.K, with an increment of 2 W/m^2.K

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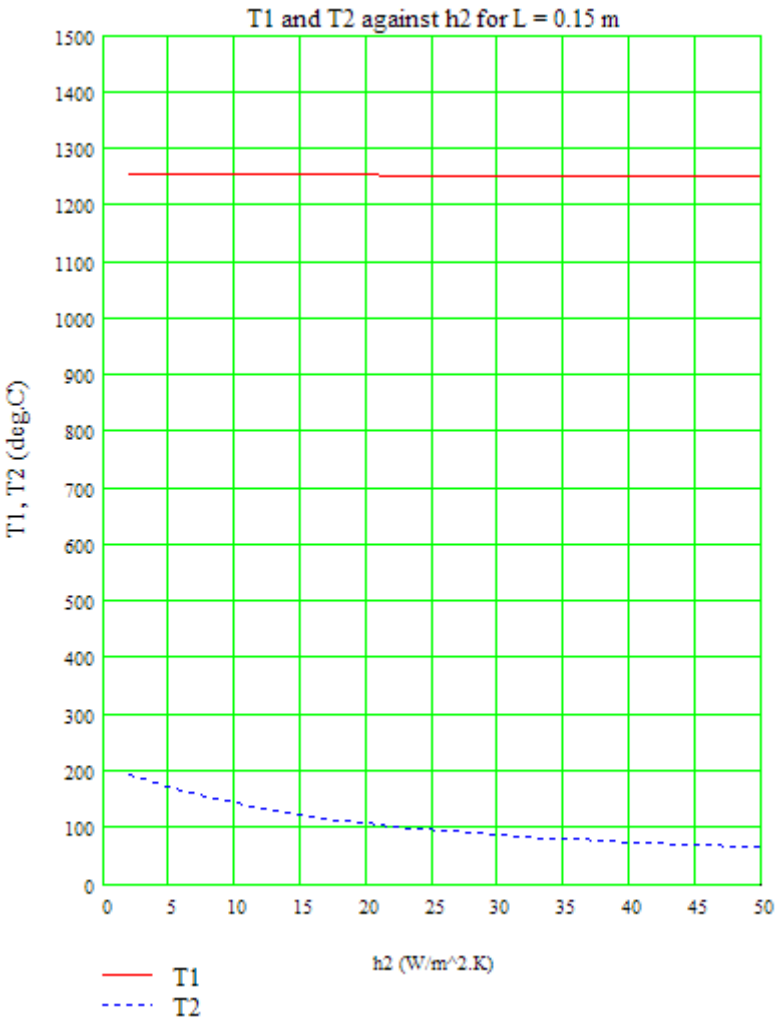
Plot of T1 and T2 against h2 for L = 0.15 m:



Note: In the Solve Block, we defined T2 as a function of L and h2. Then, we obtained T1 as a function of L and h2. This greatly simplifies the calculations and gives us the flexibility to calculate and plot T1 and T2 for any combination of L and h2 values.

==========

"**Prob. 1A.9:** Consider an insulated spherical liquid oxygen (LOX) tank whose outside diameter is 0.5 m and the outer surface temperature (T_surface) is -10 deg.C. The tank is kept in surroundings at 25 deg.C. Latent heat of evaporation of LOX is 214kJ/kg. (i) If the emissivity of outer surface is 0.2 and convection heat transfer coeff (h)is 10 W/m^2.K, find out the boil off rate of LOX (ii) Plot the boil off rate as a function of emissivity, with the values of T_surface and h remaining the same as earlier."

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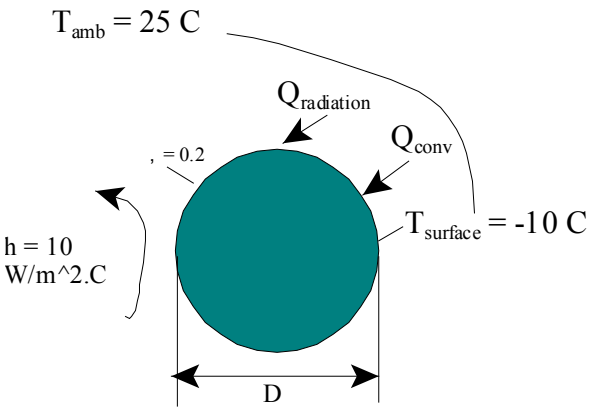

Fig.Prob.1A.9

EES Solution:

"Data:"

h_fg = 214e03 [J/kg]
D_tank = 0.5 [m]
T_surface = -10 [C]
T_amb = 25 [C]
epsilon = 0.2
h = 10 [W/m^2-K]
sigma = 5.67e-08 [W/m^2-K^4] "Stefan-Boltzmann constant"

"Calculations:"

A = pi * D_tank^2 "[m^2] … surface area of the tank"
Q_conv = h * A * (T_amb – T_surface) "[W] … heat transfer to tank by convection"
Q_rad = epsilon * sigma * A * ((T_amb + 273)^4 – (T_surface + 273)^4) "[W]…. heat transfer to tank by radiation"

"Now, (Q_conv + Q_rad) reaches the LOX and results in boil off:"

m_boiloff = (Q_conv + Q_rad)/h_fg "[kg/s] …. boil off rate of LOX"

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Results:

Unit Settings: SI C kPa kJ mass deg

$A = 0.7854$ [m^2]	$D_{tank} = 0.5$ [m]	$\varepsilon = 0.2$ [-]
$h = 10$ [W/m^2K]	$h_{fg} = 214000$ [J/kg]	$m_{boiloff} = 0.001414$ [kg/s]
$Q_{conv} = 274.9$ [W]	$Q_{rad} = 27.63$ [W]	$\sigma = 5.670E-08$ [W/m^2K^4]
$T_{amb} = 25$ [C]	$T_{surface} = -10$ [C]	

Thus: m_boiloff = 0.001414 kg/s …. Ans.

"To plot m_boil-off vs. emissivity with T_surface = -10 C and h = 10 W/m^2.K:"

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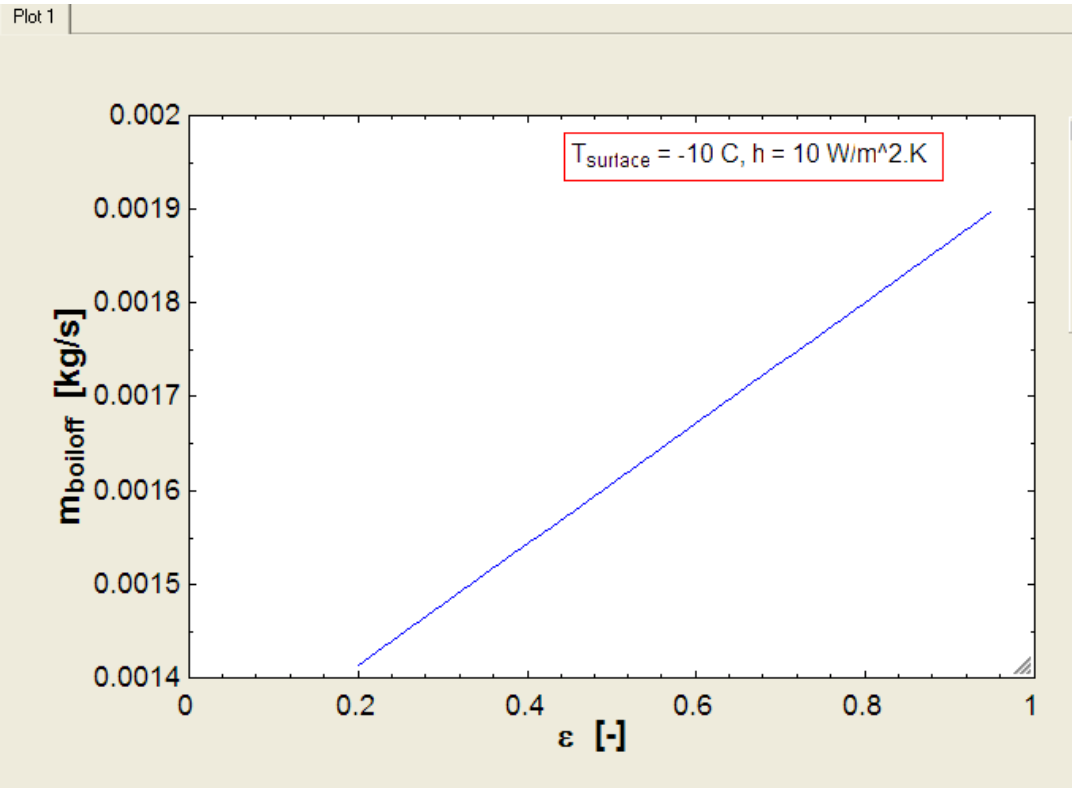
First construct a parametric Table as shown below:

Table 1

1..10	1 ε [-]	2 $m_{boiloff}$ [kg/s]
Run 1	0.2	0.001414
Run 2	0.3	0.001478
Run 3	0.4	0.001543
Run 4	0.5	0.001607
Run 5	0.6	0.001672
Run 6	0.7	0.001736
Run 7	0.8	0.001801
Run 8	0.85	0.001833
Run 9	0.9	0.001865
Run 10	0.95	0.001898

Then, create the plot:



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"**Prob. 1A.10:** Wall of an oven is 0.05 m thick. Its outer surface is at 420 K and is exposed to a surroundings at 300 K. Emissivity of exposed surface is 0.8 and the convection coeff is 25 W/m^2.K.

1. What is the temp of inner surface if the thermal conductivity of the wall is 0.7 W/m.K?
2. Consider the case when the inner surface temp is 650 K. Taking the base conditions as: k = 10 W/m.K, h = 25 W/m^2.K and emissivity = 0.5, plot the variation of temperature of outer surface, T2, conduction heat flux through the wall, q_cond, convection heat flux, q_conv and radiation heat flux, q_rad when k, h and emissivity are varied by turn."

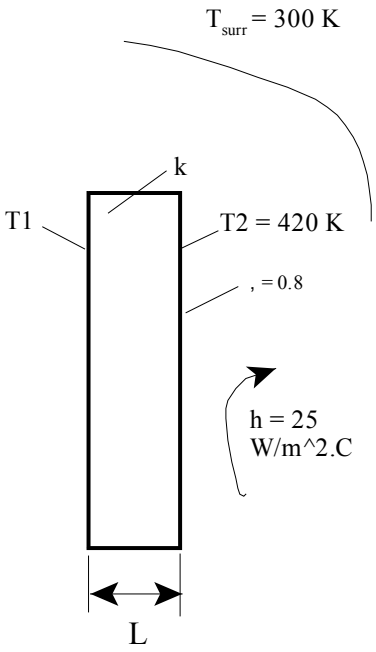

Fig.Prob.1A.10

Mathcad Solution:

Data:

$L := 0.05$ m $T_{surr} := 300$ K $T2 := 420$ K $h := 25$ W/m^2.K $\varepsilon := 0.8$

$k := 0.7$ W/m.K $A := 1$ m^2....assumed $\sigma := 5.67 \cdot 10^{-8}$ W/m^2.K^4

Case 1: To find T1:

$$R_{cond} := \frac{L}{k \cdot A} \qquad R_{cond} = 0.071 \quad C/W$$

Use the Solve Block to find the value of T1. Start with a trial value for T1:

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$T1 := 450$ K.... trial value

Given

$$\frac{T1 - T2}{R_{cond}} = h \cdot A \cdot \left(T2 - T_{surr}\right) + \sigma \cdot \varepsilon \cdot A \cdot \left(T2^4 - T_{surr}^4\right)$$

$T1 := \text{Find}(T1)$

$T1 = 708.861$ **K..temp. of inner surface....Ans.**

Case 2: Find T2, q_cond, q_conv and q_rad as functions of k, h and ε:

By data: $T1 := 650$ K $T_{surr} := 300$ K

Now, apply heat balance on the outer surface of wall:

Heat transfer by conduction through wall = heat transfer from the wall by convection + heat transfer from wall by radiation to the surroundings

Use the Solve Block to find T2. Start with a trial value for T2:

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$T2 := 450$ K.... trial value

Given

$$\frac{T1 - T2}{\frac{L}{k \cdot A}} = h \cdot A \cdot \left(T2 - T_{surr}\right) + \sigma \cdot \varepsilon \cdot A \cdot \left(T2^4 - T_{surr}^4\right)$$

$T2(k, h, \varepsilon) := \text{Find}(T2)$ i.e. $T2(k, h, \varepsilon) = 404.06$ K....Ans.

Note that in the Solve Block above, T2 is written as function of k, h and ε. This makes it very easy to plot T2 with the variation of any of the parameters as will be shown below.

Now, the conduction, convection and radiation heat fluxes are also written as functions of k, h and ε:

$$q_{cond}(k, h, \varepsilon) := \frac{T1 - T2(k, h, \varepsilon)}{\frac{L}{k \cdot A}}$$ i.e. $q_{cond}(k, h, \varepsilon) = 3.443 \cdot 10^3$ W/m^2

$q_{conv}(k, h, \varepsilon) := h \cdot A \cdot \left(T2(k, h, \varepsilon) - T_{surr}\right)$ i.e. $q_{conv}(k, h, \varepsilon) = 2.601 \cdot 10^3$ W/m^2

$q_{rad}(k, h, \varepsilon) := \sigma \cdot \varepsilon \cdot A \cdot \left(T2(k, h, \varepsilon)^4 - T_{surr}^4\right)$ i.e. $q_{rad}(k, h, \varepsilon) = 841.666$ W/m^2

To draw the graphs:

$k := 10$ W/m.K $h := 25$ W/m^2.K $\varepsilon := 0.5$ **...base values of k, h and ε**

(i) Effect of varying k:

$k := 0.1, 20 .. 400$ W/m.K...define a range variable k from 0.1 to 400.1 with an increment of 20

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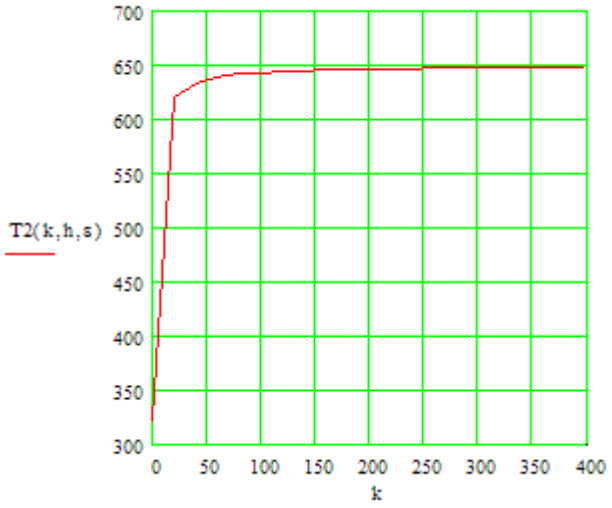

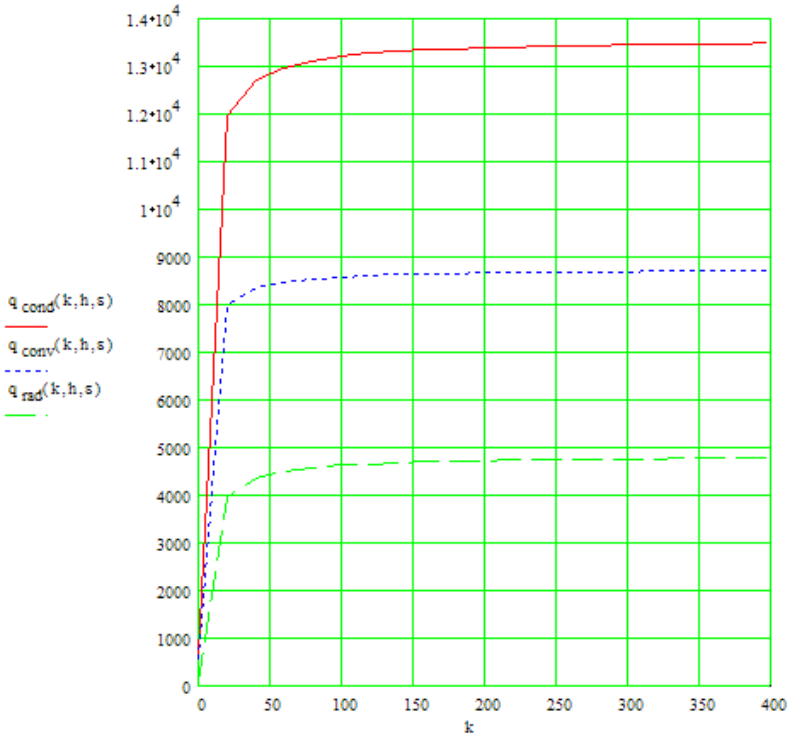

(ii) Effect of varying h:

k := 10 W/m.K h := 25 W/m^2.K ε := 0.5 **...base values of k, h and ε**

h := 2, 11.. 200 W/m^2.K....define a range variable h from 2 to 200 with an increment of 9

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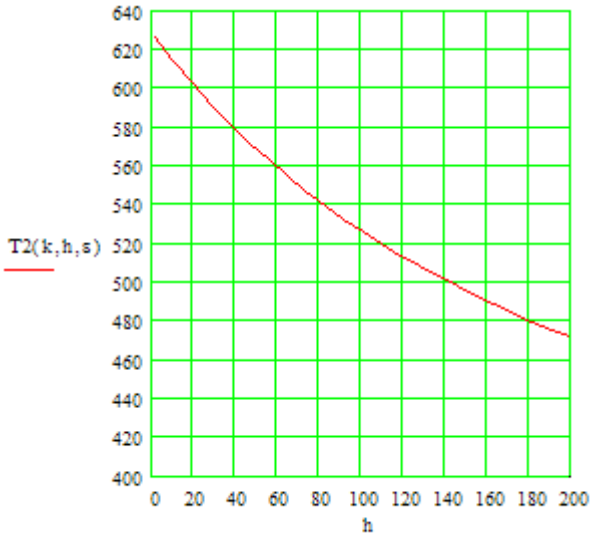

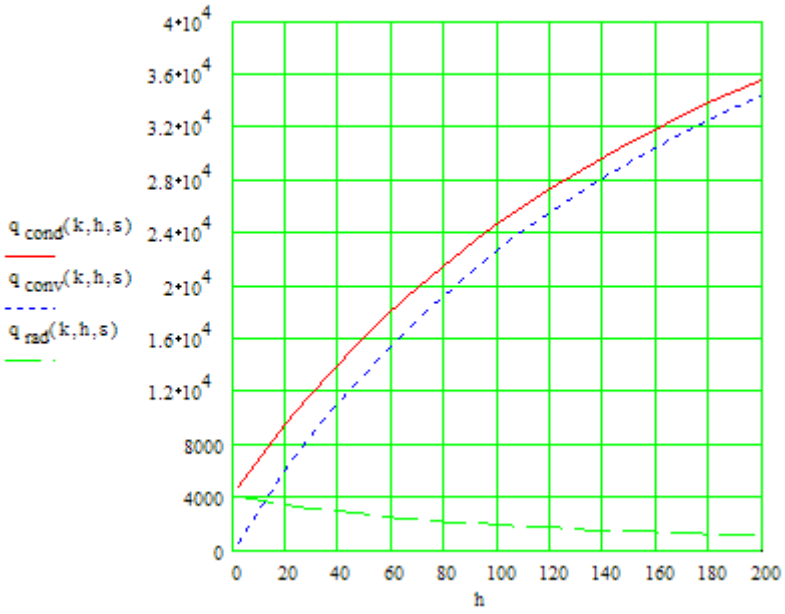

(iii) Effect of varying ε:

k := 10 W/m.K h := 25 W/m^2.K ε := 0.5 **...base values of k, h and ε**

ε := 0.05, 0.1.. 1 ....define a range variable ε from 0.05 to 1 with an increment of 0.05

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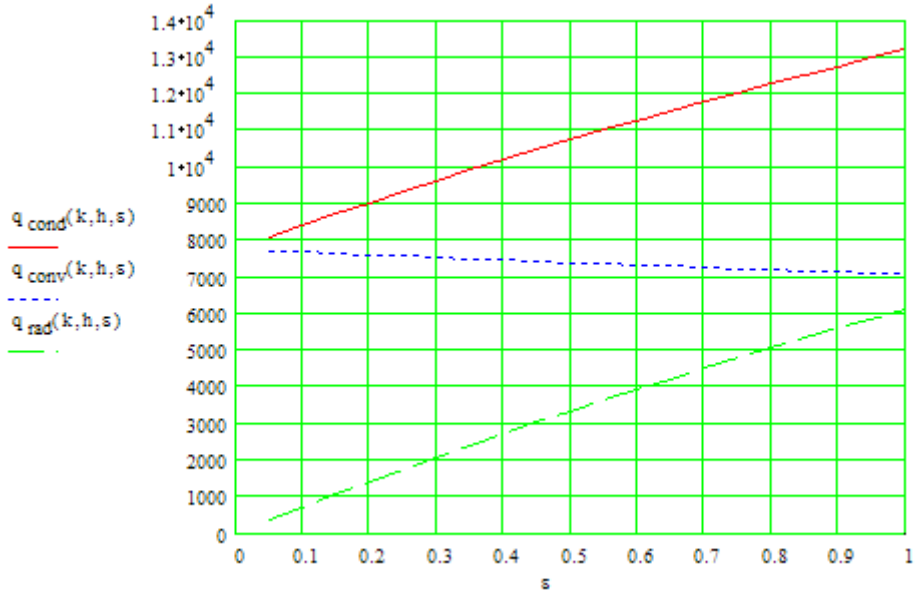

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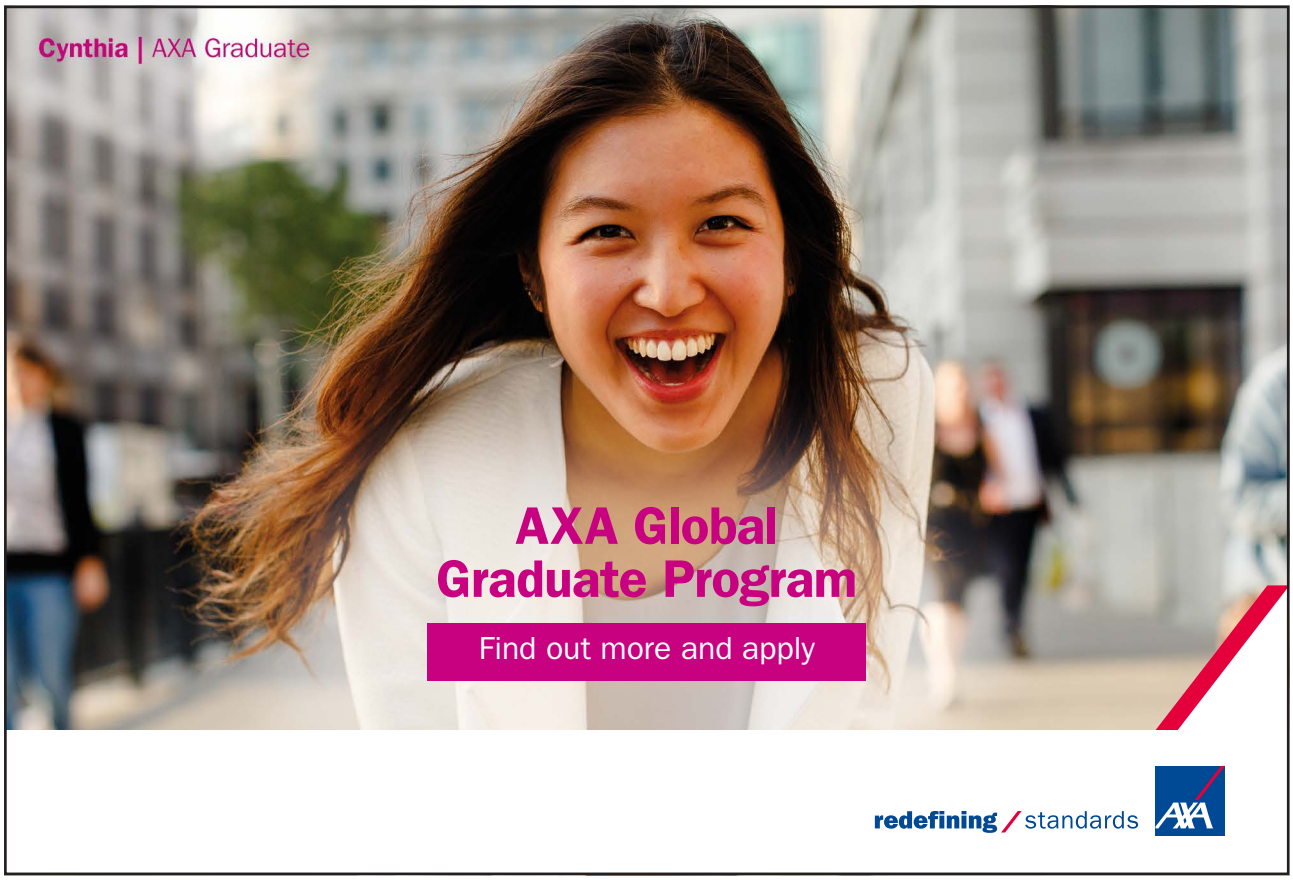

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"**Prob.1A.11.** A copper wire 1 mm dia is insulated with plastic to an outer dia of 3 mm and is exposed to an environment at 40 C. Find the max current carried by the wire in Amperes without heating any part of the plastic above 90 C. Heat transfer coeff from the outer surface of plastic to surroundings is 10 W/m^2.C, k_plastic = 0.4 W/m.C. Electrical conductivity of copper is 5 × 10^7 ohm^{-1} cm^{-1}. Also find the max temp of wire. [M.U – Dec. 2000]"

EES Solution:

"Data:"

r_1 = 0.5E-03 [m]
r_2 = 1.5e-03[m]
T_s = 90 [C]
k_plastic = 0.4 [W/m-C]
h = 10 [W/m^2-C]
T_a = 40 [C]
L = 1[m]
k_e = 5e07 "[1/ohm-cm]… electrical conductivity of copper wire"
rho_e = (1/k_e)/100 "[ohm-m] … resistivity of copper"

"Calculations:"

"Temp is max at the inner surface of insulation, since heat flow id from inside to outside:

Heat transferred by conduction to outer surface is dissipated to ambient by convection:

heat transferred is equal to heat generated by Joule heating in the wire"

A_wire = pi * r_1^2 "[m^2] … area of cross-section of wire"
Q = I^2 * R_e "[W]… where I is the current, R_e is the electrical resist in ohms"
R_e = rho_e * L / A_wire "[ohms]..electrical resist of wire"
R_tot = ln(r_2/r_1)/(2*pi*k_plastic*L) + 1/(h*2*pi*r_2*L) "[C/W] … total thermal resistance = conduction + convection"
Q = (T_s – T_a)/ R_tot "[W]…..heat transferred"

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"To find max temp in the wire:

This occurs when there is no insulation and heat generated in the wire is transferre to ambient by convection:"

Q = h * (2 * pi * r_1 * L) * (T_max – T_a) "….finds T_max on the surface of wire"

Results:

A_{wire} = 7.854E-07 [m^2]	h = 10 [W/m^2-C]	I = 133.3 [Amp]
k_e = 5.000E+07 [1/(Ω-cm)]	$k_{plastic}$ = 0.4 [W/m-C]	L = 1 [m]
Q = 4.526 [W]	ρ_e = 2.000E-10 [Ω-m]	r_1 = 0.0005 [m]
r_2 = 0.0015 [m]	R_e = 0.0002546 [Ω]	R_{tot} = 11.05 [C/W]
T_a = 40 [C]	T_{max} = 184.1 [C]	T_s = 90 [C]

Thus:

I = 133.3 Amp….. max. current carried by the wire …. Ans.

T_max = 184.1 C….. max. temp of the wire …. Ans.

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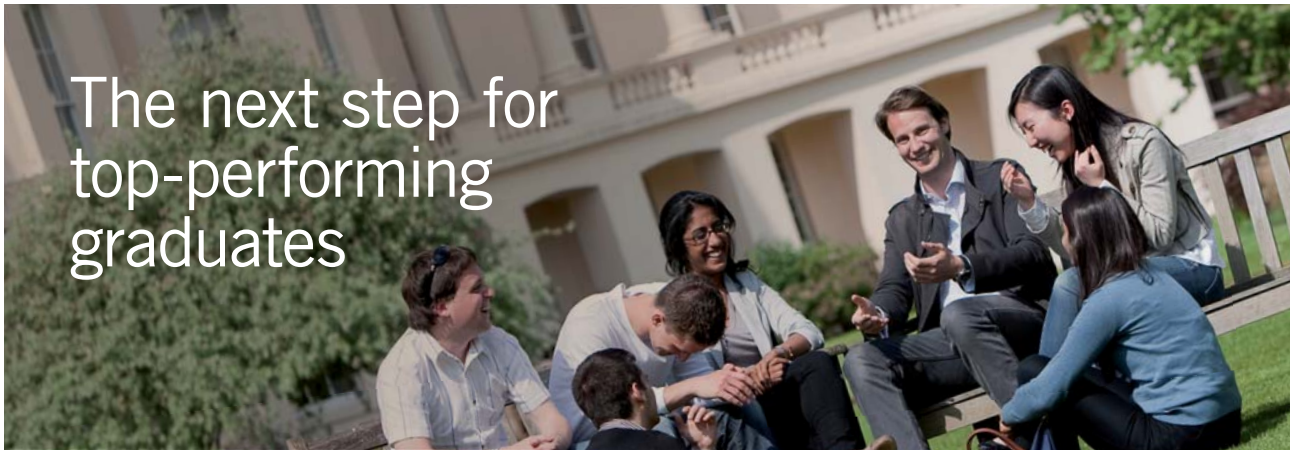

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1B One-Dimensional, Steady state heat transfer without heat generation: Thermal resistance concept – PLANE WALL with constant k and variable k:

Learning objectives:

4. *Thermal resistance* is an extremely useful concept in solving problems in One-dimensional, steady state heat transfer with no internal heat generation.
5. This concept is similar to the concept of electrical resistance where we write: Resistance = Potential divided by Current. i.e. Thermal resistance = Temp. difference (i.e. driving potential) divided by heat flow rate. i.e. $R_{th} = \Delta T/Q$. Thermal resistances in series, or parallel, or (series and parallel) are dealt with, just as in the case of electric resistances.
6. Thermal resistance is defined in the same manner for convection, and also for radiation, i.e. Resistance = $\Delta T/Q$. Thus, this concept is useful in solving multi-mode heat transfer too.
7. *'Thermal Contact resistance'* comes in o picture when two surfaces are in contact with each other. If there is 'perfect thermal contact', there is no contact resistance and this is signified by a continuity in the temperature profile, i.e. there is no temperature drop at the interface. However, if there is a contact resistance, there will be a discontinuity in the temperature profile and there will be a temperature drop at the interface.
8. In this section, popular problems, frequently asked in University question papers, and some more complicated problems are solved using Mathcad, EES, FEHT or EXCEL. Studying these problems will help in consolidating the concept of Thermal resistance and Contact resistance.

"**Prob. 1B.1.** The inside surface of an insulating layer is at 270 C and the outside surface is dissipating heat by convection into air at 20 C. The insulation is 40 mm thick and has a thermal conductivity of 1.2 W/m.C. What is the minimum value of heat transfer coeff. at the outside surface, if the surface temperature should not exceed 70 C? Also calculate the rate of heat transfer. [VTU-7th Sem-B.E.-Dec.2007/Jan.2008]"

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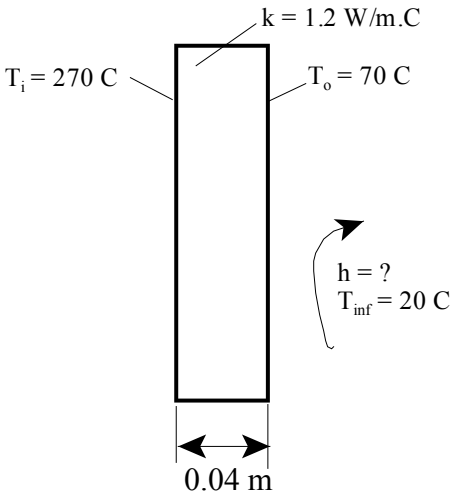

Fig.Prob.1B.1

EES Solution:

"Data:"

T_i = 270 "C"
T_inf = 20 "C"
L_ins = 0.04 "m"
k_ins = 1.2 "W/m.C"
T_0 = 70 "C"
A = 1 "m^2 … assumed"

"Calculations:"

R_ins = L_ins/(k_ins*A) "C/W …. Conductive resistance"
Q = (T_i-T_0)/R_ins "W …. Rate of heat transfer"
"In steady state, Q is the same through each layer; So, writing for the outside convective layer:"
Q = h*A*(T_0-T_inf) "Finds h, W/m^2-C"

Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]	$h = 120$ [W/m^2-C]	$k_{ins} = 1.2$ [W/m-C]	$L_{ins} = 0.04$ [m]
$Q = 6000$ [W]	$R_{ins} = 0.03333$ [C/W]	$T_0 = 70$ [C]	$T_i = 270$ [C]
$T_{inf} = 20$ [C]			

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Thus:

h = 120 W/m^2-C … Ans.

Q = 6000 W …. Ans.

Now, consider another variation of this problem:

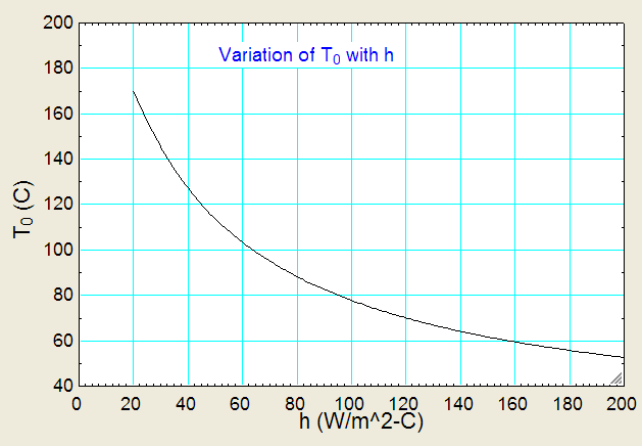
If the heat transfer coefficient h varies from 20 to 200 W/m^2.C, plot the variation of the temp of surface on RHS, i.e. T_0:

First, generate a parametric table:

Table 1

1..10	1 h [W/m2-C]	2 T_0 [C]	3 Q [W]
Run 1	20	170	3000
Run 2	40	127.1	4286
Run 3	60	103.3	5000
Run 4	80	88.18	5455
Run 5	100	77.69	5769
Run 6	120	70	6000
Run 7	140	64.12	6176
Run 8	160	59.47	6316
Run 9	180	55.71	6429
Run 10	200	52.61	6522

And, then, plot:



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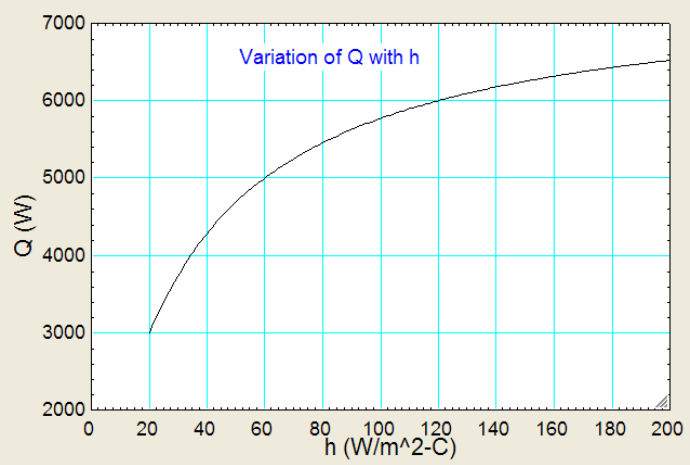

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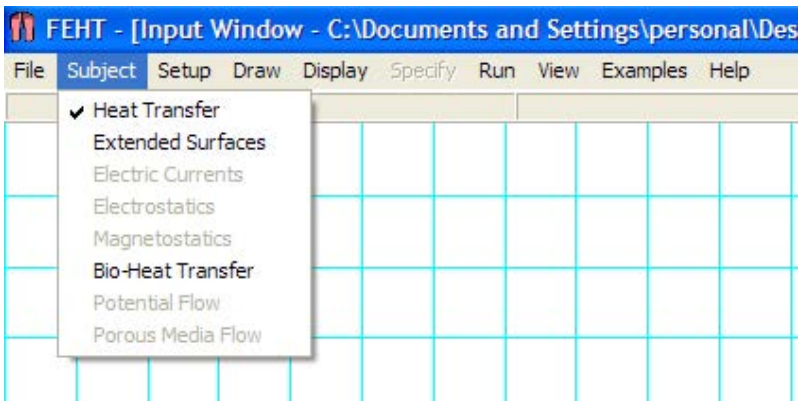
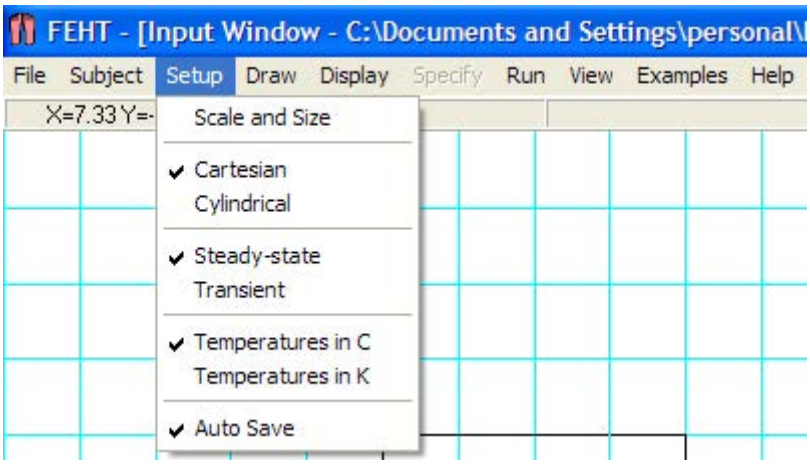
Now, let us solve this problem with Finite Element Heat Transfer (FEHT) software:

Following are the different steps:

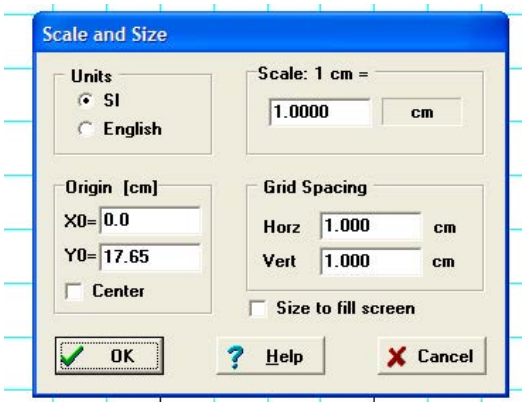
2. **Start FEHT; In the Subject menu, Heat transfer is automatically selected:**



3. **From the Setup menu, select: Cartesian coords, steady state as shown:**



4. **From the Setup – Scale and Size, choose the scale 1 cm = 1 cm:**



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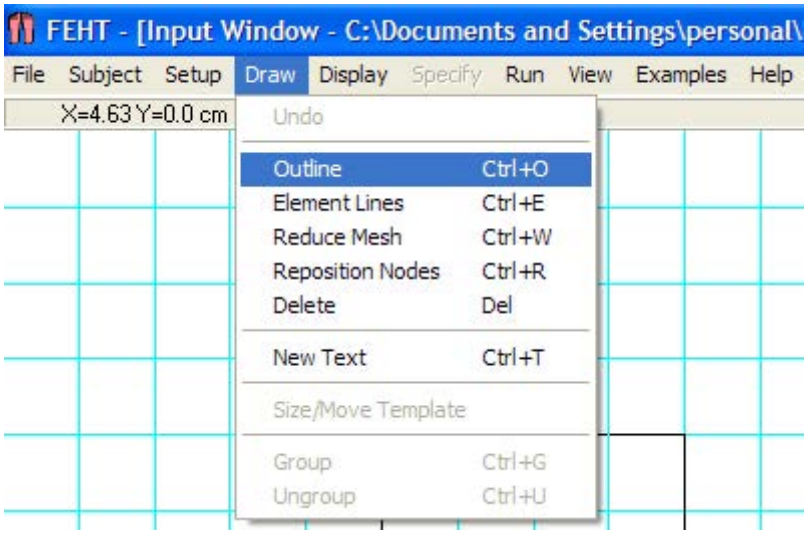
5. **Then, from the Draw menu, select Outline and draw the outline of the material:**



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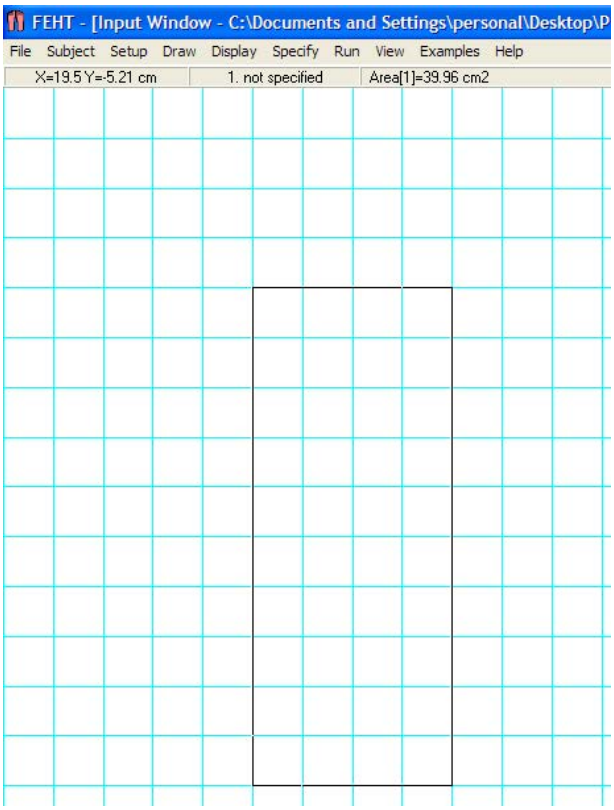
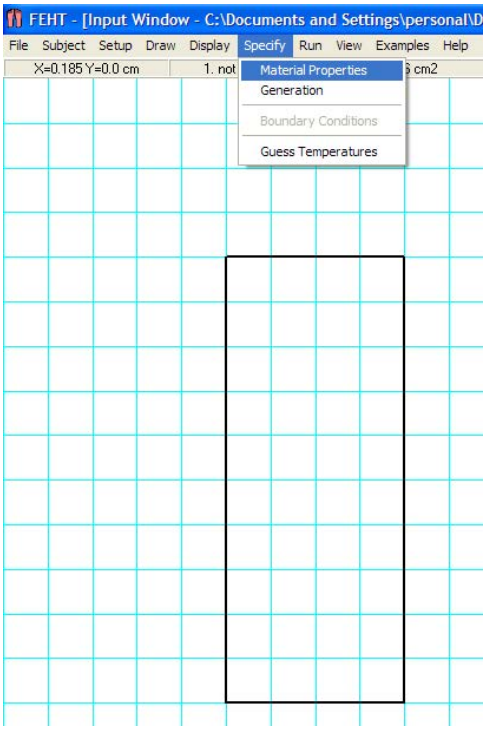


Note that we have chosen the height of the section arbitrarily as 10 cm. By default, depth perpendicular to paper is 1 m.

6. **Now, specify the material properties from the Specify menu:**



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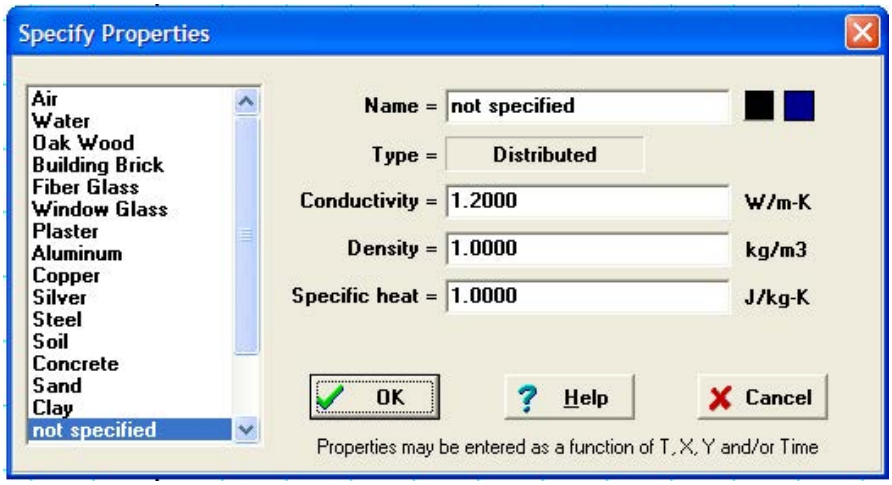
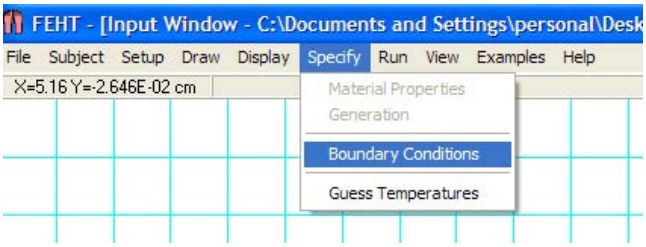


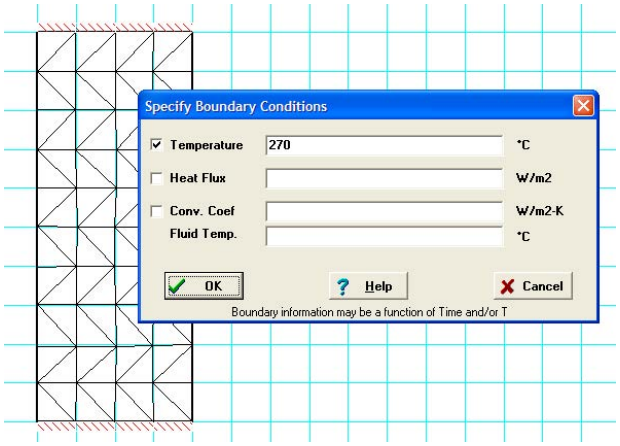
Note that we have selected material as 'not specified'. Conductivity (k) is entered as 1.2 W/m.K, as per data. Density and sp. heat are left as already entered since they are not required for steady state calculations. Hit OK to confirm.

7. **Now, choose the Boundary conditions from Specify menu:**



We have:

LHS is at a constant temp of 270 C:



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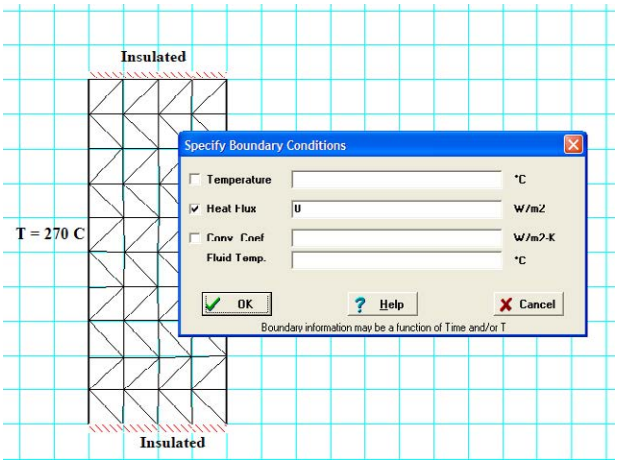
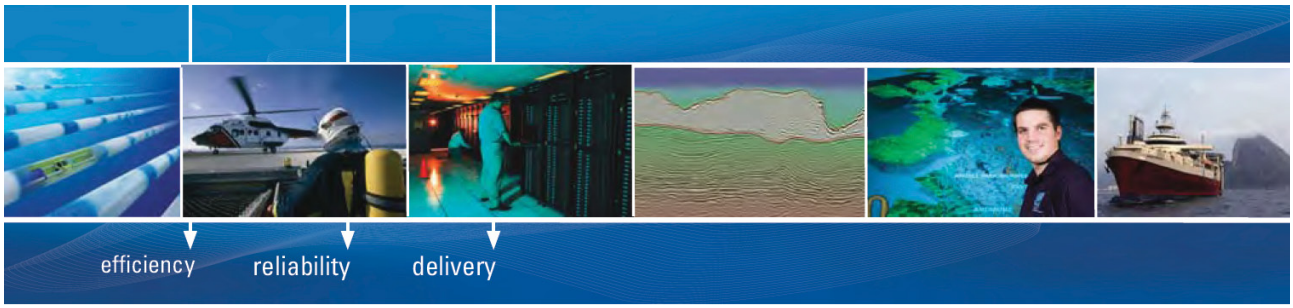
And, top and bottom surfaces are shown as insulated (i.e. zero heat flux) to force 1D conduction:



And, on RHS, we impose the convection conditions.



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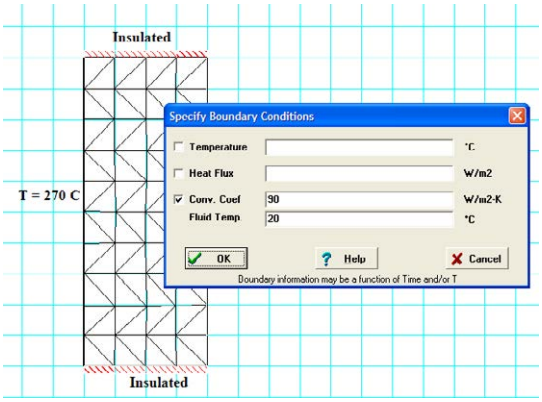
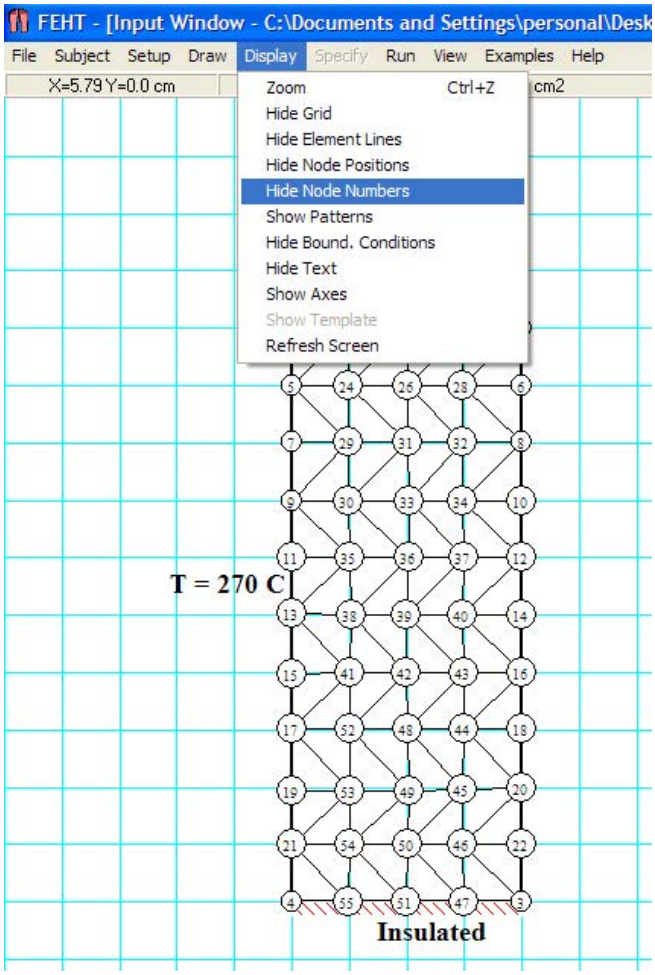
Here, h is unknown and surface temp T_0 is given as 70 C. However, we assume a value for h = say, 90 W/ m^2.K. (And, later, solve repeatedly for different values of h such that we get the surface temp T_0 as 70 C):



8. **From the Display menu, you can show or hide Node positions, Node Nos. etc.:**



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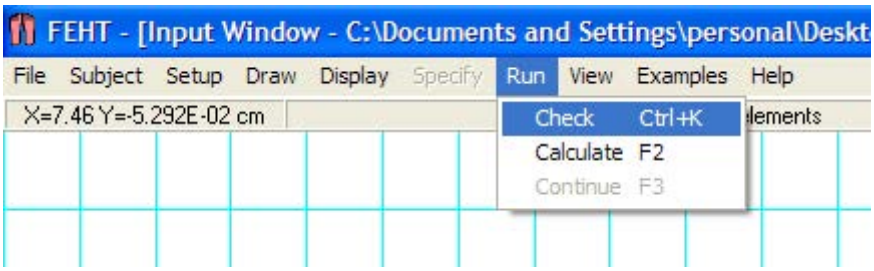
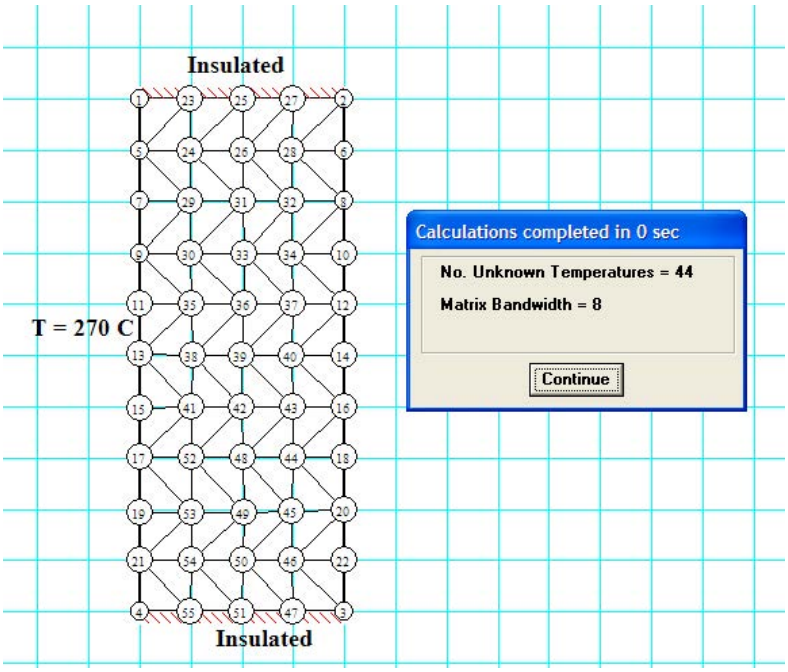
9. **Now, check that everything is OK before final calculations from the Run menu:**



We see:

i.e. there are 80 elements and no errors are found.

10. **Now, give the Calculate command from the Run menu: We get:**



Press 'Continue'.

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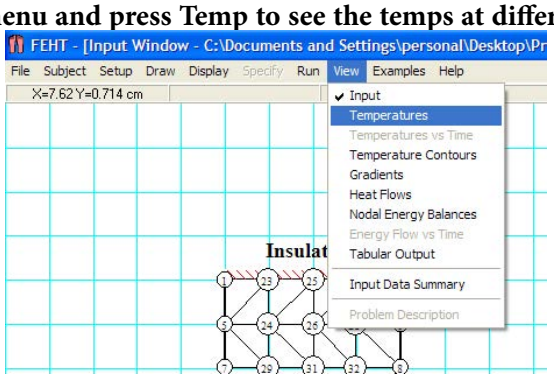
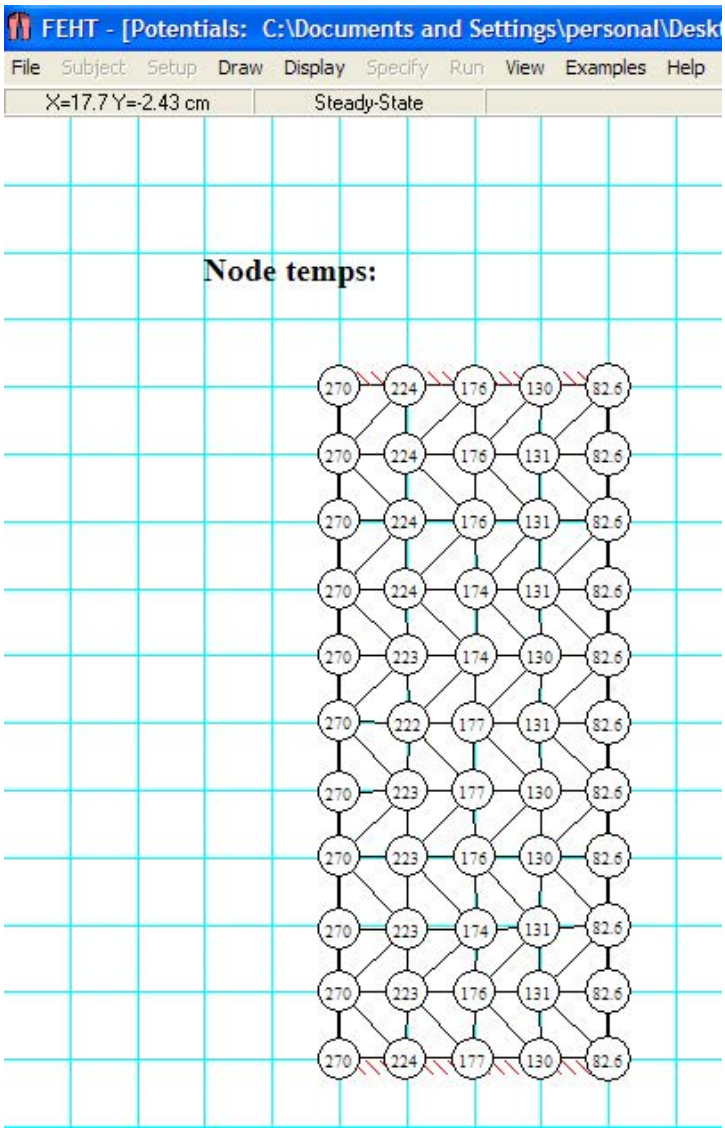
11. **Go to the View menu and press Temp to see the temps at different Nodes:**



We see:



You can easily see and correlate the Node Nos. and the corresponding temperatures.

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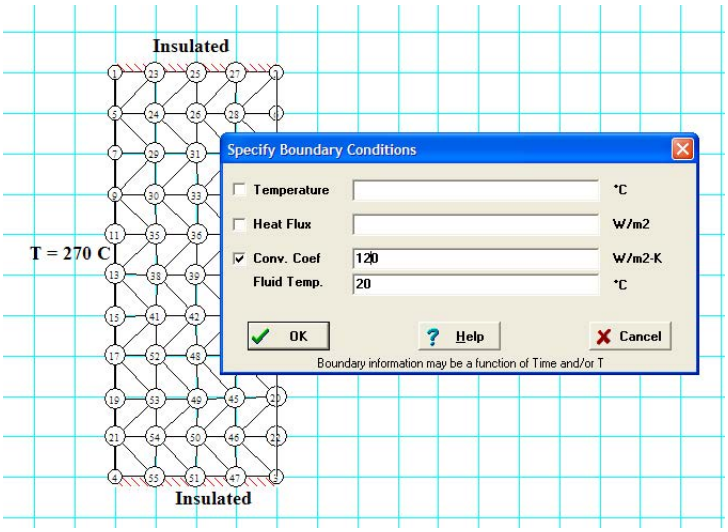
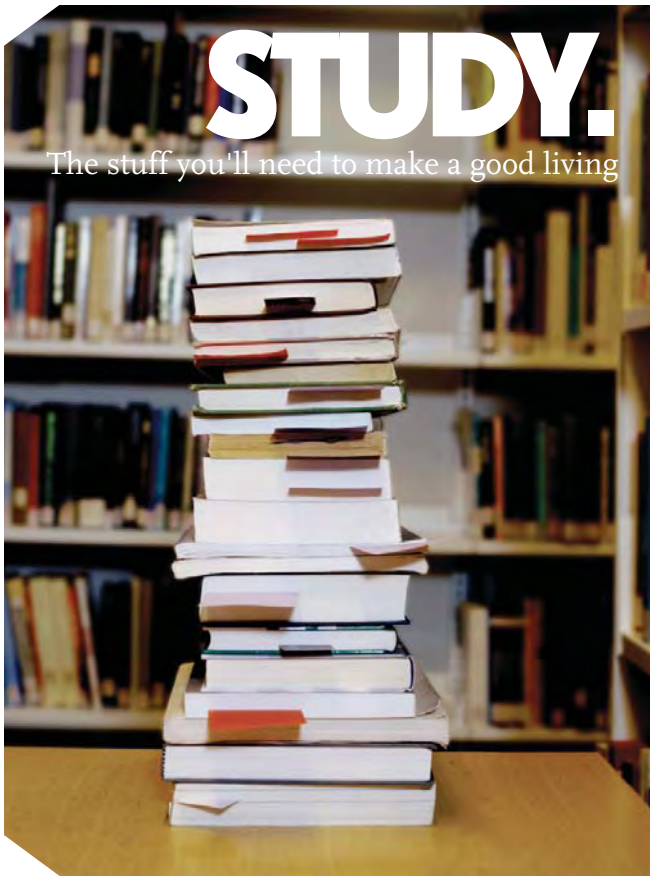
However, according to the problem, temp on the RHS should be 70 C.

So, now, we change the value of h from the Specify – Boundary conditions menu such that T_0 becomes 70 C. ***This is a trial and error process***: Finally, we get:





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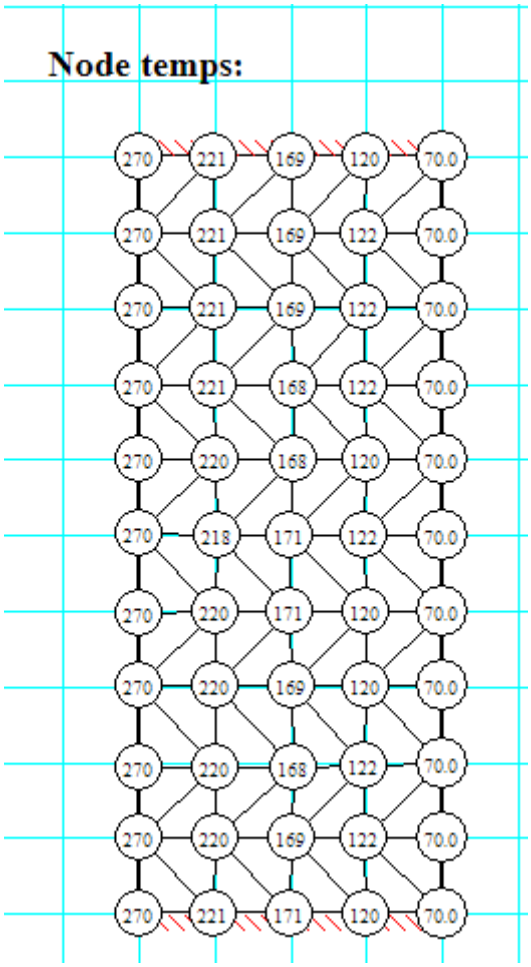
And Calculate from Run menu and then, Temps from the View menu:



Now, the temp on RHS is 70 C, as required.

Therefore: the value of h = 120 W/m^2.K, same as obtained earlier.

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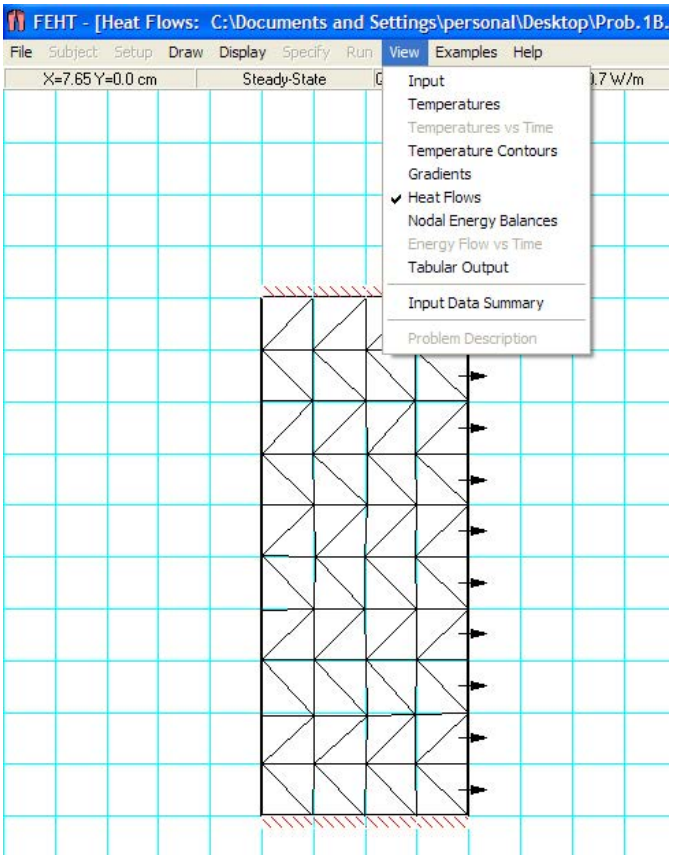
Heat transfer, Q is obtained by choosing View – Heat flows:



On the RHS, as we can see, the heat flow is outwards. Its value is shown on the top of the same screen as 600.7 W/m:

The section extends to 1 m depth perpendicular to paper, and the height of the section was arbitrarily taken as 10 cm. **Therefore, area for heat transfer is: 1 × 0.1 = 0.1 m^2.**

i.e. Q = 600.7 / 0.1 W/m^2 = 6007 W/m^2.

Compare this value with 6000 W/m^2, obtained earlier with EES.

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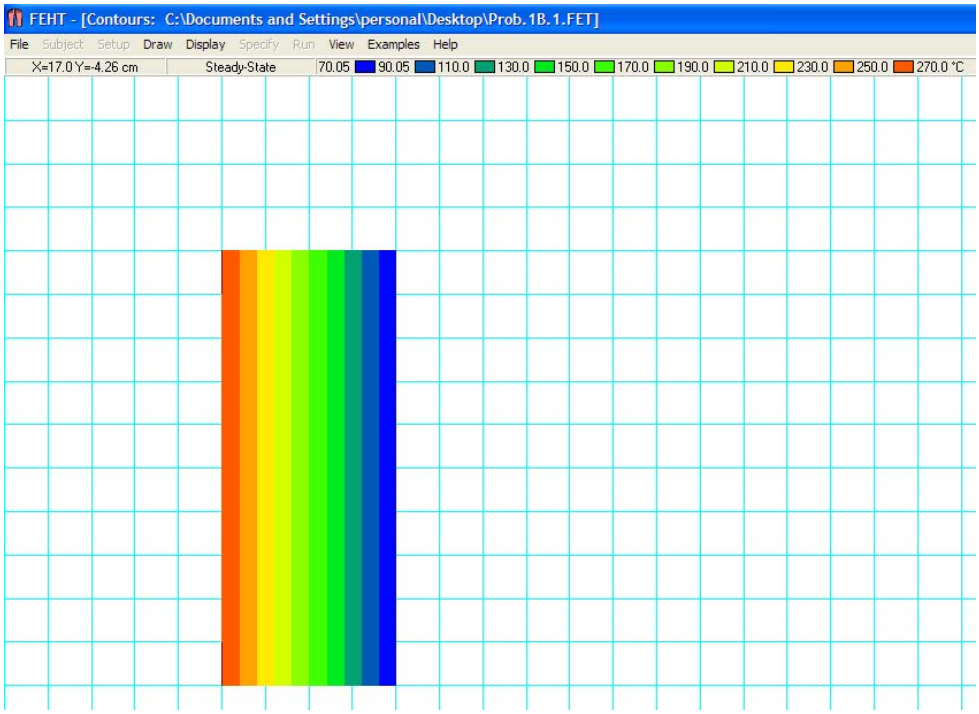
Temp. contour: This is obtained by clicking Temp contour from the View menu:



It also shows the color scheme on top of the screen.

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Next, calculate Temperatures on RHS for different values of h:

This is obtained in a straight forward manner by changing the value of h in 'Boundary conditions' in the Specify menu, for the RHS:

We get:

h (W/m^2.K)	T_0 (deg.C)	Q (W)
20	170	3002
40	127	4289
60	103	5005
80	88.2	5460
100	77.7	5775
120	70	6007
140	64.2	6183
160	59.5	6323
180	55.8	6436
200	52.6	6529

Comparing these values of T_0 and Q with those obtained with EES above, we find that they match very well.

==========

"Prob. 1B.2. What is the thickness required of a masonry wall having thermal conductivity of 0.75 W/m-C if the heat transfer rate is to be 80 % of the heat transfer rate through a composite structural wall having a thermal conductivity of 0.25 W/m-C and a thickness of 100 mm. Both walls are subjected to the same surface temperatures. …. [VTU-7th Sem-B.E.- Jan./Feb.2006]"

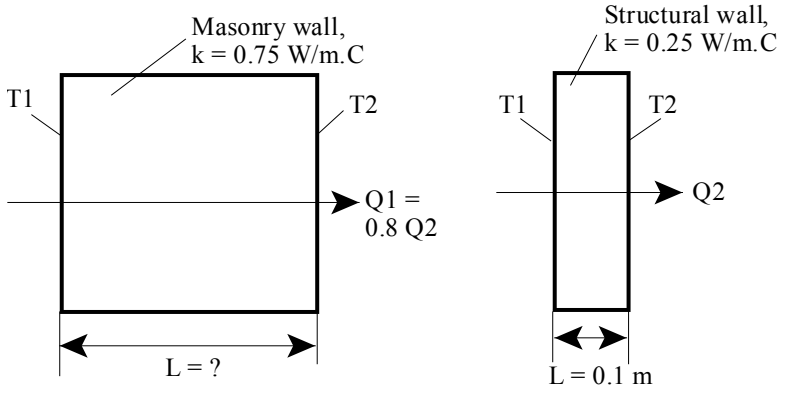

Fig.Prob.1B.2

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EES Solution:

"Data:"

k_masonry =0.75 "[W/m.C]"
k_structural = 0.25 "[W/m.C]"
L_structural = 0.1 "[m]"
A = 1 "[m2] … assumed"

"Calculations:"

R_structural = L_structural/(k_structural*A) "[C/W] … thermal resist of structural wall"

R_masonry = L_masonry/(k_masonry*A) "[C/W] … thermal resist of masonry wall"

"Now, by data:

DELTAT/R_masonry = 0.8*DELTAT/R_strucural, where DELTAT is the temp. difference"

"Therefore:"

1/R_masonry = 0.8*1/R_structural "calculates L_masonry, since L_masonry is the only unknown in this eqn."

Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]
$k_{structural} = 0.25$ [W/m-C]
$L_{structural} = 0.1$ [m]
$R_{structural} = 0.4$ [C/W]

$k_{masonry} = 0.75$ [W/m-C]
$L_{masonry} = 0.375$ [m]
$R_{masonry} = 0.5$ [C/W]

Thus:
L_masonry = 0.375 m … Ans.

==========

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"Prob. 1B.3. The exterior wall of a building is constructed of four materials: 12 mm thick gypsum board, 75 mm thick fiberglass insulation, 20 mm thick plywood and 20 mm thick hardboard siding. The inside and outside air temperatures are 20 C and -10 C respectively. The convective heat transfer coeff on the inner and outer surfaces of the wall are 6 W/m^2-C and 10 W/m^2-C respectively. Determine the heat flux and the overall heat transfer coeff. Thermal conductivity values of the four materials are given below: [VTU-6th Sem-B.E.- Aug.2001]"

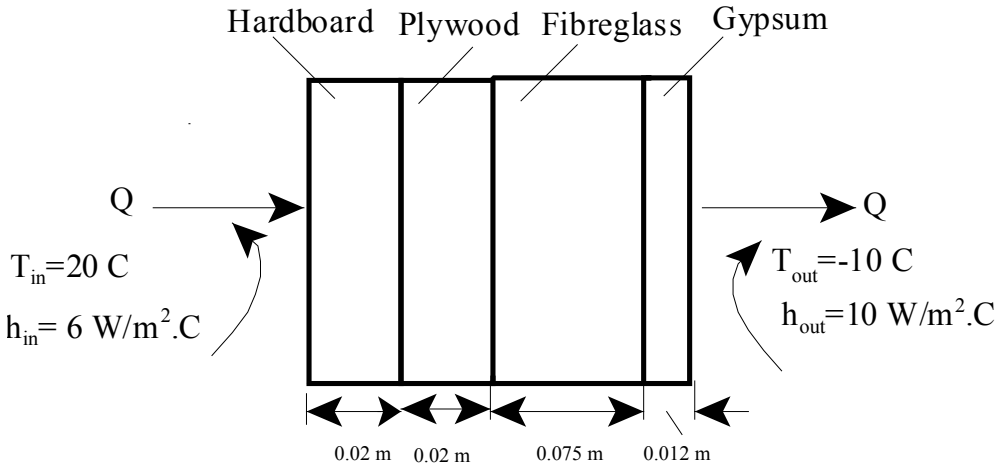
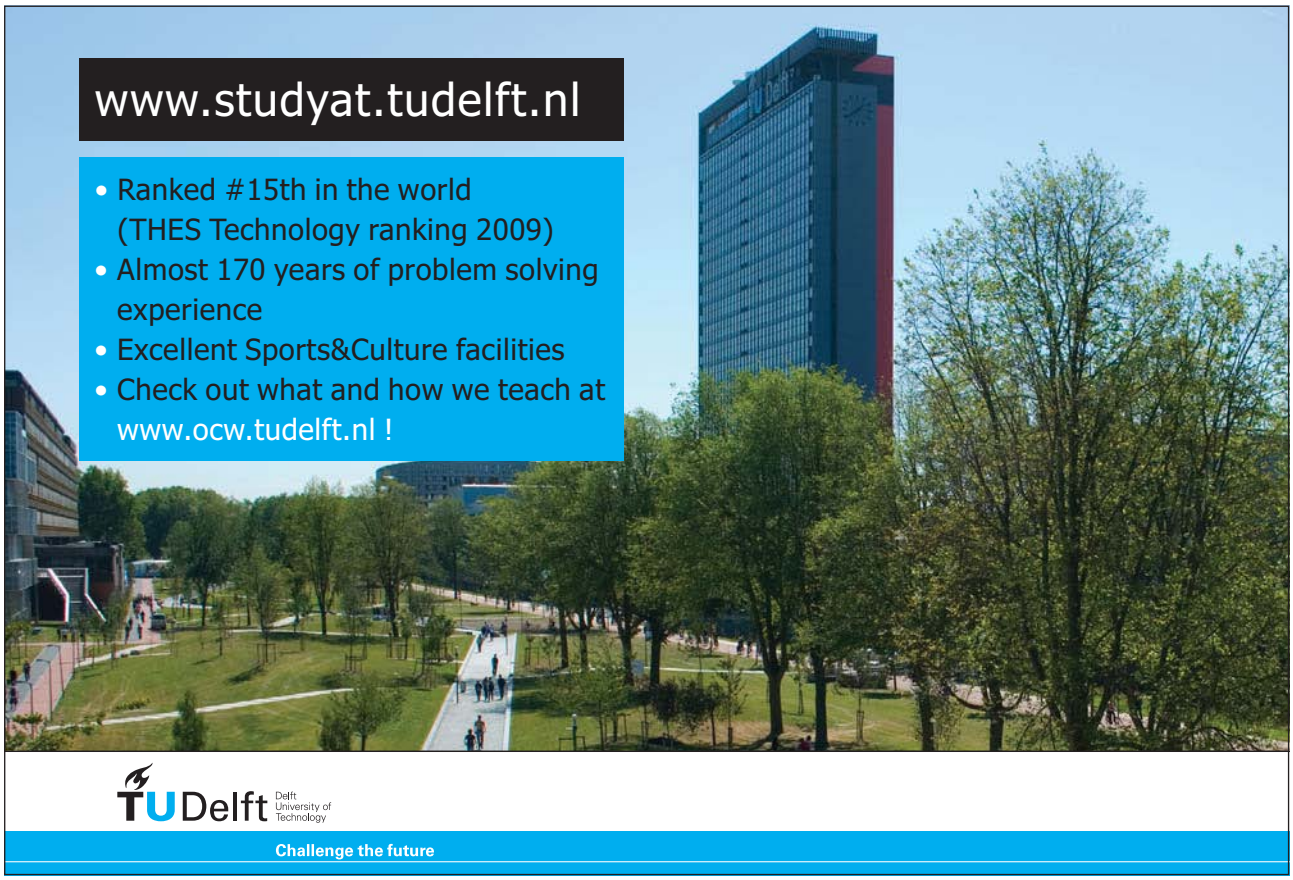


Fig. Prob.1B.3



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Solution:

"Data:"

k_gypsum =0.176 "[W/m.C]"
k_plywood = 0.115 "[W/m.C]"
k_fglass = 0.036 "[W/m.C]"
k_hardboard = 0.215 "[W/m.C]"
L_gypsum =0.012 "[m]"
L_plywood = 0.02 "[m]"
L_fglass = 0.075 "[m]"
L_hardboard = 0.02 "[m]"
T_in = 20 "[C]"
T_out = -10 "[C]"
h_in = 6 "[W/m^2.C]"
h_out = 10 "[W/m^2.C]"
A = 1 "[m^2] … assumed"

"Calculations:"

R_c1 = 1/(h_in*A) "[C/W] … convective resistance on the inside"
R_c2 = 1/(h_out*A) "[C/W] … convective resistance on the outside"
R_gypsum =L_gypsum/(k_gypsum*A) "[C/W] …thermal resistance of gypsum layer"
R_plywood = L_plywood/(k_plywood*A) "[C/W] …thermal resistance of plywood layer"
R_fglass = L_fglass/(k_fglass*A) "[C/W] …thermal resistance of fibreglass layer "
R_hardboard = L_hardboard/(k_hardboard*A) "[C/W] …thermal resistance of hardboard layer"

R_tot=R_c1+R_c2+R_gypsum+R_plywood+R_fglass+R_hardboard"[C/W]…totalthermalresistance"
q = (T_in-T_out)/R_tot "[W/m^2] …. Heat flux"
U = 1/(A*R_tot) "[W/m^2.C] … overall heat transfer coeff."

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Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]	$h_{in} = 6$ [W/m^2-C]	$h_{out} = 10$ [W/m^2-C]
$k_{fglass} = 0.036$ [W/m-C]	$k_{gypsum} = 0.176$ [W/m-C]	$k_{hardboard} = 0.215$ [W/m-C]
$k_{plywood} = 0.115$ [W/m-C]	$L_{fglass} = 0.075$ [m]	$L_{gypsum} = 0.012$ [m]
$L_{hardboard} = 0.02$ [m]	$L_{plywood} = 0.02$ [m]	$q = 11.17$ [W/m^2]
$R_{c1} = 0.1667$ [C/W]	$R_{c2} = 0.1$ [C/W]	$R_{fglass} = 2.083$ [C/W]
$R_{gypsum} = 0.06818$ [C/W]	$R_{hardboard} = 0.09302$ [C/W]	$R_{plywood} = 0.1739$ [C/W]
$R_{tot} = 2.685$ [C/W]	$T_{in} = 20$ [C]	$T_{out} = -10$ [C]
$U = 0.3724$ [W/m^2-C]		

Thus:

q = 11.17 [W/m^2]….Ans.

U = 0.3724 [W/m^2.C]….Ans.

==========

"**Prob. 1B.4.** A 0.8 m high and 1.5 m wide double pane window consists of two 4 mm thick layers of glass (k = 0.78 W/m-C), separated by a 10 mm wide stagnant air space (k = 0.026 W/m-C). Determine the rate of heat transfer through this window and the temperature of the inside surface, when the room is maintained at 20 C and the outside air is at -10 C. Take the convection heat transfer coefficients on the inside and outside surfaces of the window as 10 and 40 W/m^2-C respectively. [VTU-6th Sem-B.E.-June.2012]"

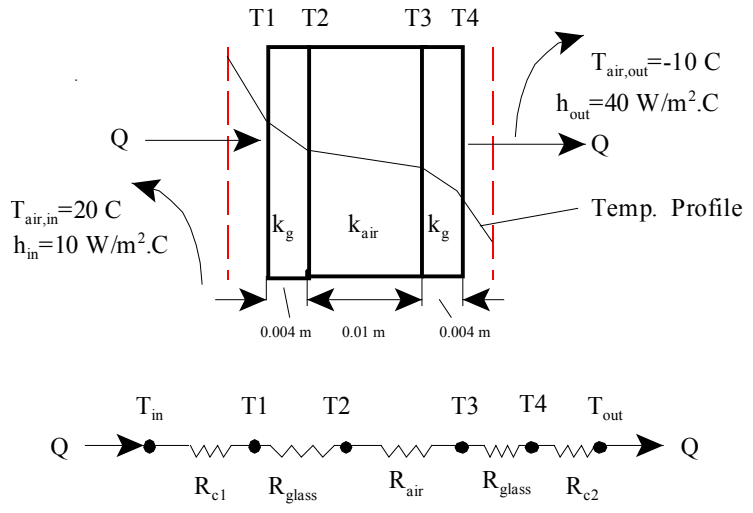

Fig. Prob.1B.4

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EES Solution:

"Data:"

k_glass =0.78 "[W/m.C]"
k_air = 0.026 "[W/m.C]"

L_glass =0.004 "[m]"
L_air = 0.01 "[m]"

T_air_in = 20 "[C]"
T_air_out = -10 "[C]"
h_in = 10 "[W/m^2.C]"
h_out = 40 "[W/m^2.C]"

A = 0.8 * 1.5 "[m^2]"

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"Calculations:"

R_c1 = 1/(h_in*A) "[C/W] … convective resistance on the inside"
R_c2 = 1/(h_out*A) "[C/W] … convective resistance on the inside"
R_glass =L_glass/(k_glass*A) "[C/W] … thermal resist of glass layer"
R_air = L_air/(k_air*A) "[C/W] …. Thermal resist of air layer"
R_tot = R_c1+2 * R_glass + R_air + R_c2 "[C/W] … total thermal resistance"
Q = (T_air_in-T_air_out)/R_tot "[W] … heat transfer rate"
U = 1/(A*R_tot) "[W/m^2.C] … overall heat transfer coeff."

"Q is the same through each layer. Then, for the inside convective layer:"

T_air_in – Tglass_in =Q * R_c1 "finds T_glass_in, temp. of inside glass surface"

"Again, for the outside convective layer:"

Tglass_out – T_air_out = Q * R_c2 "finds T_glass_in, temp. of outside glass surface"

Results:

Unit Settings: SI C Pa J mass deg

$A = 1.2$ [m^2]	$h_{in} = 10$ [W/m^2-C]	$h_{out} = 40$ [W/m^2-C]
$k_{air} = 0.026$ [W/m-C]	$k_{glass} = 0.78$ [W/m-C]	$L_{air} = 0.01$ [m]
$L_{glass} = 0.004$ [m]	$Q = 69.25$ [W]	$R_{air} = 0.3205$ [C/W]
$R_{c1} = 0.08333$ [C/W]	$R_{c2} = 0.02083$ [C/W]	$R_{glass} = 0.004274$ [C/W]
$R_{tot} = 0.4332$ [C/W]	$Tglass_{in} = 14.23$ [C]	$Tglass_{out} = -8.557$ [C]
$T_{air,in} = 20$ [C]	$T_{air,out} = -10$ [C]	$U = 1.924$ [W/m^2-C]

Thus:

Q = 69.25 [W]….Ans.
T_glass_in= 14.23 [C]….Ans.

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Additionally:

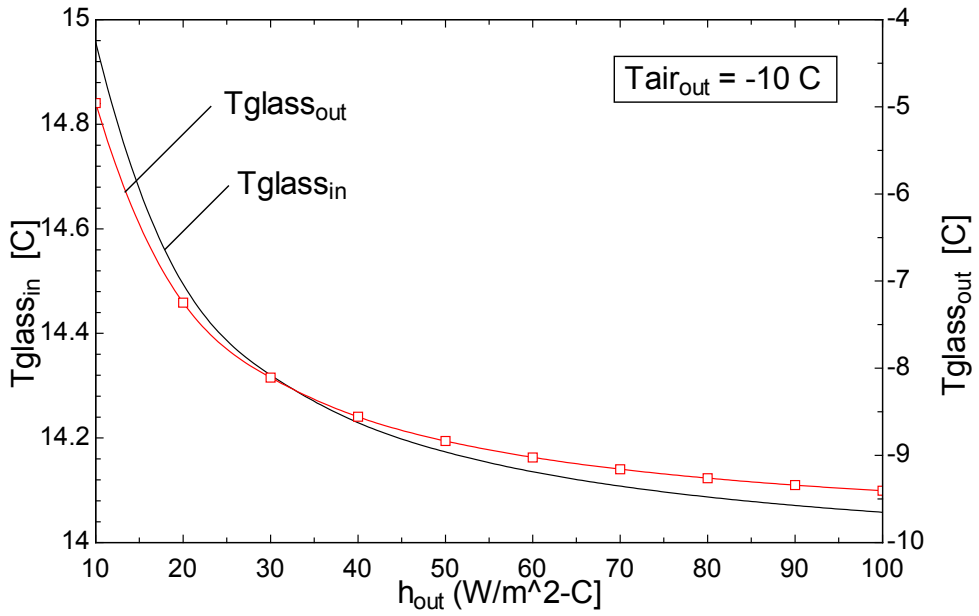
It is obvious that the outside air temperature and convective heat transfer coefficients depend on atmospheric and wind conditions.

Draw the variation of inside and outside glass surface temperatures when the outside air temp is -10 C and the outside convective heat transfer coefficient varies from 10 to 100 W/m^2-C.

This demonstrates the capability of EES to generate a parametric table and the graph:

Table 1

1..10	1 $T_{air,out}$ [C]	2 h_{out} [W/m2-C]	3 $Tglass_{in}$ [C]	4 $Tglass_{out}$ [C]
Run 1	-10	10	14.96	-4.957
Run 2	-10	20	14.49	-7.247
Run 3	-10	30	14.32	-8.107
Run 4	-10	40	14.23	-8.557
Run 5	-10	50	14.17	-8.835
Run 6	-10	60	14.14	-9.023
Run 7	-10	70	14.11	-9.158
Run 8	-10	80	14.09	-9.261
Run 9	-10	90	14.07	-9.341
Run 10	-10	100	14.06	-9.406



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"**Prob. 1B.5.** A furnace wall is made up of three layers. First layer is of insulation brick of 12 cm thickness (k = 0.6 W/m-K). The face is exposed to gases at 870 C with convection coeff. of 110 W/m^2-K. It is covered with (backed with) a 10 cm thick layer of fire brick (k = 0.8 W/m-K), with a contact resistance of 2.6 x 10^-4 m^2.K/W between the first and second layer. The third layer is a plate of 10 cm thickness (k = 4 W/m-K) with a contact resistance between second and third layer of 1.5 x 10^-4 m^2.K/W. The plate is exposed to air at 30 C with convection coeff of 15 W/m^2-K. Determine the heat flow and overall heat transfer coeff. Also find the temperature on the interface of first and second layer. [VTU-6th Sem-B.E.- July/Aug.2002]"

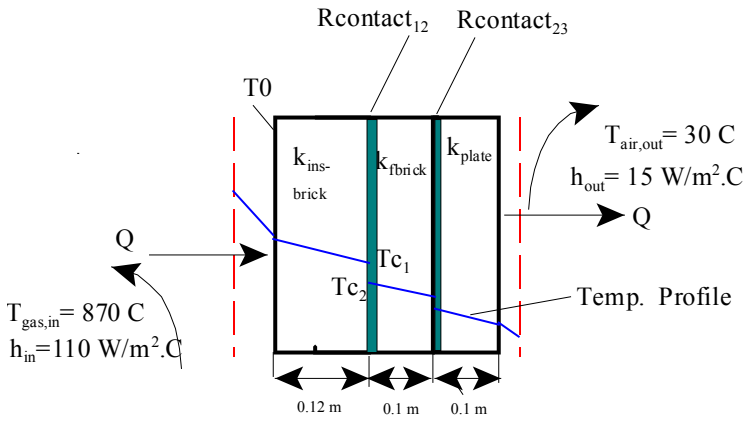

Fig.Prob.1B.5

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EES Solution:

"Data:"

"Note: W/m^2-K is equivalent to W/m^2-C (units of heat tr coeff. h) since K and C refer to temp differences and not actual value of temp. Similarly, W/m-K and W/m-C (units of thermal cond. k) are equivalent."

k_ins_brick =0.6 "[W/m.C]"
k_firebrick = 0.8 "[W/m.C]"
k_plate = 4.0 "[W/m.C]"

L_ins_brick =0.12 "[m]"
L_firebrick = 0.1 "[m]"
L_plate = 0.1 "[m]"

Tgas_in = 870 "[C]"
Tair_out = 30 "[C]"
h_in = 110 "[W/m^2.C]"
h_out = 15 "[W/m^2.C]"

Rcontact_12 = 2.6E-04 "m^2.C/W – contact resist between layers 1-2"
Rcontact_23 = 1.5E-04 "m^2.C/W – contact resist between layers 2-3"

A = 1 "[m^2]….assumed"

"Calculations:"

R_c1 = 1/(h_in*A) "[C/W] … convective resistance on the inside"
R_c2 = 1/(h_out*A) "[C/W] … convective resistance on the outside"

R_ins_brick =L_ins_brick/(k_ins_brick*A) "[C/W]…conductive resist."
R_firebrick = L_firebrick/(k_firebrick*A) "[C/W]]…conductive resist."
R_plate = L_plate/(k_plate*A) "[C/W] …conductive resist."

R_tot = R_c1+R_ins_brick+Rcontact_12/A+R_firebrick+Rcontact_23/A+R_plate+R_c2 "[C/W]…total resist.

Note that Rcontact_12 and Rcontact_23 are divided by A so that all factors have the same units, i.e.[C/W]"

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q = (Tgas_in-Tair_out)/R_tot "[W/m^2]….heat flux"
U = 1/(A*R_tot) "[W/m^2.C]….overall heat transfer coeff."

"Now, using the fact that , in steady state, q is the same through each layer:"

Tgas_in-T_0 =q*R_c1 "finds T_0, temp. on LHS of insulating brick"
T_0-Tc1 = q*R_ins_brick "finds Tc1, temp at RHS of layer1, i.e. insulating brick"
Tc1-Tc2 = q*Rcontact_12 "finds Tc2, temp at LHS of layer2, i.e. fire brick"

Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]	$h_{in} = 110$ [W/m^2C]	$h_{out} = 15$ [W/m^2C]
$k_{firebrick} = 0.8$ [W/m-C]	$k_{ins,brick} = 0.6$ [W/m-C]	$k_{plate} = 4$ [W/m-C]
$L_{firebrick} = 0.1$ [m]	$L_{ins,brick} = 0.12$ [m]	$L_{plate} = 0.1$ [m]
$q = 1971$ [W/m^2]	$Rcontact_{12} = 0.00026$ [m^2C/W]	$Rcontact_{23} = 0.00015$ [m^2C/W]
$R_{c1} = 0.009091$ [C/W]	$R_{c2} = 0.06667$ [C/W]	$R_{firebrick} = 0.125$ [C/W]
$R_{ins,brick} = 0.2$ [C/W]	$R_{plate} = 0.025$ [C/W]	$R_{tot} = 0.4262$ [C/W]
$Tair_{out} = 30$ [C]	$Tc1 = 457.9$ [C]	$Tc2 = 457.4$ [C]
$Tgas_{in} = 870$ [C]	$T_0 = 852.1$ [C]	$U = 2.346$ [W/m^2C]

Thus:

Q = 1971 [W/m2]…Ans.

Tc1 = 457.9 C…Ans.

Tc2 = 457.4 C….Ans.

U = 2.346 [W/m2.K]….Ans.

==========

"**Prob. 1B.6.** The walls of a house in cold region consist of three layers: an outer brick work 15 cm thick, an inner wooden panel 1.2 cm thick; the intermediate layer is made of an insulating material 7 cm thick. The thermal conductivity of brick and wood are 0.7 W/m.K and 0.18 W/m.K respectively. The inside and outside temperatures of the composite wall are 21 C and -15 C respectively. If the layer of insulation offers twice the thermal resistance of the brick wall, calculate: (i) heat loss per unit area of the wall (ii) thermal conductivity of the insulating material. [VTU-6th Sem-B.E.- Dec.2010]:"

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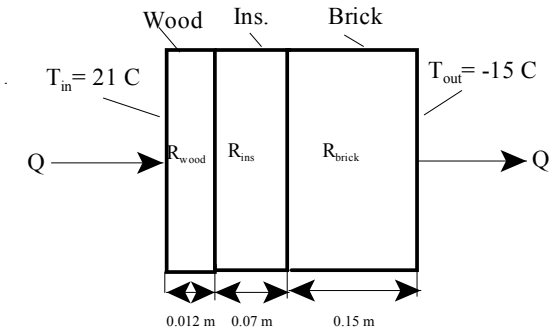

Fig. Prob.1B.6

EES Solution:

"Data:"

L_brick = 0.15[m]
L_wood = 0.012[m]
L_ins = 0.07[m]
k_brick = 0.7[W/m-C]
k_wood = 0.18[W/m-C]
T_A = 21[C]
T_B = -15[C]
A = 1 [m^2]

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"Calculations:"

R_brick = L_brick/(k_brick*A) "[C/W]… thermal resistance of brick wall"
R_wood = L_wood/(k_wood*A) "[C/W]… thermal resistance of wood"
R_ins = 2*R_brick "[C/W]..by data… finds R_ins, thermal resistance of insulating layer"
R_ins = L_ins/(k_ins*A) "[C/W]…finds k_ins, thermal conductivity of ins. layer"
Q = (T_A-T_B)/(R_brick + R_wood + R_ins) "[W]….Finds Q"

Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]	$k_{brick} = 0.7$ [W/m-C]	$k_{ins} = 0.1633$ [W/m-C]	$k_{wood} = 0.18$ [W/m-C]
$L_{brick} = 0.15$ [m]	$L_{ins} = 0.07$ [m]	$L_{wood} = 0.012$ [m]	$Q = 50.74$ [W]
$R_{brick} = 0.2143$ [C/W]	$R_{ins} = 0.4286$ [C/W]	$R_{wood} = 0.06667$ [C/W]	$T_A = 21$ [C]
$T_B = -15$ [C]			

Thus:

k_ins = 0.1633 [W/m-C]…Ans.

Q = 50.74 [W]….Ans.

==========

"**Prob. 1B.7.** An electrical resistance of mattress type is inserted in between two slabs of different materials on a panel heater. On one side, the material has a thermal conductivity of 0.174 W/m.K and 10 mm thick. On the other side of the heater, the material has a thermal conductivity of 0.05 W/m.K and 25 mm thick. The convection heat transfer coeff from the thinner and thicker slabs are 23.26 and 11.63 W/m^2.K. The temp of the surrounding air on both the sides is 15 C. If the energy dissipation for each square meter of the mattress is 5 kW, neglecting edge effects, find: (i) the surface temperatures of the slab, (ii) the temp of mattress, assuming it to be the same as the inner surface of the slabs. [VTU-6th Sem-B.E.- June–July.2009]:"

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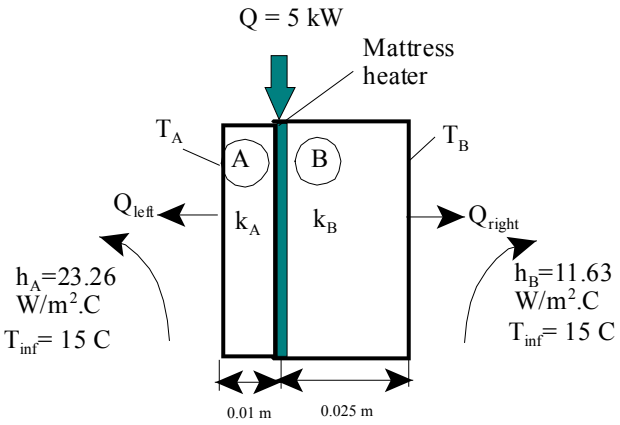

Fig. Prob.1B.7

EES Solution:

"Data:"

L_A = 0.01[m]
L_B = 0.025[m]
k_A = 0.174[W/m-C]
k_B = 0.05[W/m-C]
h_A = 23.26[W/m^2-C]
h_B = 11.63[W/m^2-C]
T_inf = 15[C]
A = 1[m^2]
Q_tot = 5000[W]

"Calculations:"

R_cond_A = L_A/(k_A*A) "[C/W] .. thermal resist of layer A"
R_cond_B = L_B/(k_B*A) "[C/W] .. thermal resist of layer B"
R_conv_A = 1/(h_A*A) "[C/W] .. thermal resist of convective layer outside A"
R_conv_B = 1/(h_B*A) "[C/W] .. thermal resist of convective layer outside B"

"Mattress is in between layers A and B, i.e. at the centre. So,"

R_left = R_cond_A + R_conv_A "[C/W] … thermal resist to the left of centre"
R_right = R_cond_B + R_conv_B "[C/W] … thermal resist to the right of centre"

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Q_left = (T_M – T_inf)/R_left "[W] …heat flowing to the left; T_M is temp of mattress, to be found out"
Q_right = (T_M – T_inf)/R_right "[W] …heat flowing to the right"
Q_tot = Q_left + Q_right "[W] … total heat flow. It must be equal to (Q_left + Q_right)"

"Using: Q = DELTAT /R for left and right sides:"

T_A = T_M – Q_left* L_A/(k_A*A) "[C], Temp of left slab surface"
T_B = T_M – Q_right* L_B/(k_B*A) "[C], Temp of right slab surface"

Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]	$h_A = 23.26$ [W/m^2-C]	$h_B = 11.63$ [W/m^2-C]
$k_A = 0.174$ [W/m-C]	$k_B = 0.05$ [W/m-C]	$L_A = 0.01$ [m]
$L_B = 0.025$ [m]	$Q_{left} = 4268$ [W]	$Q_{right} = 731.8$ [W]
$Q_{tot} = 5000$ [W]	$R_{cond,A} = 0.05747$ [C/W]	$R_{cond,B} = 0.5$ [C/W]
$R_{conv,A} = 0.04299$ [C/W]	$R_{conv,B} = 0.08598$ [C/W]	$R_{left} = 0.1005$ [C/W]
$R_{right} = 0.586$ [C/W]	$T_A = 198.5$ [C]	$T_B = 77.92$ [C]
$T_{inf} = 15$ [C]	$T_M = 443.8$ [C]	

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Thus:

T_A = 198.5 [C]….Ans…. temp on LHS of slab.

T_B = 77.92 [C]….Ans…… temp on RHS of slab.

T_M = 443.8 [C]….Ans……. temp of mattress.

==========

"**Prob. 1B.8.** The composite wall of an oven consists of three materials, two of which are of known thermal conductivities, k_A = 20 W/m.K and k_C = 50 W/m.K, and known thicknesses, L_A = 0.3 m and L_C = 0.15 m. The third material, B which is sandwiched between materials A and C, is of unknown thermal conductivity, k_B, but of known thickness L_B = 0.15 m. Under steady operating conditions, it was found that the outside surface of material C is at 20 C, the inside surface of material A is at 600 C. This surface is in contact with hot air at 800 C and the inside surface heat transfer coeff is 25 W/m^2.C. What is the value of k_B? Also, determine the overall heat transfer coeff for the composite wall. [VTU-6th Sem-B.E.-July./Aug.2004]"

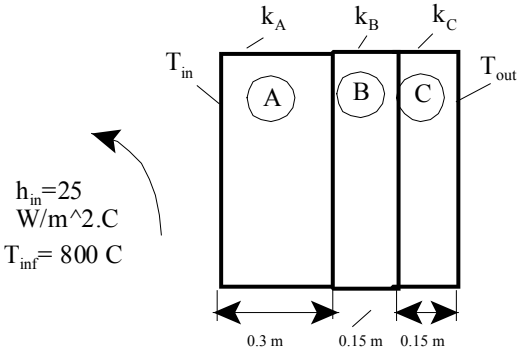

Fig.Prob.1B.8

EES Solution:

"Data:"

k_A =20 "[W/m.K]"
k_C = 50 "[W/m.K]"
L_A =0.3 "[m]"
L_C = 0.15 "[m]"
L_B = 0.15 "[m]"
T_in = 600 "[C]"
T_out = 20 "[C]"
h_in = 25 "[W/m^2.C]"
T_inf = 800 "[W/m^2.C]"
A = 1 "[m^2]… assumed"

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"Calculations:"

Q = h_in*A*(T_inf-T_in) "finds Q, W"
R_c1 = 1/(h_in*A) "[C/W]… convective resist on the inside"

R_A =L_A/(k_A*A) "[C/W]… conductive resist of A"
R_B = L_B/(k_B*A) "[C/W]]… conductive resist of B"
R_C = L_C/(k_C*A) "[C/W]]… conductive resist of C"

R_tot = R_c1+R_A+R_B+R_C "[C/W]]… total thermal resist "
Q = (T_inf-T_out)/R_tot "[W/m^2]…. Heat transfer rate per unit area"
U = 1/(A*R_tot) "[W/m^2.C]…. Overall heat transfer coeff."

Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]	$h_{in} = 25$ [W/m^2C]	$k_A = 20$ [W/m-C]	$k_B = 1.531$ [W/m-C]
$k_C = 50$ [W/m-C]	$L_A = 0.3$ [m]	$L_B = 0.15$ [m]	$L_C = 0.15$ [m]
$Q = 5000$ [W]	$R_A = 0.015$ [C/W]	$R_B = 0.098$ [C/W]	$R_C = 0.003$ [C/W]
$R_{c1} = 0.04$ [C/W]	$R_{tot} = 0.156$ [C/W]	$T_{in} = 600$ [C]	$T_{inf} = 800$ [C]
$T_{out} = 20$ [C]	$U = 6.41$ [W/m^2C]		

Thus:

k_B = 1.531 [W/m.C]….Ans.

U = 6.41 [W/m2.C]….Ans.

==========

"**Prob. 1B.9.** A fiberglass sheet (20 mm thick, k2 = 0.036 W/m.K) sandwiched between a steel plate (6 mm thick, k3 = 25 W/m.K) and gypsum sheet (25 mm thick, k1 = 0.175 W/m.K), is used as a composite material for insulating application. There are 10 equi-spaced steel bolts (25 mm dia, k = 20 W/m.K), per square meter area of the composite wall, used to keep the wall in tact. If the outer surface temperatures of gypsum sheet and steel plate are at 200 C and 50 C respectively, determine the rate of heat transfer across the wall. What is the heat transfer rate if bolts are not used? [VTU-6th Sem-B.E.-Jan./Feb.2004]"

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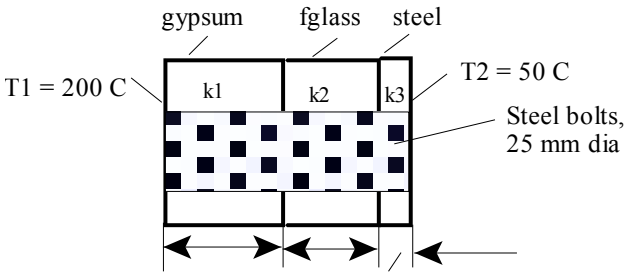

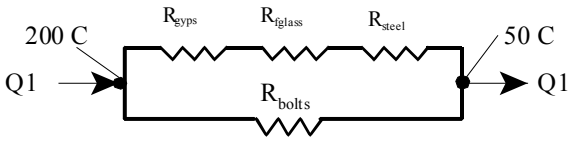

(a) Thermal circuit-- wth the bolts

(b) Thermal circuit-- wthout bolts

Fig. Prob.1B.9

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EES Solution:

"Data:"

L_gypsum = 0.025[m]
L_fglass = 0.02[m]
L_steel = 0.006[m]

k_gypsum = 0.175[W/m-C]
k_fglass = 0.036[W/m-C]
k_steel = 25[W/m-C]
N_bolts = 10
d_bolts = 0.025[m]
k_bolts = 20[W/m-C]
T_1 = 200[C]
T_2 = 50[C]

"Calculations:"

A_bolt = pi * d_bolts^2 / 4 "[m^2] … area of each bolt"
L_bolt = L_gypsum + L_fglass + L_steel "[m] …. length of each bolt"
A_slab = 1 – N_bolts * A_bolt "[m^2] …. area of each of the three slabs, after deducting the area of bolts from 1 m^2"

R_gypsum = L_gypsum/(k_gypsum * A_slab) "[C/W] …. thermal resist of gypsum"
R_fglass = L_fglass/(k_fglass * A_slab) "[C/W] …. thermal resist of fibre glass"
R_steel = L_steel/(k_steel * A_slab) "[C/W] …. thermal resist of steel"
R_slab = R_gypsum + R_fglass + R_steel "[C/W] … total resist of three sheets which are in series"
R_bolt = L_bolt /(k_bolts * A_bolt) "[C/W] …. thermal resist of one bolt"

"Now, the resistace of the slab and the resistances of 10 bolts are in parallel.
Therefore, total resistance is given by:"

1/R_total = 1/R_slab + N_bolts/R_bolt " determines R_total, [C/W]"
Q_withbolts = (T_1 – T_2)/R_total "[W] …. determines heat transfer rate, Q"

"When no bolts are used:"

"Now the area A_slab is 1 m^2."

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R_slab_nobolts = L_gypsum/(k_gypsum * 1) + L_fglass/(k_fglass * 1) + L_steel/(k_steel * 1) "[C/W] …. total thermal resist when there are no bolts"

Q_withoutbolts = (T_1 – T_2)/R_slab_nobolts

Results:

Unit Settings: SI C Pa J mass deg

A_{bolt} = 0.0004909 [m^2]	A_{slab} = 0.9951 [m^2]	d_{bolts} = 0.025 [m]
k_{bolts} = 20 [W/m-C]	k_{fglass} = 0.036 [W/m-C]	k_{gypsum} = 0.175 [W/m-C]
k_{steel} = 25 [W/m-C]	L_{bolt} = 0.051 [m]	L_{fglass} = 0.02 [m]
L_{gypsum} = 0.025 [m]	L_{steel} = 0.006 [m]	N_{bolts} = 10 [-]
$Q_{withbolts}$ = 502.4 [W]	$Q_{withoutbolts}$ = 214.7 [W]	R_{bolt} = 5.195 [C/W]
R_{fglass} = 0.5583 [C/W]	R_{gypsum} = 0.1436 [C/W]	R_{slab} = 0.7021 [C/W]
$R_{slab,nobolts}$ = 0.6987 [C/W]	R_{steel} = 0.0002412 [C/W]	R_{total} = 0.2986 [C/W]
T_1 = 200 [C]	T_2 = 50 [C]	

Thus:

Q with bolts = 502.4 W …..Ans.

Q without bolts = 214.7 W ….Ans.

==========

"**Prob. 1B.10.** A composite wall is made up of three layers of thicknesses 25 cm, 10 cm, and 15 cm of material A, B and C respectively. The thermal conductivities of A and B are 1.7 W/m.K and 9.5 W/m.K respectively. The outside surface is exposed to air at 20 C with convection coeff of 15 W/m^2.K and inside is exposed to gases at 1200 C with a convection coeff of 28 W/m^2.K and the inside surface is at 1080 C. Determine the unknown thermal cond of layer made up of material C. [VTU-6th Sem-B.E.-May/June 2010]"

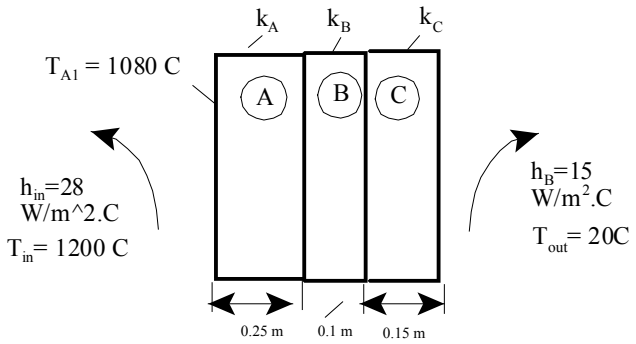

Fig.Prob.1B.10

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EES Solution:

"Data:"

L_A =0.25 "[m]"
L_B = 0.1 "[m]"
L_C = 0.15 "[m]"

k_A = 1.7 "[W/m.C]"
k_B = 9.5 "[W/m.C]"

Tgas_in = 1200 "[C]"
Tair_out = 20 "[C]"
h_in = 28 "[W/m^2.C]"
h_out = 15 "[W/m^2.C]"
T_A_1 = 1080 "[C]"

A = 1 "[m^2]…assumed"

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"Calculations:"

R_c1 = 1/(h_in*A) "[C/W] …. convective resistance on the inside"

R_c2 = 1/(h_out*A) "[C/W] … convective resistance on the outside"

R_A =L_A / (k_A * A) "[C/W]…conductive resist. of A"
R_B = L_B / (k_b * A) "[C/W]]…conductive resist. of B"

"Now, considering the inner surface of A and the convective resistance on that surface, we can write, for heat transfer rate:"

Q = (Tgas_in – T_A_1) / R_c1 "[W] …on the inner surface of layer A"

R_C = L_C/(k_C * A) "[C/W] …conductive resist. of C"

R_tot = R_c1+R_A+R_B+R_C+R_c2 "[C/W] …. total resist."

"Now, Q is also equal to overall temp difference divided by total thermal resistance. So, we write:"

Q = (Tgas_in – Tair_out) / R_tot "Calculates k_C, since it is the only unknown in this eqn."

Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]	$h_{in} = 28$ [W/m^2-C]	$h_{out} = 15$ [W/m^2-C]	$k_A = 1.7$ [W/m-C]
$k_B = 9.5$ [W/m-C]	$k_C = 1.644$ [W/m-C]	$L_A = 0.25$ [m]	$L_B = 0.1$ [m]
$L_C = 0.15$ [m]	$Q = 3360$ [W]	$R_A = 0.1471$ [C/W]	$R_B = 0.01053$ [C/W]
$R_C = 0.09122$ [C/W]	$R_{c1} = 0.03571$ [C/W]	$R_{c2} = 0.06667$ [C/W]	$R_{tot} = 0.3512$ [C/W]
$Tair_{out} = 20$ [C]	$Tgas_{in} = 1200$ [C]	$T_{A,1} = 1080$ [C]	

Thus:

k_C = 1.644 W/m.C …..Ans.

Q = 3360 W ….Ans.

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"**Prob. 1B.11.** A wall of a furnace is made up of inside layer of silica brick 120 mm thick covered with a layer of magnesite brick 240 mm thick. The temp at the inside surface of silica brick wall and outside surface of magnesite brick wall are 725 C and 110 C respectively. The contact thermal resistance between the two walls at the interface is 0.0035 C/W per unit wall area. If the thermal conductivities of silica and magnesite bricks are 1.7 W/m.C and 5.8 W/m.C, calculate: (i) the rate of heat loss per unit area of walls, and (ii) the temp drop at the interface. [VTU-6th Sem-B.E.-Dec.2009/Jan. 2010]"

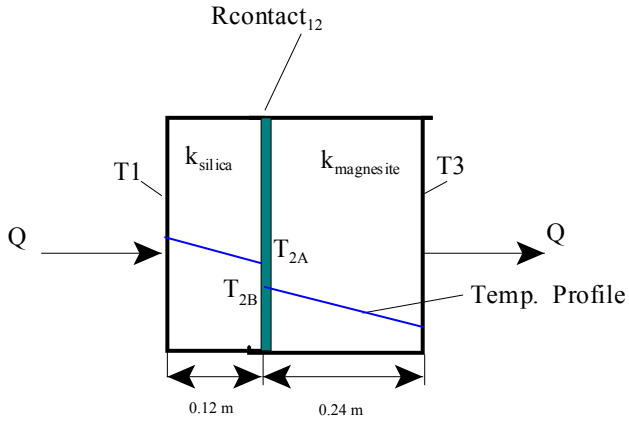

Fig.Prob.1B.11

EES Solution:

"Data:"

k_silicabrick = 1.7 "[W/m.C]"
k_magnesitebrick = 5.8 "[W/m.C]"
L_silicabrick =0.12 "[m]"
L_magnesitebrick = 0.24 "[m]"
T_1 = 725 "[C]"
"T_1 to T_2A is the temp drop in the silica brick;
T_2A to T_2B is the temp drop in the interface between silica and magnesite bricks;
T_2B to T_3 is the temp drop in the magnesite brick."
T_3 = 110 "[C]"
Rcontact_12 = 0.0035 "C/W – contact resist. between layers 1-2"
A = 1 "[m^2]….assumed"

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"Calculations:"

R_silicabrick =L_silicabrick/(k_silicabrick*A) "[C/W]…conductive resistance of silica brick"
R_magnesitebrick = L_magnesitebrick/(k_magnesitebrick*A) "[C/W]]…conductive resistance of magnesite brick"

R_tot = R_silicabrick++Rcontact_12+R_magnesitebrick "[C/W]….total resistance"

Q = (T_1-T_3)/R_tot "[W]….heat flow rate"

"Temp drop at the interface:"
"Now, using the fact that, in steady state, Q is the same through each layer:"

Q = (T_1 – T_2A)/R_silicabrick "finds T_2A,"
Q = (T_2A – T_2B)/Rcontact_12 "finds T_2B"
DELTAT_interface = (T_2A – T_2B) "[C]….temp drop at the interface"

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Results:

Unit Settings: SI C kPa kJ mass deg

A = 1 [m2]

$k_{magnesitebrick}$ = 5.8 [W/m-C]

$L_{magnesitebrick}$ = 0.24 [m]

Q = 5326 [W]

$R_{magnesitebrick}$ = 0.04138 [C/W]

R_{tot} = 0.1155 [C/W]

T_{2A} = 349 [C]

T_3 = 110 [C]

$\Delta T_{interface}$ = 18.64 [C]

$k_{silicabrick}$ = 1.7 [W/m-C]

$L_{silicabrick}$ = 0.12 [m]

$Rcontact_{12}$ = 0.0035 [C/W]

$R_{silicabrick}$ = 0.07059 [C/W]

T_1 = 725 [C]

T_{2B} = 330.4 [C]

Thus:

Q = 5326 W …..Ans; DELTAT_interface = 18.64 C ….Ans.

==========

"**Prob. 1B.12.** A composite slab is made of 2 layers of different materials A and B such that layer A has conductivity as: k_A = 0.5 (1 + 0.08. T) and is 5 cm thick, while the layer B has conductivity of 24 W/m.K and is 2 cm thick. The exposed surface of layer A is insulated while that of the layer B is exposed to a fluid at 20 C where the heat transfer coeff is 30 W/m^2.K. If the temperature at the interface between the two layers is 80 C, find: (i) rate of heat flux from the slab to the fluid (ii) max. temp in the system, and (iii) the distance of a point at 85 C from the insulated surface. [VTU-6th Sem-B.E.-Jan./Feb. 2003]"

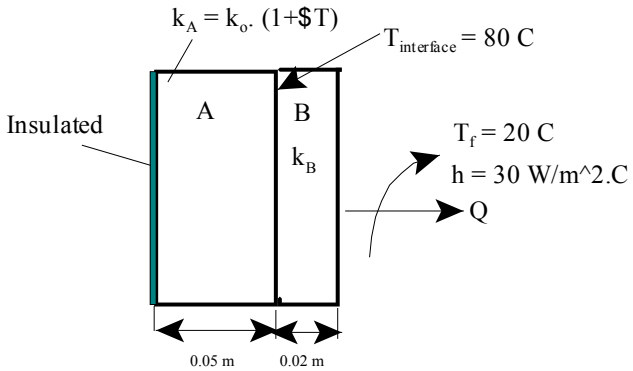

Fig.Prob.1B.12

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EES Solution:

"Data:"

"k_A = k_0 * (1 + beta * T) …. k varies linearly with Temp where:"

k_0 = 0.5
beta = 0.08
L_A = 0.05 [m]
k_B = 24 [W/m-K]
L_B = 0.02 [m]
T_fluid = 20 [C]
h = 30 [W/m^2-C]
T_interface = 80 [C]
A = 1 [m^2] "….assumed"

"Calculations:"

R_B =L_B/(k_B * A) "[C/W] …. thermal resistance of slab B"
R_conv = 1/(h * A) "[C/W] …. convective resistance on outer surface of slab B"
Q = (T_interface – T_fluid) / (R_B + R_conv) "[W] … heat flow rate"

T_m = (T_1 + T_interface)/2 "C.. mean temp of slab A"
k_m = k_0 * (1 + beta * T_m) "[W/m-K]…mean thermal cond. of slab A"
R_Am = L_A/(k_m * A) "[C/W] … mean thermal resistance of slab A"
Q = (T_1 – T_interface)/R_Am "W … heat flow through each layer is same …. finds T_1"
"…also T_1 is the max temp since that surface is insulated"

"Distance of a point at 85 C from insulated surface:"

"Let the distance be L_85"
"Then, Q is the same through each layer:"
k_mean = k_0 * (1 + beta * (T_1 + 85)/2) "… finds k_mean from left surface at T_1 to that surface where the temp is 85 C. Then applying Fourier's Law:"
Q = (T_1 – 85)/(L_85/(k_mean * A)) "… finds L_85"

"----------"

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"In addition: let us plot the temp profile for the slab A:"

"To find T(x) at x = 0.04 m from LHS and to draw T(x) vs x for x = 0 to x = 0.05 m:"

x = 0.04 "[m].. "
Q = (T_1 – Tx)/ R_mean_x "….finds Tx"
R_mean_x = x/(k_0 * (1 + beta * (T_1 + Tx)/2)) "… finds R_meanx"

"Also, plot T_1 and Q against h with T_interface remaining the same:"

"Now, the max. temp in slab, i.e. T_1 will vary as the value of convection coeff on the outside varies. Maintaining the interface temp as 80 C itself, calculate and plot the variation of T_1 and Q as h varies from 10 to 150 W/m^2.K:

Construct the parametric table, and then plot the graph:"

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Results:

Unit Settings: SI C Pa J mass deg

$A = 1$ [m^2]	$\beta = 0.08$ [1/C]	$h = 30$ [W/m^2-C]
$k_0 = 0.5$ [W/m-C]	$k_B = 24$ [W/m-K]	$k_m = 4.126$ [W/m-K]
$k_{mean} = 4.226$ [W/m-K]	$L_{85} = 0.03918$ [m]	$L_A = 0.05$ [m]
$L_B = 0.02$ [m]	$Q = 1756$ [W]	$R_{Am} = 0.01212$ [C/W]
$R_B = 0.0008333$ [C/W]	$R_{conv} = 0.03333$ [C/W]	$R_{mean,x} = 0.009483$ [C/W]
$Tx = 84.63$ [C]	$T_1 = 101.3$ [C]	$T_{fluid} = 20$ [C]
$T_{interface} = 80$ [C]	$T_m = 90.64$ [C]	$x = 0.04$ [m]

Thus:

Q = 1756 W… heat flux (i.e. for 1 m^2 area) …. Ans.

T_1 = T_max = 101.3 C ….. Ans.

L_85 = 0.03918 m …distance from LHS at which temp is 85 C….Ans.

Plot the temp profile in slab A:

First prepare a parametric table:

Table 1

1..10	1 x [m]	2 Tx [C]
Run 1	0	101.3
Run 2	0.005556	99.12
Run 3	0.01111	96.91
Run 4	0.01667	94.66
Run 5	0.02222	92.36
Run 6	0.02778	90.01
Run 7	0.03333	87.6
Run 8	0.03889	85.13
Run 9	0.04444	82.6
Run 10	0.05	80

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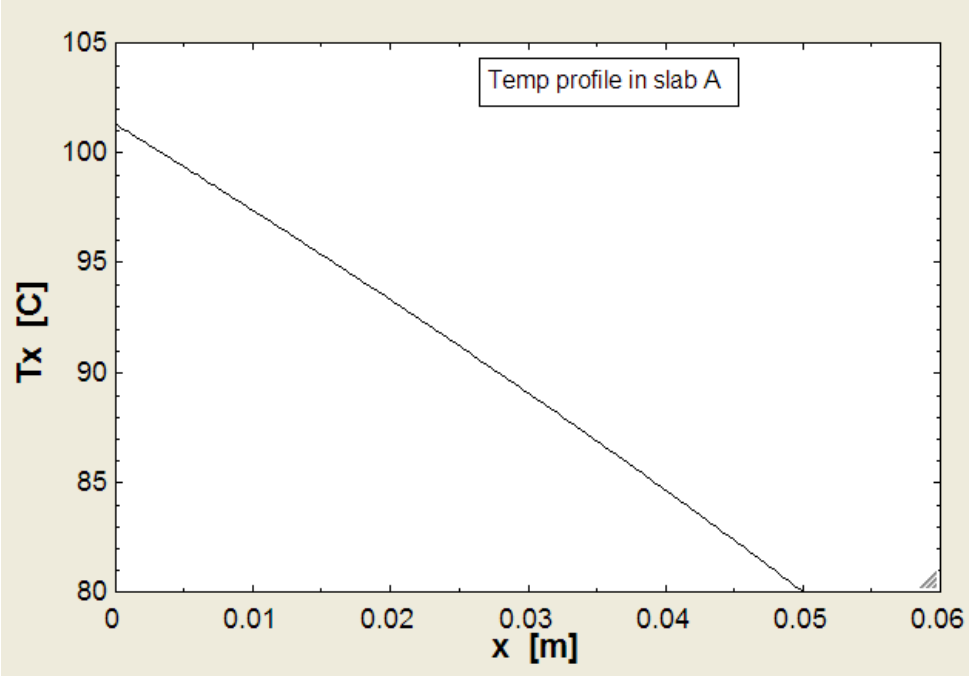
Then plot the graph:



To plot T_1 and Q against h:

First prepare a parametric table:

1..15	1 h [W/m2-C]	2 T_1 [C]	3 Q [W]
Run 1	10	87.72	595
Run 2	20	94.77	1180
Run 3	30	101.3	1756
Run 4	40	107.3	2323
Run 5	50	113	2880
Run 6	60	118.4	3429
Run 7	70	123.4	3969
Run 8	80	128.2	4500
Run 9	90	132.8	5023
Run 10	100	137.2	5538
Run 11	110	141.4	6046
Run 12	120	145.4	6545
Run 13	130	149.2	7038
Run 14	140	152.9	7522
Run 15	150	156.5	8000

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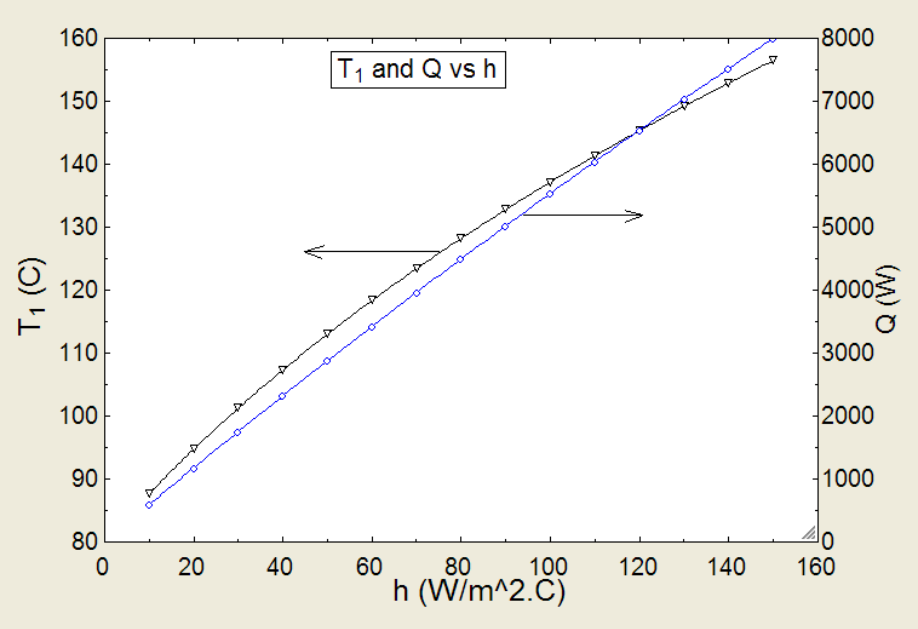
Now, plot the graph:



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"**Prob. 1B.13.** The wall of a furnace consists of 2 layers, one of fireclay of thickness 12.25 cm and the other of red brick of thickness 48 cm. Thermal cond. of fireclay is given by k1=(0.28+0.00023.T), W/m.C where T is in deg. C; k2=thermal cond. of red brick = 0.7 W/m.K. The inside surface temp of fireclay is 1150 C and the outside red brick wall temp is 55 C. Calculate the amount of heat lost per m^2 area of the furnace wall and the interface temp.[M.U. -April 1995]"

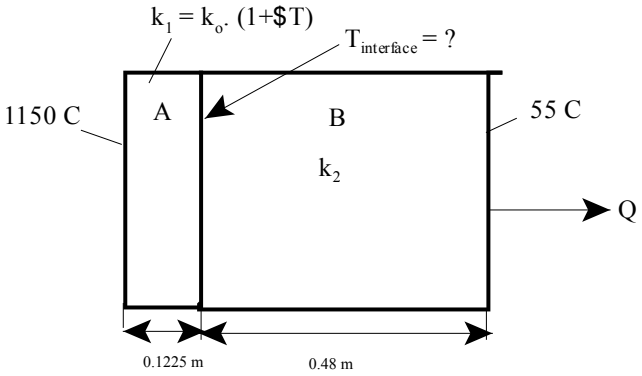

Fig.Prob.1B.13

Mathcad Solution:

Data:

T1 := 1150 C T3 := 55 C L1 := 0.1225 m L2 := 0.48 m k2 := 0.7 W/m.K

A := 1 m^2....assumed

Thermal cond. of fireclay varies linearly: k = k0 (1 + βT), where:

k_0 := 0.28 W/m.C β := 0.00023 1/C

Let T2 be the interface temperature.

For k varying linearly with T, we have:

km = k0 (1 + β. Tm) where Tm = mean temp = (T1 + T2)/2

Then, thermal resistance of that slab = L/(km . A)

Now, in steady state: heat transfer through fireclay layer = heat transfer through red brick layer.

Write the heat balance and then use the Solve Block of Mathcad to solve for T2:

Start with a guess value for T2:

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T2 := 1000 C...Guess value

Given

$$\frac{T1 - T2}{\left[\frac{L1}{k_0 \cdot \left(1 + \beta \cdot \frac{T1 + T2}{2}\right)}\right]} = \frac{T2 - T3}{\left(\frac{L2}{k2}\right)}$$

....here, LHS is the heat flow rate per sq. m area of the fireclay layer, and RHS is the heat flow rate per sq. m area of red brick layer.

Find(T2) = 774.252 i.e. T2 := 774.252 **C...Ans**

Heat flow rate, Q:

$$Q := \frac{T2 - T3}{\left(\frac{L2}{k2}\right)} \quad Q = 1.184 \cdot 10^3$$ **..W per m^2 area**

==========

"**Prob. 1B.14.** In a furnace, the gas temperature is maintained at 1300 C and the surrounding temperature is 30 C. The furnace walls are made of layer of refractory material of thickness 30 cm and thermal conductivity k1= (0.113+0.23324*10^{-3} T) W/m .C and a layer of bricks with thermal conductivity k2 = (0.113 + 0.023278 * 10^{-3} T) W/m.C. The heat transfer coefficient from gases to refractory walls is 30 W/m^2.C and that from brick to surrounding is 10 W/m^2 .C. What should be the thickness of the bricklayer of the setting so that the loss of heat to surrounding should not exceed 750W/m^2? [M.U. – April 1993]"

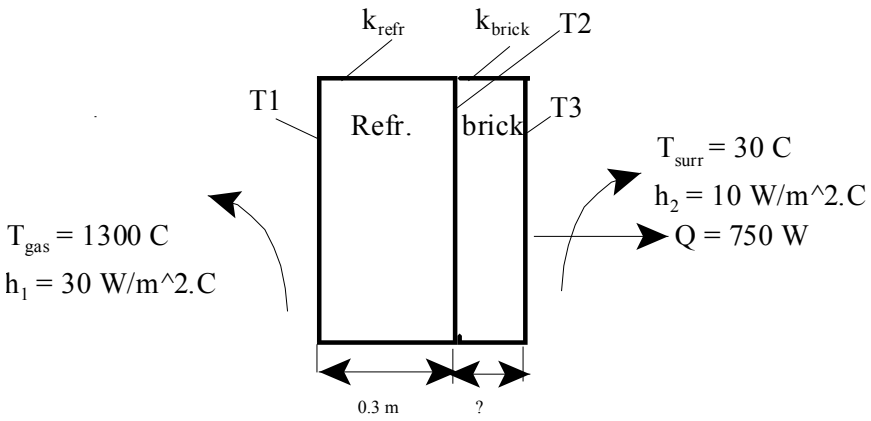

Fig.Prob.1B.14

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"EES Solution:"

"Data:"

T_gas = 1300 [C]
T_surr = 30 [C]
L_refr = 0.3 [m]

"k_refr = 0.113 * (1 +(0.23324e-03/0.113) * T)"
"i.e."

k_0_refr = 0.113
beta_refr = 0.23324e-03/0.113
h_1 = 30 [W/m^2-C]

"k_brick = 0.113 * (1 +(0.023278e-03/0.113) * T)"
"i.e."

k_0_brick = 0.113
beta_brick = 0.023278e-03/0.113
h_2 = 10 [W/m^2-C]

A = 1 [m^2] "..assumed"

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"Calculations:"

"Let the left surface temp of refractory be T_1, interface temp. T_2 and outer surface temp of brick layer be T_3"

R_refr = L_refr/(k_m_refr * A) "[C/W] … thermal resist of refr. layer, where k_m_refr is the mean thermal cond of refr. layer"

k_m_refr = k_0_refr * (1 + beta_refr * (T_1 + T_2)/2)

R_brick = L_brick/(k_m_brick * A) "[C/W] … thermal resist of brick layer, where k_m_brick is the mean thermal cond of brick layer"

k_m_brick = k_0_brick * (1 + beta_brick * (T_2 + T_3)/2)

R_conv1 = 1/(h_1 * A) "[C/W] … convection resist on the inside surface of refr. layer"

R_conv2 = 1/(h_2 * A) "[C/W] … convection resist on the outside surface of brick layer"

"Now, remembering that in steady state, heat transfer rate is same through each layer:"

Q = 750 [W]
Q = h_2 * A * (T_3 – T_surr) "[W] … heat transfer by convection from outer brick layer … finds T_3"
Q = h_1*A*(T_gas-T_1) "[W]… heat transfer by convection from hot gas to refr. layer … finds T_1"

Q = (T_2 – T_3)/R_brick "[W] … heat transfer through brick layer"
Q = (T_gas – T_2) / (R_conv1 + R_refr) "[W]… heat transfer through the inside convective + refractory layer"

"Verify:"

Q_verify = (T_2 – T_surr)/(R_brick + R_conv2) "[W] … heat transfer through the (brick layer + conv on RHS)…**must be equal to Q = 750 W**"

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Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]	$\beta_{brick} = 0.000206$ [1/C]	$\beta_{refr} = 0.002064$ [1/C]	$h_1 = 30$ [W/m^2-C]
$h_2 = 10$ [W/m^2-C]	$k_{0,brick} = 0.113$ [W/m-C]	$k_{0,refr} = 0.113$ [W/m-C]	$k_{m,brick} = 0.1212$ [W/m-C]
$k_{m,refr} = 0.3311$ [W/m-C]	$L_{brick} = 0.07924$ [m]	$L_{refr} = 0.3$ [m]	$Q = 750$ [W]
$Q_{verify} = 750$ [W]	$R_{brick} = 0.654$ [C/W]	$R_{conv1} = 0.03333$ [C/W]	$R_{conv2} = 0.1$
$R_{refr} = 0.906$ [C/W]	$T_1 = 1275$ [C]	$T_2 = 595.5$ [C]	$T_3 = 105$ [C]
$T_{gas} = 1300$ [C]	$T_{surr} = 30$ [C]		

Thus:

L_brick = 0.07924 m … thickness of brick layer… Ans.

T_1 = 1275 C …. Temp of left face of refractory layer… Ans.

T_2 = 595.5 C …. Temp of interface…Ans.

T_3 = 105 C …. Temp of right face of brick layer… Ans.

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"**Prob. 1B.15.** The inside surface of an insulating layer is at 270 C and the outside surface is dissipating heat by convection into air at 20 C. The insulation is 40 mm thick and has a thermal conductivity of 1.2 W/m.C. What is the minimum value of heat transfer coeff. at the outside surface, if the surface temperature should not exceed 70 C? Also calculate the rate of heat transfer. [VTU-7th Sem-B.E.-Dec.2007/Jan.2008]"

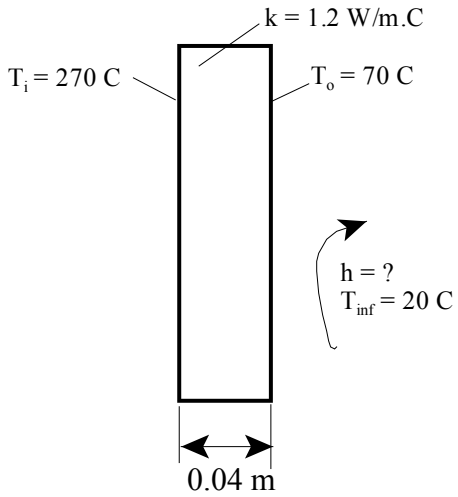

Fig.Prob.1B.15

Note that this is the same as Prob. 1B.1.

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But, we will solve this problem with EXCEL:

Following are the steps:

1. Set up the EXCEL worksheet, enter the data and name the cells:

	A	B	C	D	E
1					
2					
3		Data:			
4			T_i=	270	C
5			T_inf=	20	C
6			L_ins=	0.04	C
7			k_ins=	1.2	W/m.C
8			T_0=	70	C
9			A=	1	m^2
10		Find out Q and h:			

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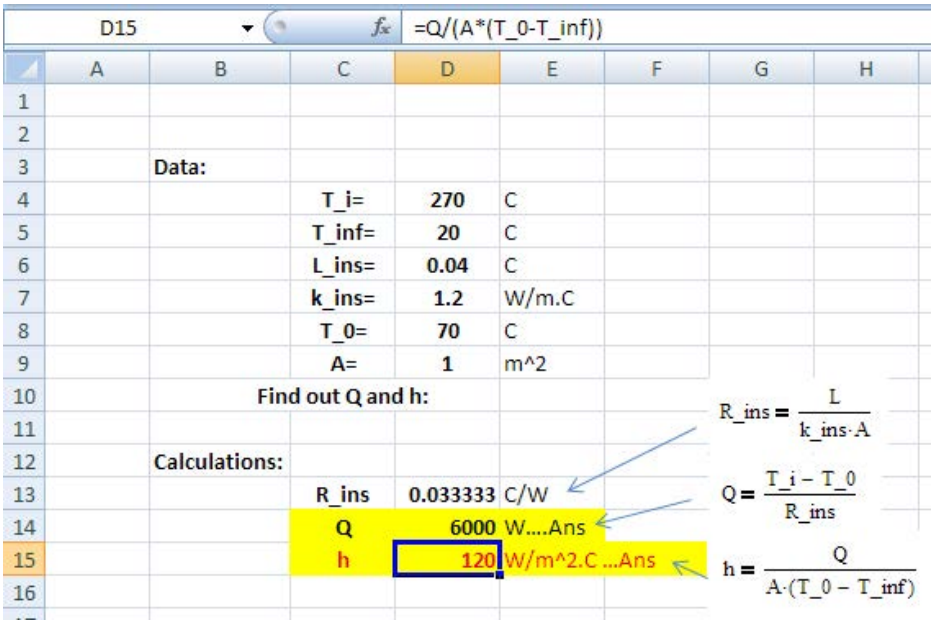
2. Enter the calculations. Formulas used are shown in the worksheet, for ready reference:



Thus: Q = 6000 W, and h = 120 W/m^2.C …. Ans.

3. **If the heat transfer coefficient h varies from 20 to 200 W/m^2.C, plot the variation of Q and the temp of surface on RHS, i.e. T_0:**

To find T_0 when h is given:

Apply the condition that in steady state, heat transfer by conduction should be equal to heat transfer by convection from the surface. i.e.

$$Q = \frac{T_i - T_0}{R_ins} = h \cdot A \cdot (T_0 - T_inf)$$

From the above eqn, we get:

$$T_0 = \frac{(h \cdot A \cdot T_inf \cdot R_ins + T_i)}{(h \cdot A \cdot R_ins + 1)}$$

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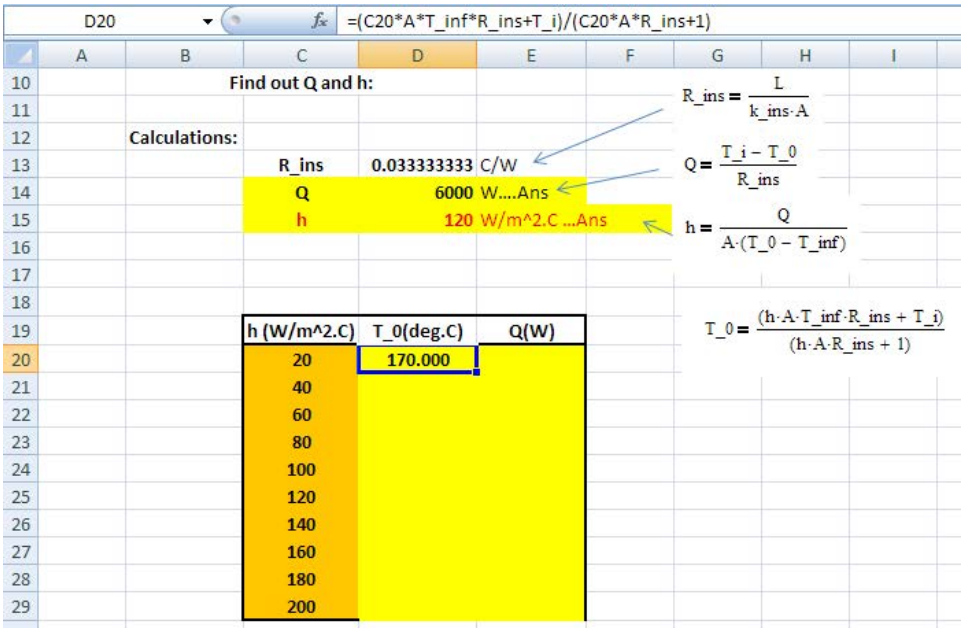
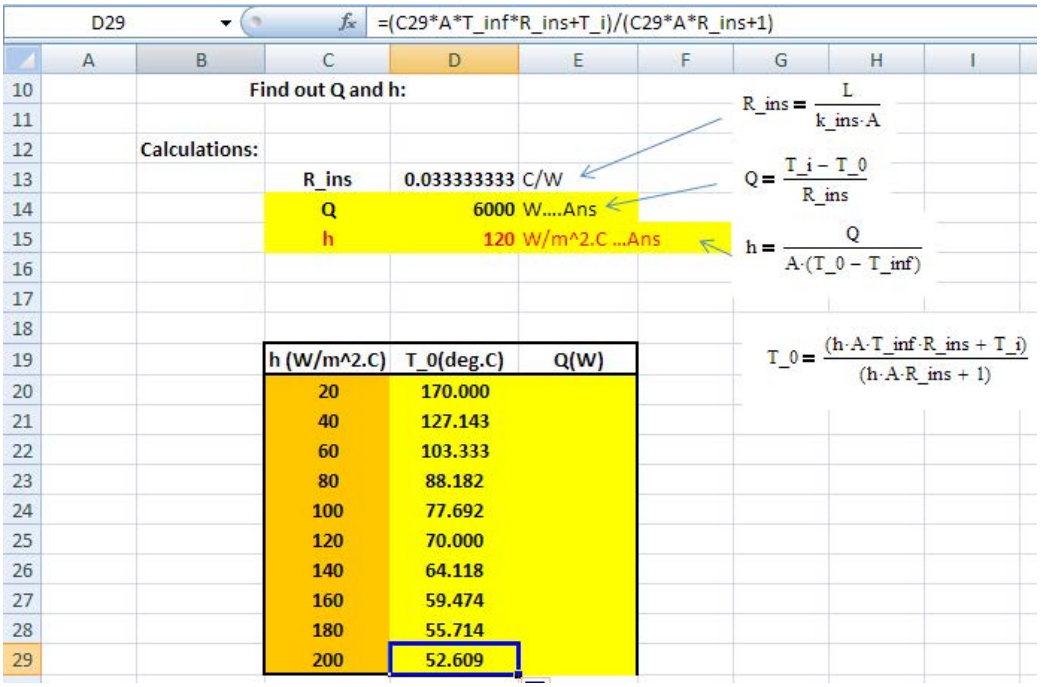
Now, prepare a Table with h varying from 20 to 200 W/m^2.C in one column, and T_0 and Q in the adjacent columns as shown:



4. Now, observe in the Formula bar the formula for T_0 in cell D20; here all terms, except 'h' are named cells (i.e. absolute reference), but for h, we write C20 so that it is relative reference.
5. Then, drag-copy cell D20 vertically up to cell D29 and all T_0 values are immediately calculated:



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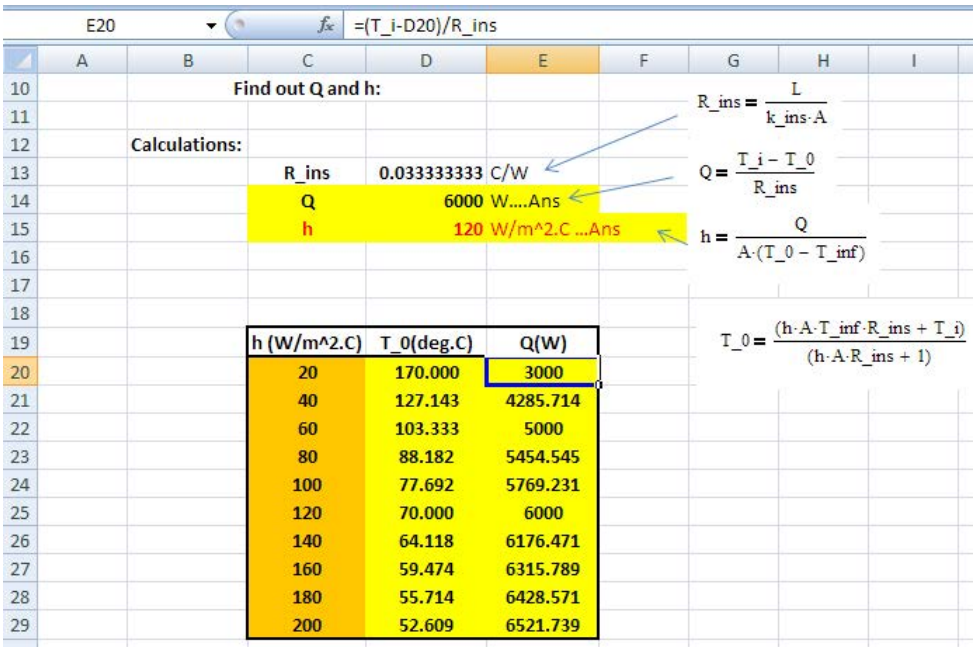
Observe in the Formula bar the eqn for T_0 in cell D29.

6. Now, enter the formula for Q in cell E20, with the T_0 as cell D20 in relative reference, and then drag-copy as earlier. The values of Q are immediately calculated:



E20 | =(T_i-D20)/R_ins

	A	B	C	D	E	F	G	H	I
10			Find out Q and h:						
11									
12		Calculations:							
13			R_ins	0.033333333	C/W				
14			Q	6000	W....Ans				
15			h	120	W/m^2.C ...Ans				
16									
17									
18									
19			h (W/m^2.C)	T_0(deg.C)	Q(W)				
20			20	170.000	3000				
21			40	127.143	4285.714				
22			60	103.333	5000				
23			80	88.182	5454.545				
24			100	77.692	5769.231				
25			120	70.000	6000				
26			140	64.118	6176.471				
27			160	59.474	6315.789				
28			180	55.714	6428.571				
29			200	52.609	6521.739				

$$R_{ins} = \frac{L}{k_{ins} \cdot A}$$

$$Q = \frac{T_i - T_0}{R_{ins}}$$

$$h = \frac{Q}{A \cdot (T_0 - T_{inf})}$$

$$T_0 = \frac{(h \cdot A \cdot T_{inf} \cdot R_{ins} + T_i)}{(h \cdot A \cdot R_{ins} + 1)}$$

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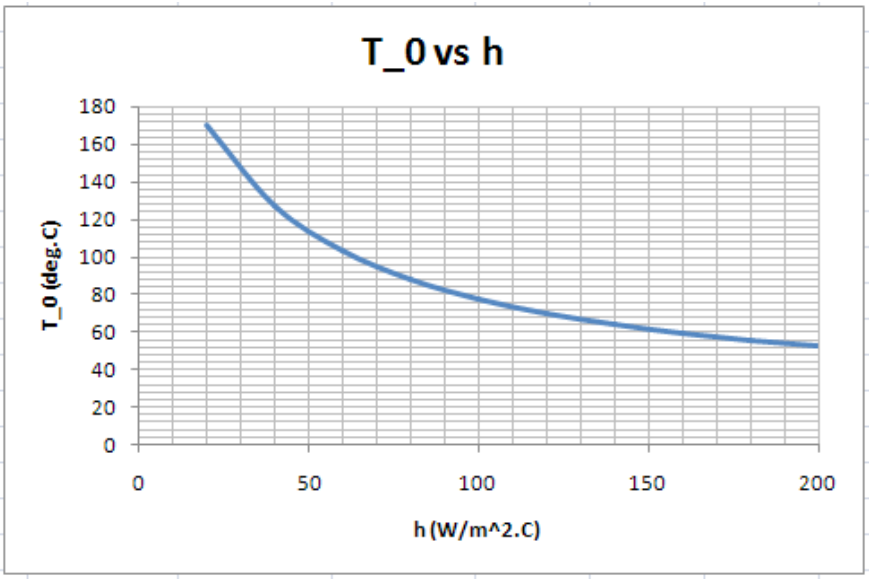
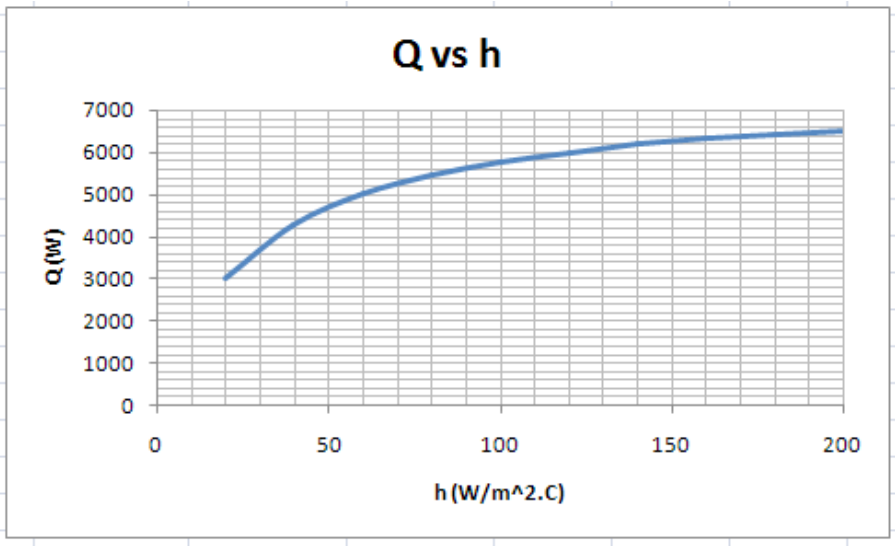
Observe in the Formula bar the eqn for Q in cell E20.

Compare the values for T_0 and Q obtained here with those obtained with EES earlier. They match very well.

7. Now, draw the plots in EXCEL:





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"**Prob. 1B.16.** A composite slab is made of 2 layers of different materials A and B such that layer A has conductivity as: k_A = 0.5 (1 + 0.08. T) and is 5 cm thick, while the layer B has conductivity of 24 W/m.K and is 2 cm thick. The exposed surface of layer A is insulated while that of the layer B is exposed to a fluid at 20 C where the heat transfer coeff is 30 W/m^2.K. If the temperature at the interface between the two layers is 80 C, find: (i) rate of heat flux from the slab to the fluid (ii) max. temp in the system, and (iii) the distance of a point at 85 C from the insulated surface. [VTU-6th Sem-B.E.-Jan./Feb. 2003]"

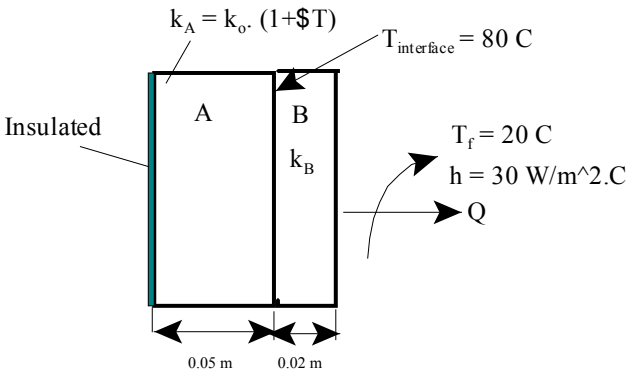

Fig.Prob.1B.16

Note that this is the same as Prob. 1B.12.

But, we will solve this problem with EXCEL:

Following are the steps:

1. Set up the EXCEL worksheet, enter the data and name the cells:

T_interface | fx | 80

	A	B	C	D	E
1					
2					
3		Data:			
4			k_0	0.5	
5			beta	0.08	
6			L_A	0.05	m
7			L_B	0.02	m
8			k_B	24	W/m.C
9			T_fluid	20	C
10			h	30	W/m^2.C
11			T_interface	80	C
12			A	1	m^2

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2. Considering slab B and convection from its RHS, Q = $(T_{interface} - T_{inf})/(R_{cond} + R_{conv})$. These preliminary calculations are done:

Q =(T_interface-T_fluid)/(R_B+R_conv)

	A	B	C	D	E	F
10			h	30	W/m^2.C	
11			T_interface	80	C	
12			A	1	m^2	
13						
14		Calculations:				
15		Cond. resist.	R_B	0.000833	C/W	
16		Conv. Resist.	R_conv	0.033333	C/W	
17		Heat tr.	Q	1756.098	W	

3. Now, Q is known. In steady state it is the same Q for slab A too. Max temp occurs on the insulated surface, since heat flows only to the right of insulated LHS. Let this temp be assumed as T1 = 200 C to start with. Later, we will apply heat balance and get the actual value of T1 using Goal Seek in EXCEL. And thermal resistance of slab A with linearly varying k is found out readily from:

$$R_A = \frac{L_A}{k_m \cdot A}$$

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where k_m is mean thermal conductivity, given by:

$$k_m = k_0 \cdot (1 + \beta \cdot T_m)$$

And, Tm is mean temp given by:

$$T_m = \frac{T1 + T_{interface}}{2}$$

Then, Q (which is already calculated) is also equal to:

$$Q = \frac{T1 - T_{interface}}{R_A}$$

These calculations are shown below:

D23 f_x =Q-Q_A

	A	B	C	D	E	F	G
10			h	30	W/m^2.C		
11			T_interface	80	C		
12			A	1	m^2		
13							
14		Calculations:					
15		Cond. resist.	R_B	0.000833	C/W		
16		Conv. Resist.	R_conv	0.033333	C/W		
17		Heat tr.	Q	1756.098	W		
18		For slab A:	T_1	200	C....assumed		
19			T_m	140	C		
20			k_m	6.1	W/m.C		
21			R_A	0.008197	C/W		
22			Q_A	14640	W		
23		Heat balance:	Q-Q_A	-12883.9			
24							

$$R_A = \frac{L_A}{k_m \cdot A}$$

$$Q_A = \frac{T1 - T_{interface}}{R_A}$$

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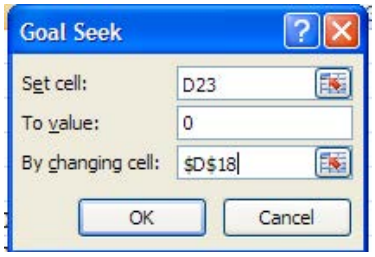
4. In steady state, D23 should be equal to zero. Now, it is not zero because we have assumed a trial value of 200 C for T1. Apply Goal Seek to make cell D23 zero, by varying T1 i.e. cell D18:

Go to Data – What If Analysis – Goal Seek:

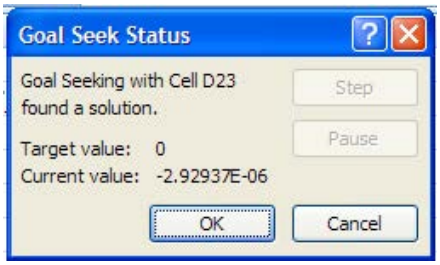
5. Click on Goal Seek. We get the pop up shown below:

6.



Here we have filled it up: Set cell D23, To value: zero, By changing cell: D18.

Click OK, and we get the message:



Press OK to accept it. Note that D23 has converged to 2.92937E-06 (not *exactly* equal to zero, but good enough for us).

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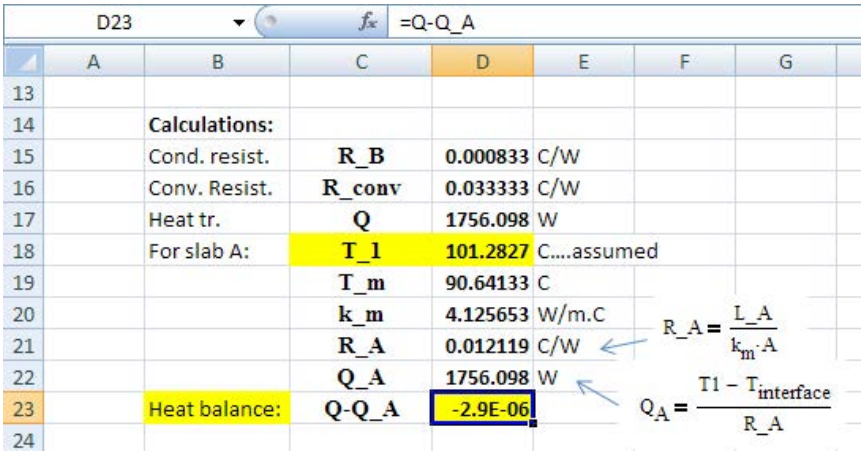
7. We get the final result:



Thus: T1 = 101.283 C…..Ans. and, Q = 1756.098 W/m^2 … Ans.
Observe that all related cells have got updated.

8. To find out the distance from LHS at which temp is 85 deg.C:

LHS is at 101.283 C, Q is 1756.098 W/m^2. Let the distance be x. Then, we have to calculate the mean temp, and then the mean thermal conductivity, and then the thermal resistance.

Then put: Q = (T1 – 85) / Thermal resist.

$$Q = \frac{T1 - 85}{\frac{x}{k_{mean} \cdot A}}$$

$$k_mean = k_0 \cdot (1 + \beta \cdot T_mean)$$

$$T_mean = \frac{T1 + 85}{2}$$

$$x = \frac{(T1 - 85) \cdot k_{mean} \cdot A}{Q}$$

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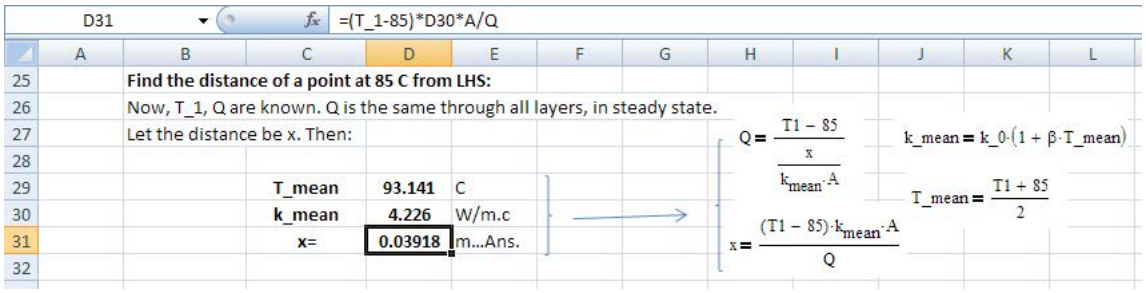
Do this calculation in EXCEL:



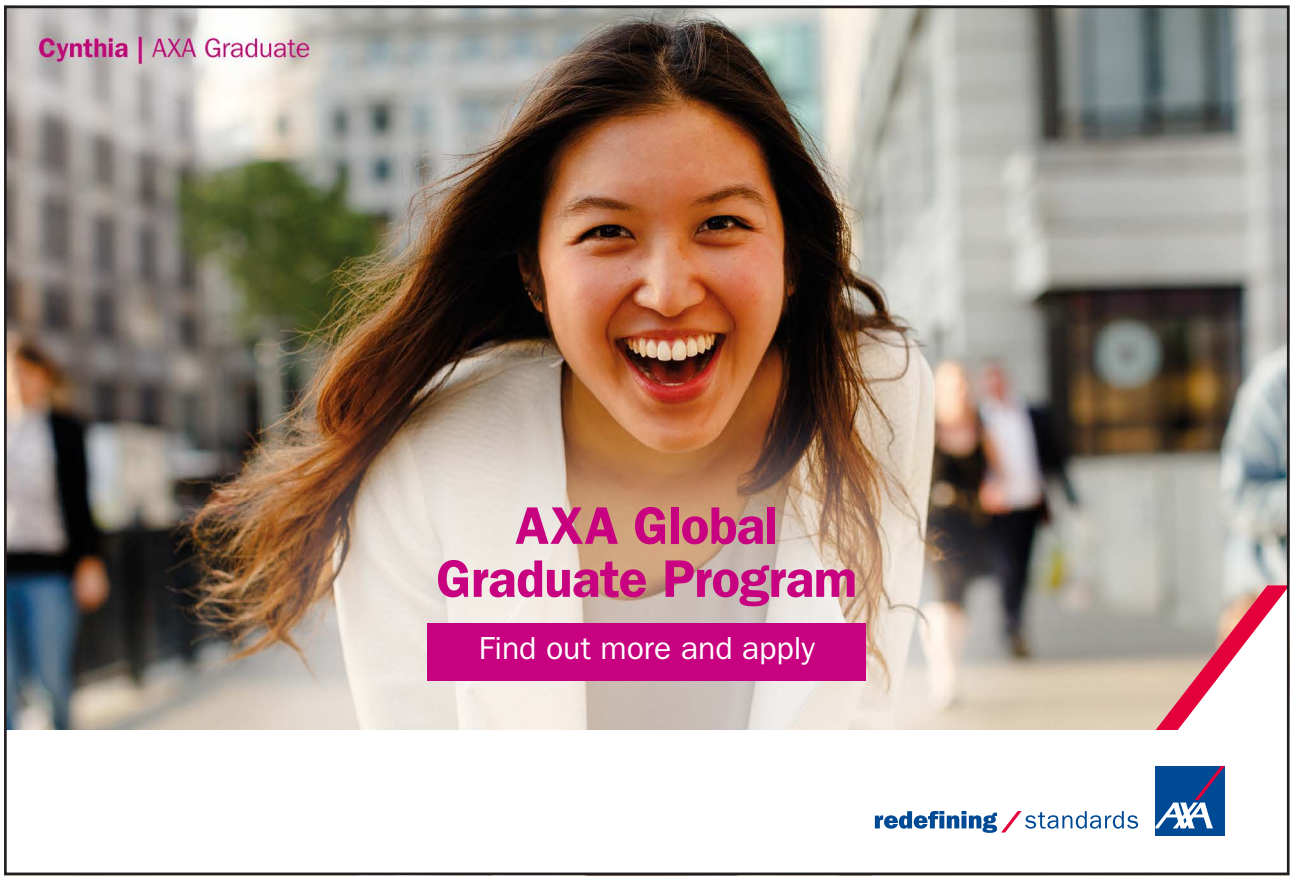
Thus: x = 0.03918 m

Note that these values match with results obtained with EES earlier, for Prob. 1B.12.

9. **To plot Temp vs x for slab A:**

Let the temp be Tx at any x. Then, we have:

$$Q = \frac{T1 - Tx}{x} \cdot A \cdot k_0 \cdot \left[1 + \beta \cdot \frac{(T1 + Tx)}{2}\right]$$



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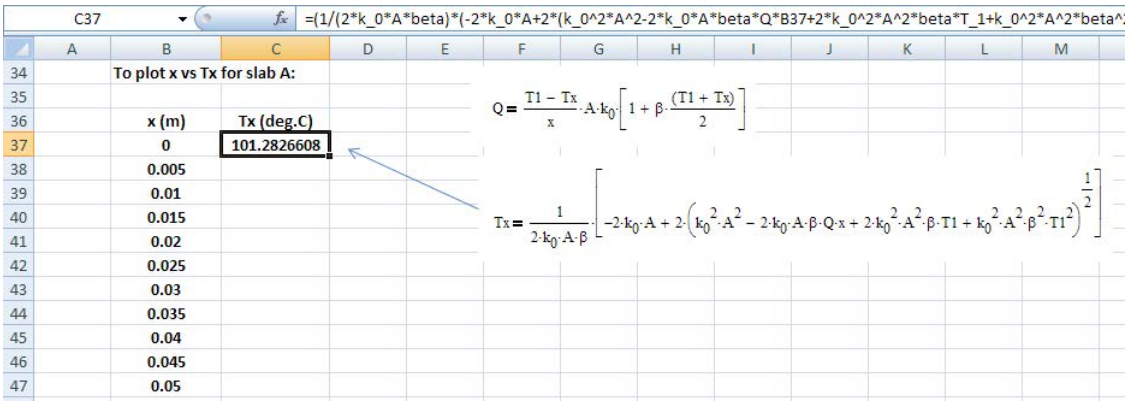
Solving for Tx:

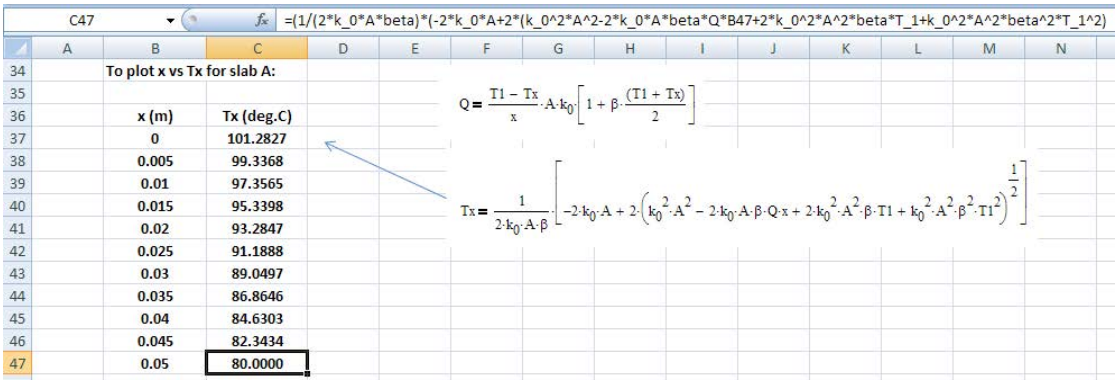
$$Tx := \frac{1}{2 \cdot k_0 \cdot A \cdot \beta} \cdot \left[-2 \cdot k_0 \cdot A + 2 \cdot \left(k_0^{\,2} \cdot A^2 - 2 \cdot k_0 \cdot A \cdot \beta \cdot Q \cdot x + 2 \cdot k_0^{\,2} \cdot A^2 \cdot \beta \cdot T1 + k_0^{\,2} \cdot A^2 \cdot \beta^2 \cdot T1^2 \right)^{\frac{1}{2}} \right]$$

Use this eqn in EXCEL and first construct a Table of Tx vs x :



Note that cell C37 contains the formula for Tx. It is verified that at x = 0, we have Tx = 101.2827 C, as it should be. Also, at x = 0.05, Tx should be 80 C.

Now, drag-copy the cell C37 up to cell C47. All values for Tx are immediately calculated:



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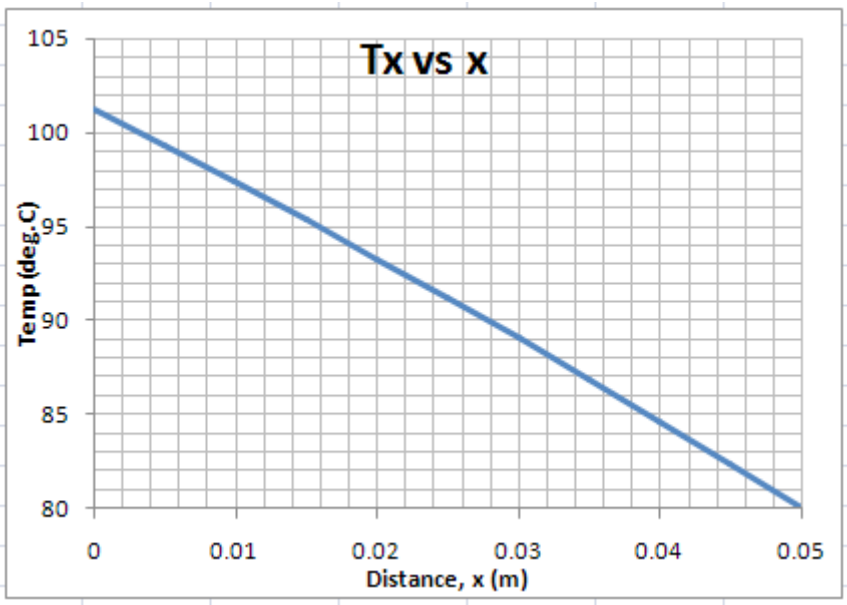
Now, plot this in EXCEL:



10. **To plot_1 and Q against h:**

a) First prepare a Table as shown:

	J	K	L
	h (W/m^2.C)	T1(deg.C)	Q(W)
	10		
	20		
	30		
	40		
	50		
	60		
	70		
	80		
	90		
	100		
	110		
	120		
	130		
	140		
	150		

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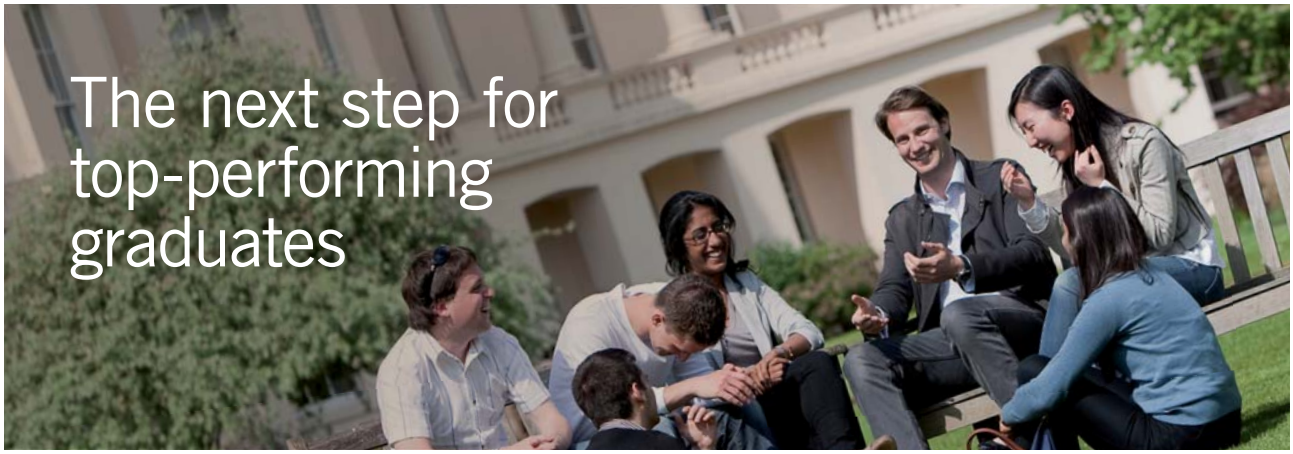
b) Now, write a VBA code to read these values of h, and then apply Goal Seek to get T_1. ***(Refer to Prob. 1A.5 to see the VBA code for that problem).*** When T_1 is found out, immediately Q is also updated. Then copy values of T_1 (i.e. cell D18) and Q (i.e. cell D17) in to the Table.

Following is the VBA code:

```
Sub Find_T1_and_Q()
'
' Find_T1_and_Q Macro
' Finds T1 and Q for different values of h
'
' Keyboard Shortcut: Ctrl+Shift+R
'

Dim i As Integer

 For i = 0 To 14
 Range("D10") = Cells(14 + i, 10)
    Range("D23").Select
    Range("D23").GoalSeek Goal:=0, ChangingCell:=Range("D18")
    Cells(14 + i, 11) = Range("D18")
    Cells(14 + i, 12) = Range("D17")
 Next i
End Sub
```



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In the above code:

1st line: declares a Subroutine with its name as Find_T1_and_Q
2nd and 3rd lines: Explains what this Macro does
4th line: gives the keyboard shortcut
5th line: Dimension statement, says i (a counter in For … Next loop), is an integer
6th line: Starts the For…Next loop, i varies from 0 to 14 since there are 15 lines in Table.
7th line: sets the cell D10 in worksheet (i.e. h) to h value in cell J14 (i.e. the first line of the Table)
8th and 9th lines: Goal Seek on cell D23, to make it zero, by changing cell D18.
10th line and 11th lines: Values of T1 and Q are copied into the respective cells in the Table.
12th line: continues the For .. Next loop to next value of i
13th line: End statement of Subroutine.

c) Now, press Ctrl+Shift+R to run the Macro. Immediately the Table is filled up:

D23 =Q-Q_A

	B	C	D	E	J	K	L
10		h	150	W/m^2.C			
11		T_interface	80	C			
12		A	1	m^2			
13					h (W/m^2.C)	T1(deg.C)	Q(W)
14	Calculations:				10	87.719	595.041
15	Cond. resist.	R_B	0.000833	C/W	20	94.771	1180.328
16	Conv. Resist.	R_conv	0.006667	C/W	30	101.283	1756.098
17	Heat tr.	Q	8000	W	40	107.344	2322.581
18	For slab A:	T_1	156.4859	C....assumed	50	113.024	2880.000
19		T_m	118.243	C	60	118.373	3428.571
20		k_m	5.229719	W/m.C	70	123.432	3968.504
21		R_A	0.009561	C/W	80	128.235	4500.000
22		Q_A	8000	W	90	132.808	5023.256
23	Heat balance:	Q-Q_A	1.17E-06		100	137.174	5538.462
24					110	141.353	6045.802
25					120	145.360	6545.455
26					130	149.210	7037.594
27					140	152.915	7522.388
28					150	156.486	8000.000

$$R_A = \frac{L_A}{k_m \cdot A}$$

$$Q_A = \frac{T1 - T_{interface}}{R_A}$$

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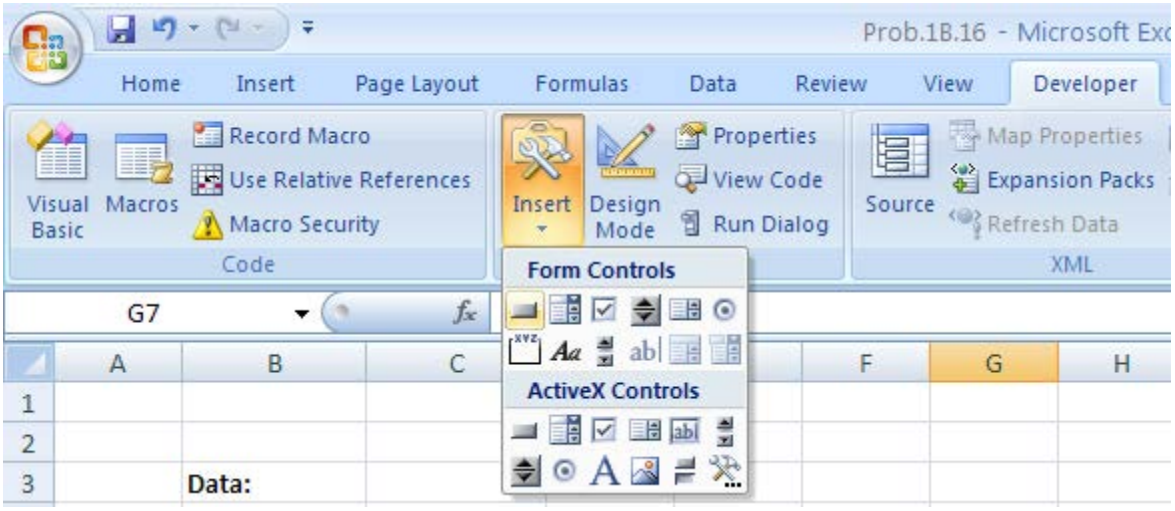
d) It is convenient *to assign this Macro to a Form control button* on the worksheet itself. Then, you will have to just click the button to run the Macro and you need not remember the key board short cut (i.e. Ctrl+Shift+R in this case). To do that:

Go to Developer-Insert-Form controls:



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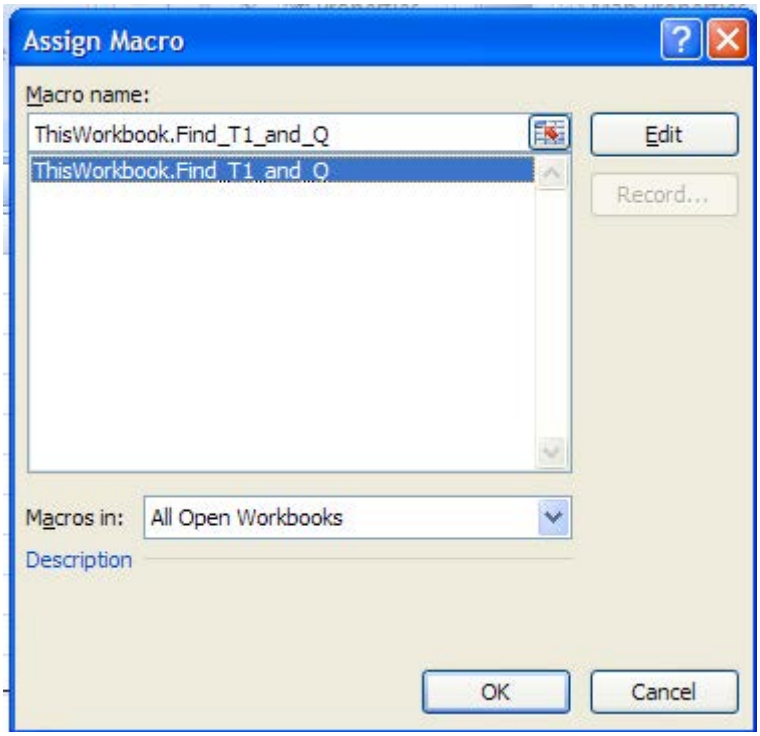
And, click on the first button in top row:

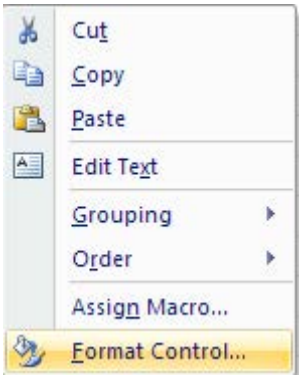
Cursor changes to a + and draw a rectangle in the worksheet and adjust its size:

Immediately following pop up also appears to assign this button to the Macro already written.



Click OK to finish.

Now, right click on the button, and you get:



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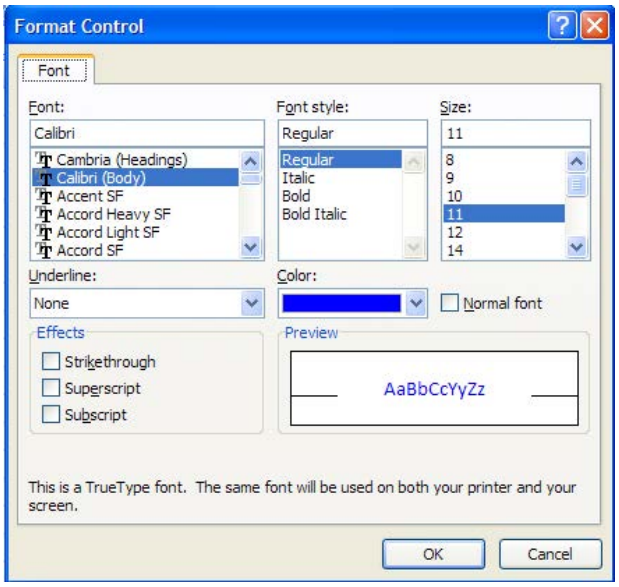
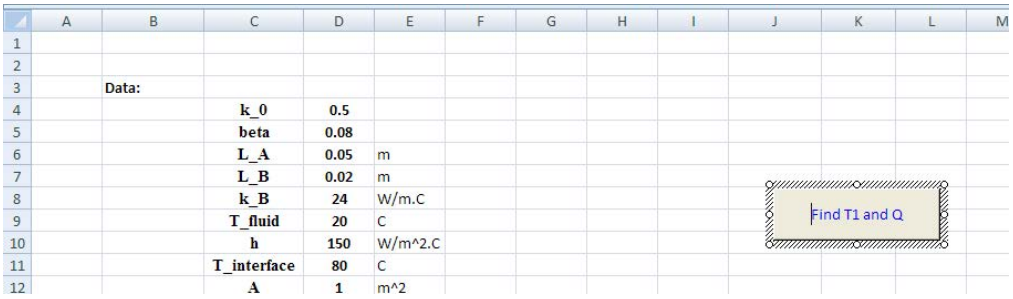
Press Format control:

You get:



And edit the words as shown, change the color to blue, and click OK.

Now, you have a button to run the Macro:



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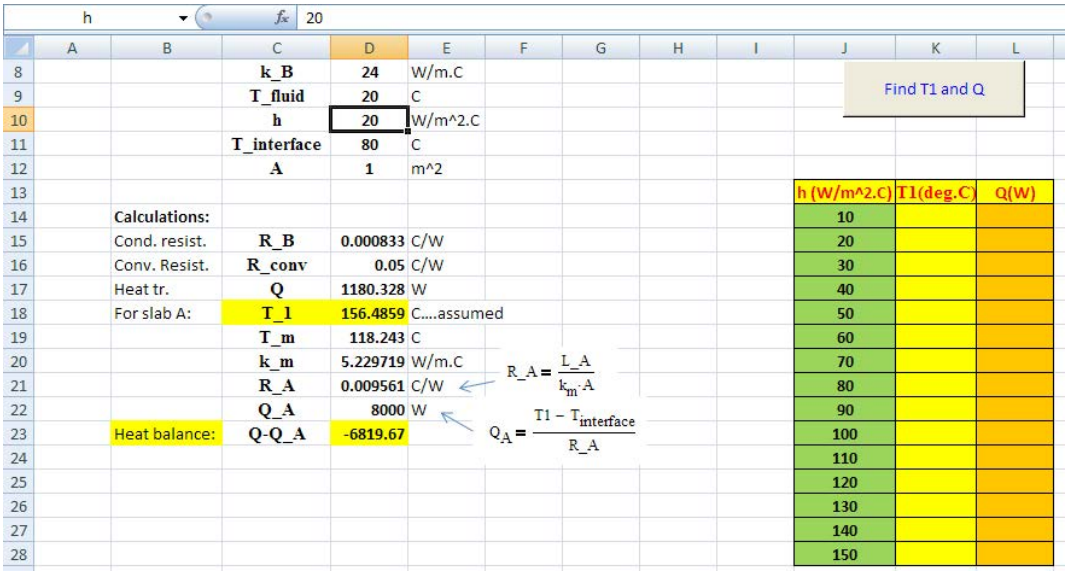
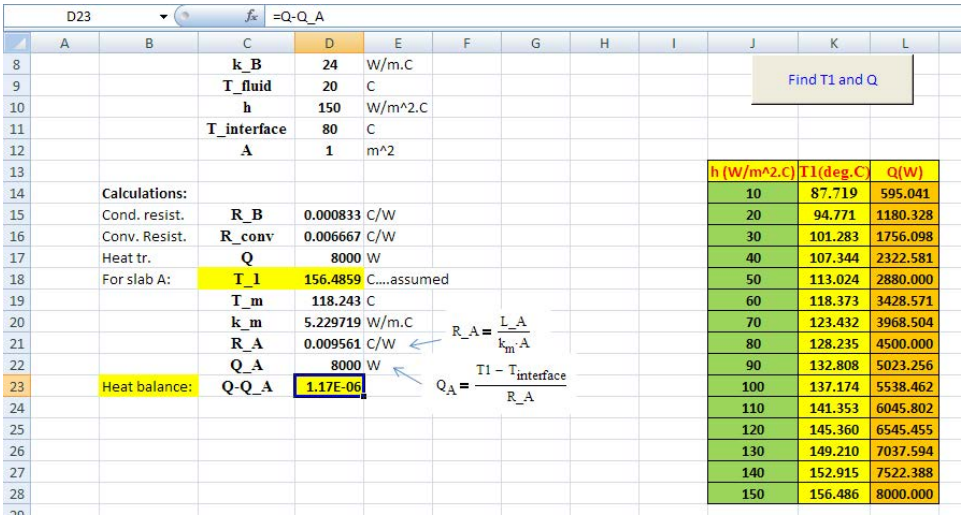
To demonstrate the use of this button to run the Macro, clear the columns containing the values of T_1 and Q, change cell D10 for h to 20. Then you get:



Now, click on the button and immediately, the Table is filled up:



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e) Compare these values with those obtained with EES earlier (See Prob. 1B.12)

1..15	h [W/m2-C]	T_1 [C]	Q [W]
Run 1	10	87.72	595
Run 2	20	94.77	1180
Run 3	30	101.3	1756
Run 4	40	107.3	2323
Run 5	50	113	2880
Run 6	60	118.4	3429
Run 7	70	123.4	3969
Run 8	80	128.2	4500
Run 9	90	132.8	5023
Run 10	100	137.2	5538
Run 11	110	141.4	6046
Run 12	120	145.4	6545
Run 13	130	149.2	7038
Run 14	140	152.9	7522
Run 15	150	156.5	8000

The values match very well.

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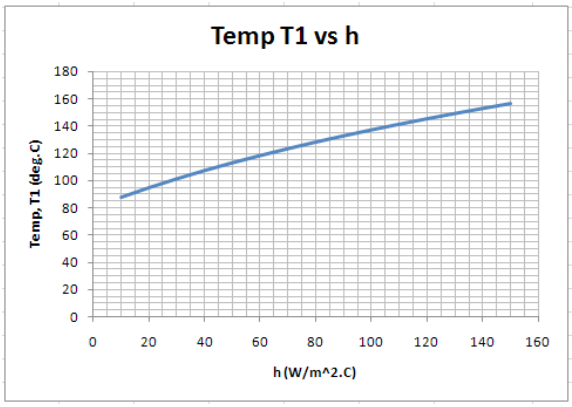
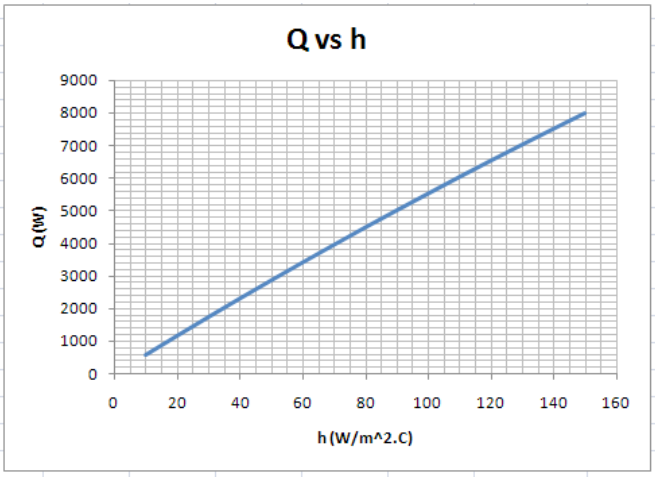
f) Now, draw the graphs of T_1 vs h and Q vs h, with EXCEL:





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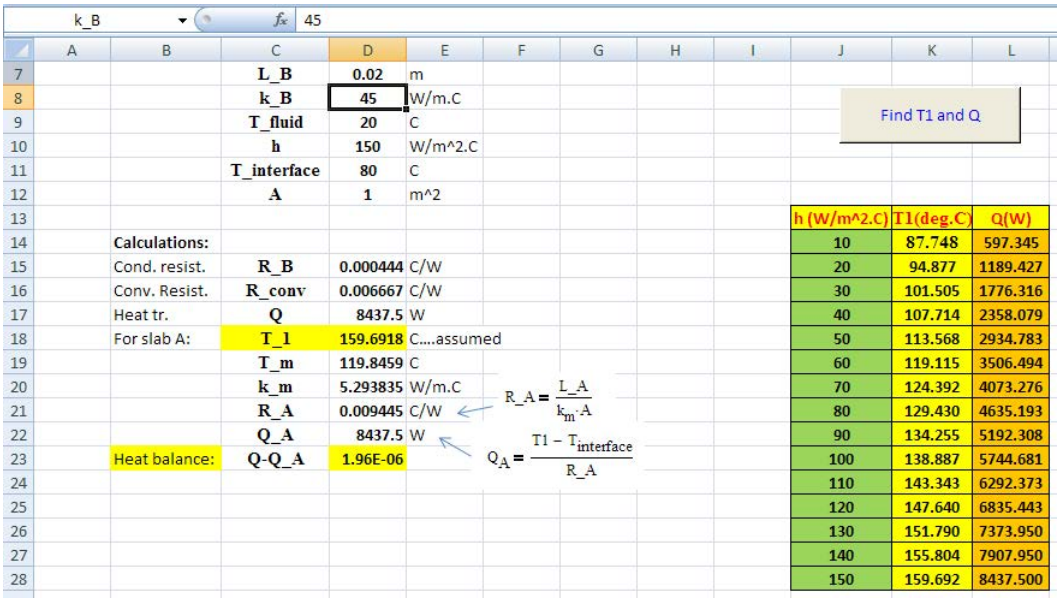
11. ***Advantage of spreadsheet*** is evident if you want to find T1 and Q with another value of, say, k_B = 45 W/m.C. Simply change k_B, and run the Macro. Of course, this assumes that you change h values as shown in the Table:



		L_B	0.02	m	
		k_B	45	W/m.C	
		T_fluid	20	C	
		h	150	W/m^2.C	
		T_interface	80	C	
		A	1	m^2	
	Calculations:				
	Cond. resist.	R_B	0.000444	C/W	
	Conv. Resist.	R_conv	0.006667	C/W	
	Heat tr.	Q	8437.5	W	
	For slab A:	T_1	159.6918	C....assumed	
		T_m	119.8459	C	
		k_m	5.293835	W/m.C	
		R_A	0.009445	C/W	
		Q_A	8437.5	W	
	Heat balance:	Q-Q_A	1.96E-06		

Find T1 and Q

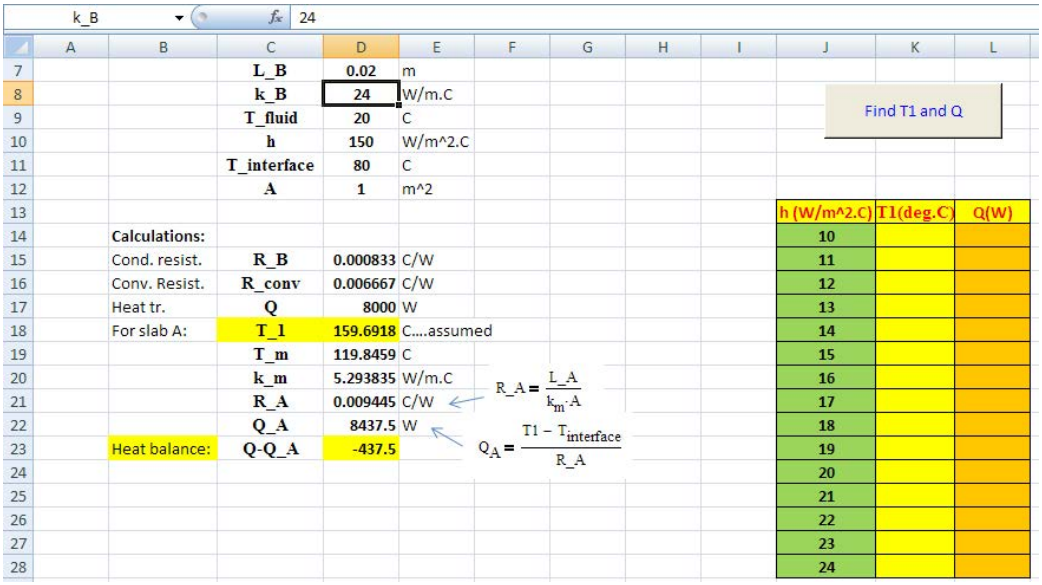
h (W/m^2.C)	T1(deg.C)	Q(W)
10	87.748	597.345
20	94.877	1189.427
30	101.505	1776.316
40	107.714	2358.079
50	113.568	2934.783
60	119.115	3506.494
70	124.392	4073.276
80	129.430	4635.193
90	134.255	5192.308
100	138.887	5744.681
110	143.343	6292.373
120	147.640	6835.443
130	151.790	7373.950
140	155.804	7907.950
150	159.692	8437.500

$$R_A = \frac{L_A}{k_m \cdot A}$$

$$Q_A = \frac{T1 - T_{interface}}{R_A}$$

Observe how all values have changed.

12. If you need to run the program for some other values of h, say from h = 10 to 24 W/m^2.C, enter them in the Table : (k_B has been reset to 24)



		L_B	0.02	m	
		k_B	24	W/m.C	
		T_fluid	20	C	
		h	150	W/m^2.C	
		T_interface	80	C	
		A	1	m^2	
	Calculations:				
	Cond. resist.	R_B	0.000833	C/W	
	Conv. Resist.	R_conv	0.006667	C/W	
	Heat tr.	Q	8000	W	
	For slab A:	T_1	159.6918	C....assumed	
		T_m	119.8459	C	
		k_m	5.293835	W/m.C	
		R_A	0.009445	C/W	
		Q_A	8437.5	W	
	Heat balance:	Q-Q_A	-437.5		

Find T1 and Q

h (W/m^2.C)	T1(deg.C)	Q(W)
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		

$$R_A = \frac{L_A}{k_m \cdot A}$$

$$Q_A = \frac{T1 - T_{interface}}{R_A}$$

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And, press the button to run the Macro. We get:

Find T1 and Q

h (W/m^2.C)	T1(deg.C)	Q(W)
10	87.719	595.041
11	88.452	654.005
12	89.178	712.871
13	89.898	771.641
14	90.612	830.313
15	91.319	888.889
16	92.021	947.368
17	92.717	1005.752
18	93.407	1064.039
19	94.092	1122.231
20	94.771	1180.328
21	95.445	1238.329
22	96.113	1296.236
23	96.777	1354.047
24	97.435	1411.765

Thus, EXCEL when coupled with the power of VBA programming, is a very powerful tool to solve heat transfer problems.

==========

"**Prob. 1B.17.** In a furnace, the gas temperature is maintained at 1300 C and the surrounding temperature is 30 C. The furnace walls are made of layer of refractory material of thickness 30 cm and thermal conductivity k1= (0.113+0.23324*10^{-3} T) W/m .C and a layer of bricks with thermal conductivity k2 = (0.113 + 0.023278 * 10^{-3} T) W/m.C. The heat transfer coefficient from gases to refractory walls is 30 W/m^2.C and that from brick to surrounding is 10 W/m^2 .C. What should be the thickness of the bricklayer of the setting so that the loss of heat to surrounding should not exceed 750W/m^2? [M.U. – April 1993]"

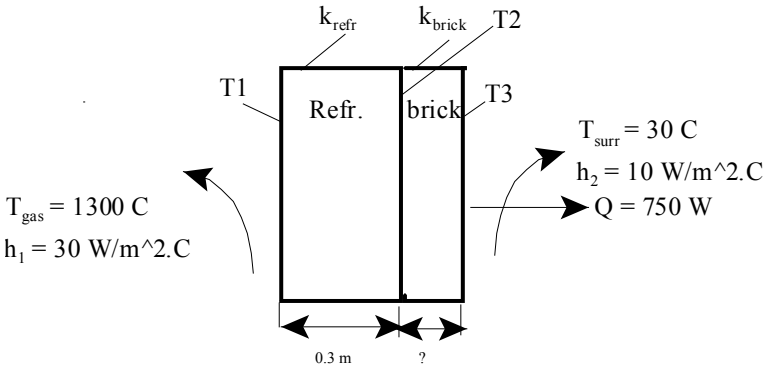

Fig.Prob.1B.17

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Note: This is the same as Problem 1B.14. solved with EES.

But, we will solve this problem in EXCEL:

Here, thermal cond. of both the slabs vary linearly with temp. i.e. variation is of the form:

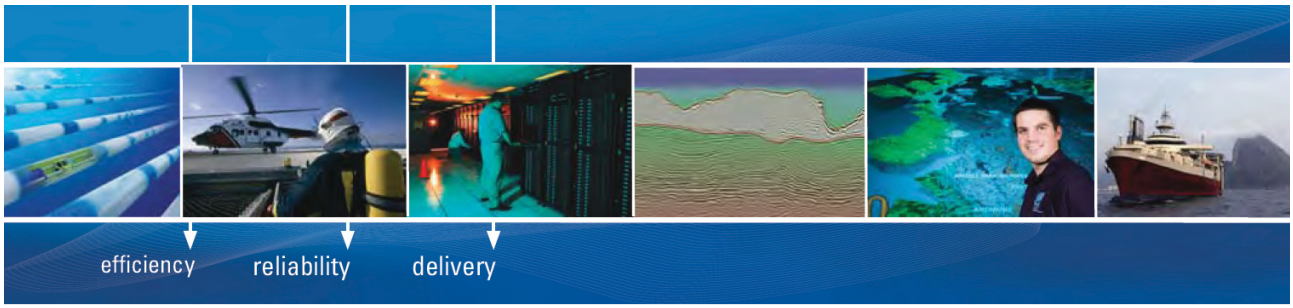
$$k = k_0 \cdot (1 + \beta \cdot T)$$

Then, in steady state, with no internal heat generation, the thermal rsistance of each slab is given by:

$$R_slab = \frac{L_slab}{k_m \cdot A} \qquad \text{where}$$

$$k_m = k_0 \cdot (1 + \beta \cdot T_m)$$

k_m is the mean thermal conductivity, Tm is the average of the temperatures on the left and right faces, for each slab.



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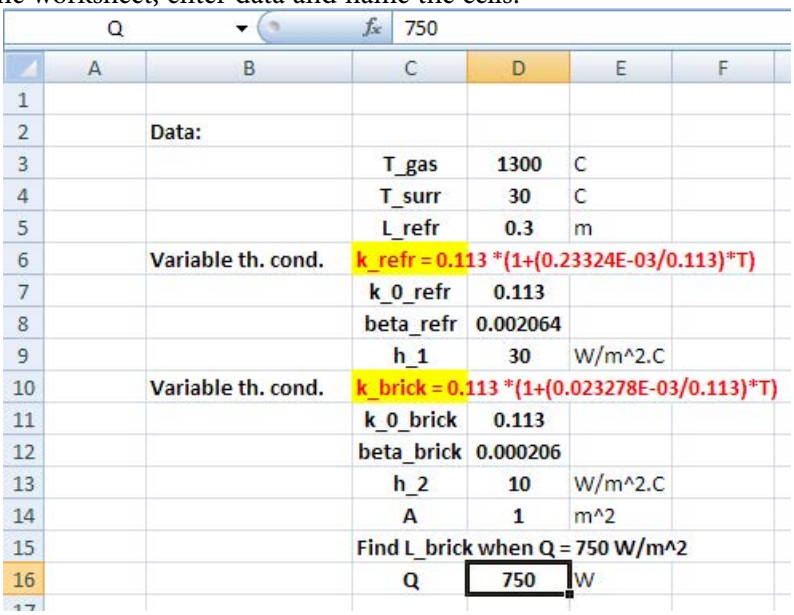
Following are the steps while solving in EXCEL:

1. Set up the worksheet, enter data and name the cells:



	A	B	C	D	E	F
1						
2		Data:				
3			T_gas	1300	C	
4			T_surr	30	C	
5			L_refr	0.3	m	
6		Variable th. cond.	k_refr = 0.113 *(1+(0.23324E-03/0.113)*T)			
7			k_0_refr	0.113		
8			beta_refr	0.002064		
9			h_1	30	W/m^2.C	
10		Variable th. cond.	k_brick = 0.113 *(1+(0.023278E-03/0.113)*T)			
11			k_0_brick	0.113		
12			beta_brick	0.000206		
13			h_2	10	W/m^2.C	
14			A	1	m^2	
15			Find L_brick when Q = 750 W/m^2			
16			Q	750	W	

2. Enter the calculations: Referring to the above fig, T1 and T2 (i.e. the temps at the left face and right face of the combined slab) are calculated in a straight forward manner by applying the Newton's Law:

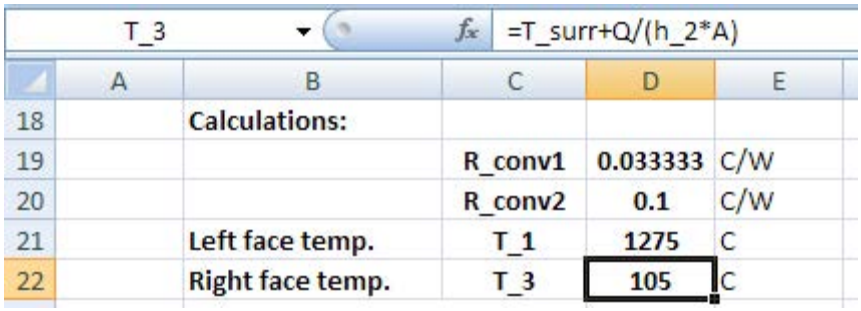
$$Q = h \cdot A \cdot \Delta T$$

i.e.

$$Q = h_1 \cdot A \cdot (T_gas - T_1) \quad \text{...finds } T_1$$

And,

$$Q = h_2 \cdot A \cdot (T_3 - T_surr) \quad \text{...finds } T_3$$



	A	B	C	D	E
18		Calculations:			
19			R_conv1	0.033333	C/W
20			R_conv2	0.1	C/W
21		Left face temp.	T_1	1275	C
22		Right face temp.	T_3	105	C

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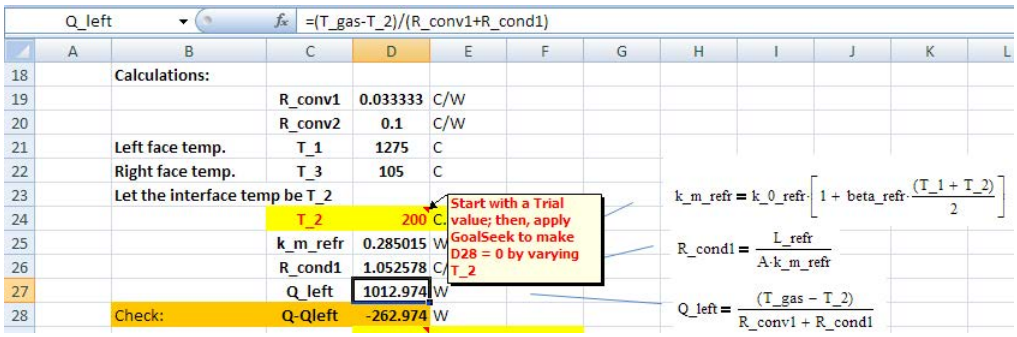
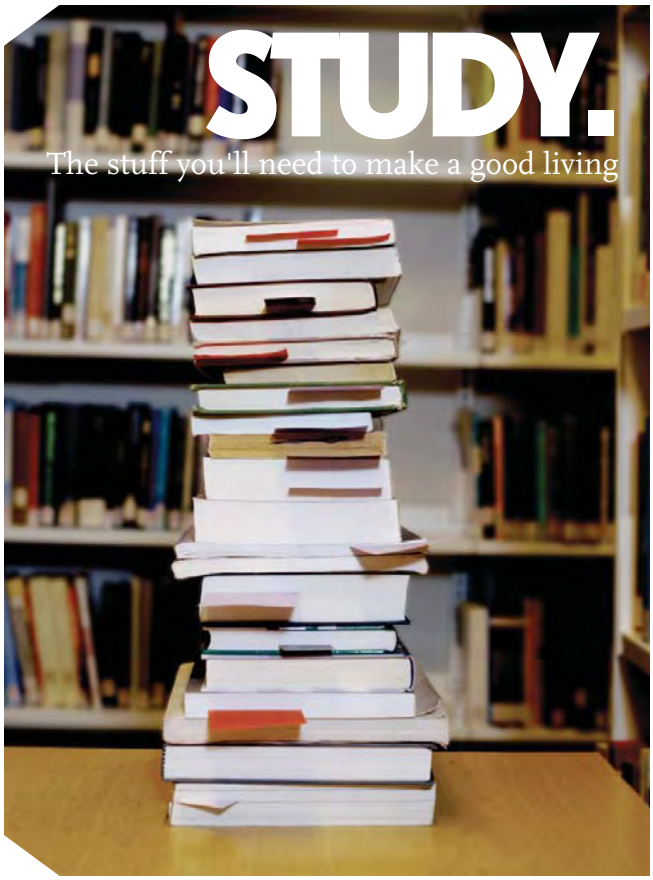
3. Continuing, let the interface temp be T_2. Since we are going to use iteration in EXCEL to find out T_2, start with a guess value for T_2, say T_2 = 200, and proceed with the calculations.



In the above fig, starting from left side, we have found Q_left (cell D27, see the formula in formula bar) by taking the convective resistance on the left surface and the conductive resistance of refractory.

Note that we have included a comment in cell D24 about the procedure to find T_2.



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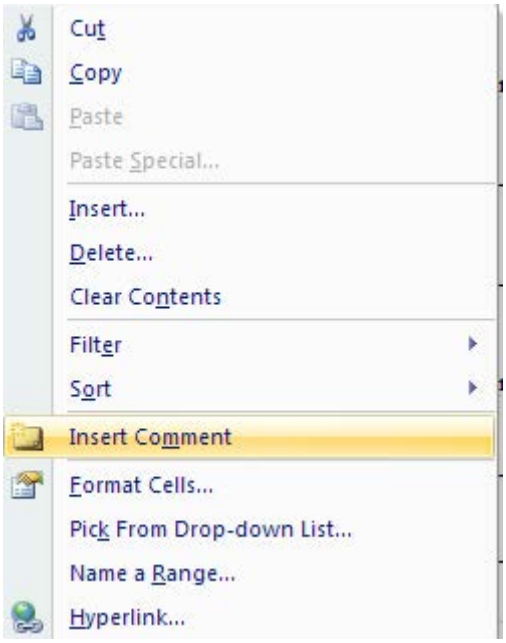
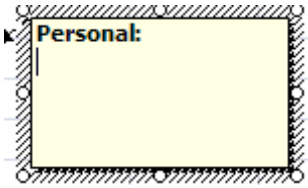
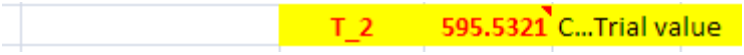
To insert comment in a cell: Locate the cursor on the cell and right click on the mouse. WE get:



Click on Insert Comment. We see:



Now, write the comment in the box. You can format it for making bold/italics, changing color etc. A cell having a comment attached to it is indicated by a *small triangle* at its right corner, as shown below:



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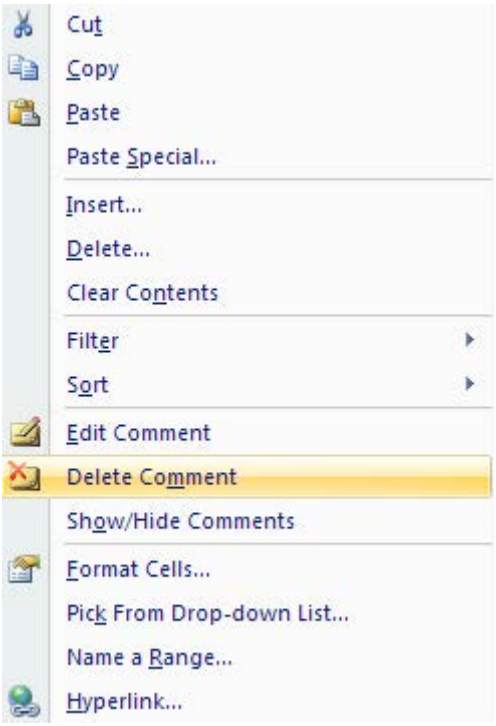
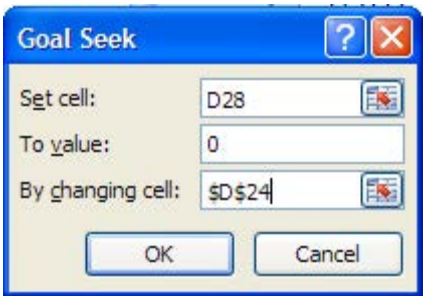
You can delete the comment in a similar manner, by right clicking the mouse in the cell to which a comment is attached:



And click on Delete Comment, and the comment is deleted.

Since Q is the same through all layers in steady state, we apply Goal seek to make (Q-Q_left) to zero by changing T_2. This is shown below:

4. Click on Data-What If Analysis-Goal Seek, and we get:



We have Set cell: D28
To value: zero
By changing cell: D24 (i.e. T_2)
Click OK, and get:

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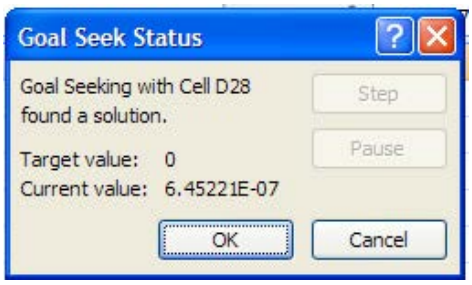

Accept the values by clicking OK, and, the values have changed to:

Q_Qleft =Q-D27

	A	B	C	D	E	F	G
21		Left face temp.	T_1	1275	C		
22		Right face temp.	T_3	105	C		
23		Let the interface temp be T_2					
24			T_2	595.5321	C...Trial value		
25			k_m_refr	0.331141	W/m.C		
26			R_cond1	0.905957	C/W		
27			Q_left	750	W		
28		Check:	Q-Qleft	6.45E-07	W		

Thus: T_2 = 595.5321 C….Ans.

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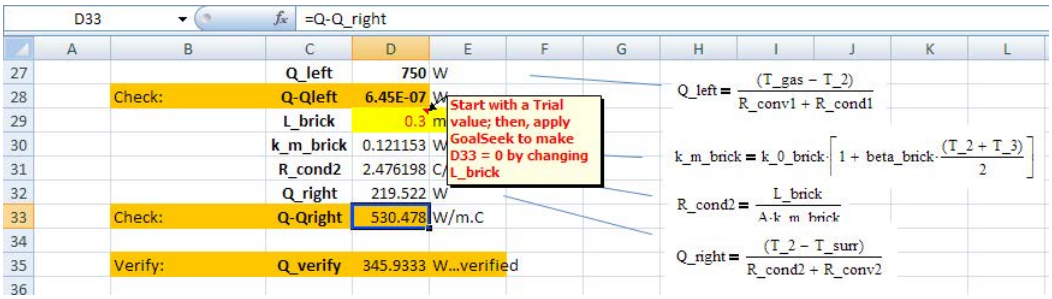
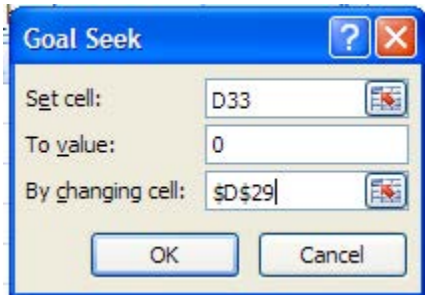
5. Next, to find L_brick, the thickness of brick layer on the right: Again, we start with a guess value for L_brick and apply the condition that Q is the same for combination of:(conduction through the brick and convection from the right side surface):

$$Q_right = \frac{(T_2 - T_surr)}{R_cond2 + R_conv2}$$

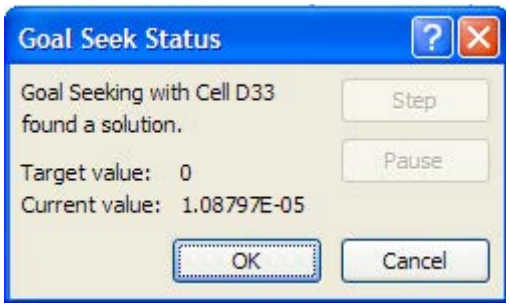


Again, for clarity, a cell note has been inserted in cell D29.

Now, apply Goal Seek to make D33 zero by changing cell D29:



And, we get:



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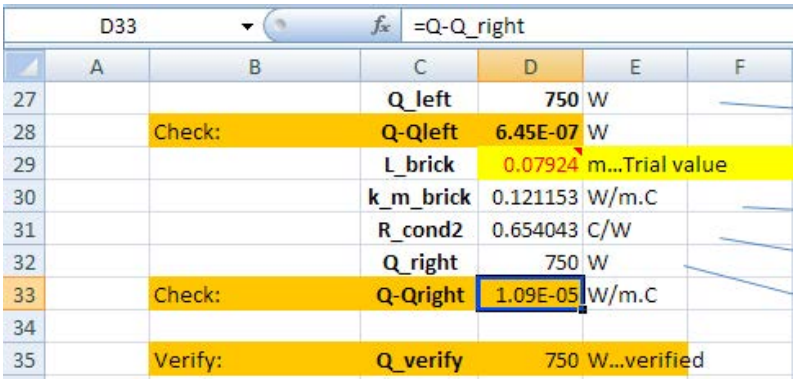
Click OK, and, the result is:

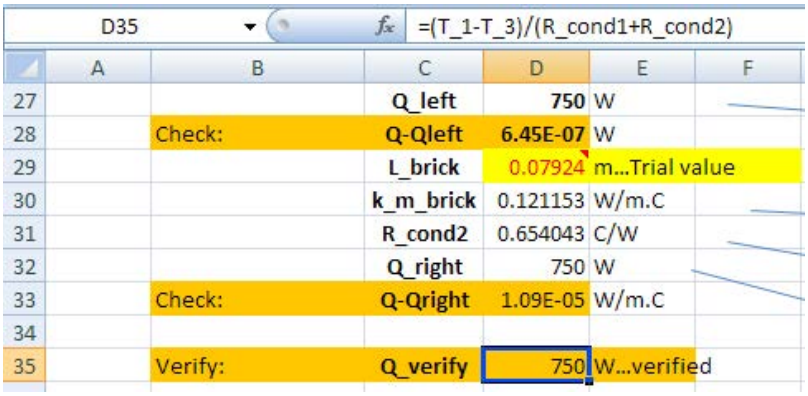


D33 =Q-Q_right

	A	B	C	D	E	F
27			Q_left	750	W	
28		Check:	Q-Qleft	6.45E-07	W	
29			L_brick	0.07924	m...Trial value	
30			k_m_brick	0.121153	W/m.C	
31			R_cond2	0.654043	C/W	
32			Q_right	750	W	
33		Check:	Q-Qright	1.09E-05	W/m.C	
34						
35		Verify:	Q_verify	750	W...verified	

Thus: L_brick = 0.07924 m … Ans.

Note: We have also included a check to the calculations: See cell D35 in the above fig. Formula for that cell is shown in the formula bar:



D35 =(T_1-T_3)/(R_cond1+R_cond2)

	A	B	C	D	E	F
27			Q_left	750	W	
28		Check:	Q-Qleft	6.45E-07	W	
29			L_brick	0.07924	m...Trial value	
30			k_m_brick	0.121153	W/m.C	
31			R_cond2	0.654043	C/W	
32			Q_right	750	W	
33		Check:	Q-Qright	1.09E-05	W/m.C	
34						
35		Verify:	Q_verify	750	W...verified	

i.e. We have considered the combination of *both the slabs only*, and shown that Q through the combination is also 750 W, as it should be.

Also, note that values for T_2 and L_brick are the same as obtained with EES in Prob.1B.14.

Again, *advantage of EXCEL* is that all related values such as thermal cond, thermal resistances etc. get updated automatically.

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1C One-dimensional steady state heat transfer with no internal heat generation:

Cylindrical and Spherical systems:

Learning objectives:

1. In this section, cylindrical and spherical systems are considered. Here, it is important to remember that area perpendicular to direction of heat transfer is equal to (2.π. r. L) for a cylinder and (4.π. r^2) for a sphere. So, *heat transfer area varies with radius*, whereas heat transfer area was a constant in the case of a slab.
2. Popular problems involve heat transfer in bare or insulated steam pipes, refrigerant lines or cylindrical or spherical containers or reactors. Such problems, including some University problems are solved using Mathcad, EES, FEHT or EXCEL. Studying these problems will help in consolidating the concept of Thermal resistance and Contact resistance for cylindrical and spherical systems.

"Prob. 1C.1. A steam pipe of 5 cm inside dia and 6.5 cm outside dia is insulated with a 2.75 cm radial thickness of high temp insulation having k = 1.1 W/m.C. The surface heat transfer coeff for inside and outside surfaces are 4650 and 11.5 W/m^2.C. respectively. The thermal cond. of pipe material is 45 W/m.C. If the steam temp is 200 C and the ambient temp is 25 C, determine: (i) heat loss per metre length of pipe, (ii) temp at the interface, and (iii) overall heat transfer coeff. [VTU-6th Sem-B.E.-July/Aug. 2002]"

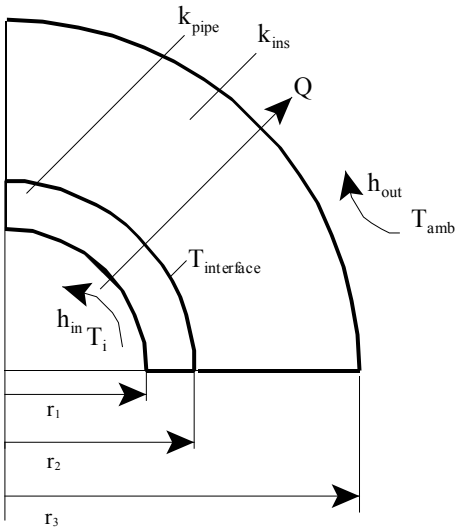

Fig.Prob.1C.1

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EES Solution:

"Data:"

r_1 = 0.025 [m]
r_2 = 0.0325 [m]
r_3 = r_2 + 0.0275 "[m]"
k_ins = 1.1 [W/m-C]
k_pipe = 45 [W/m-C]
h_in = 4650 [W/m^2-C]
h_out = 11.5 [W/m^2-C]
T_i = 200 [C]
T_amb = 25 [C]
L = 1 [m] "…..length of pipe … assumed"

"Calculations:"

R_c1 = 1/(h_in * 2 * pi * r_1 * L) "[C/W] … convective resist on inside of pipe"
R_pipe = ln(r_2/r_1)/(2 * pi * k_pipe * L) "[C/W] … thermal resist of pipe material"
R_ins = ln(r_3/r_2)/(2 * pi * k_ins * L) "[C/W] … thermal resist of insulation material"
R_c2 = 1/(h_out * 2 * pi * r_3 * L) "[C/W] … convective resist on outside of insulation"
R_total = R_c1 + R_pipe + R_ins + R_c2 "[C/W]"

"Heat transfer per metre length of pipe:"

Q = (T_i – T_amb)/R_total "[W]"

"Temp at the interface:"

"Now, in steady state, heat transfer through each layer is the same:"

Q = (T_i – T_interface)/(R_c1 + R_pipe) "…finds T_interface"

"Overall heat transfer coeff….. based on outer surface:"

A_o = (2 * pi * r_3 * L) "[m^2] …. outer surface area"

A_i = (2 * pi * r_1 * L) "[m^2] …. inner surface area"

U_o = 1/(A_o * R_total) "[W/m^2-C] ..overall heat tr coeff. based on outer surface area"

U_o * A_o = U_i * A_i "… determines U_i"

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Results:

Unit Settings: SI C kPa kJ mass deg

A_i = 0.1571 [m^2]	A_o = 0.377 [m^2]	h_{in} = 4650 [W/m^2-C]
h_{out} = 11.5 [W/m^2-C]	k_{ins} = 1.1 [W/m-C]	k_{pipe} = 45 [W/m-C]
L = 1 [m]	Q = 544 [W]	r_1 = 0.025 [m]
r_2 = 0.0325 [m]	r_3 = 0.06 [m]	R_{c1} = 0.001369 [C/W]
R_{c2} = 0.2307 [C/W]	R_{ins} = 0.08871 [C/W]	R_{pipe} = 0.0009279 [C/W]
R_{total} = 0.3217 [C/W]	T_{amb} = 25 [C]	T_i = 200 [C]
$T_{interface}$ = 198.8 [C]	U_i = 19.79 [W/m^2-C]	U_o = 8.246 [W/m^2-C]

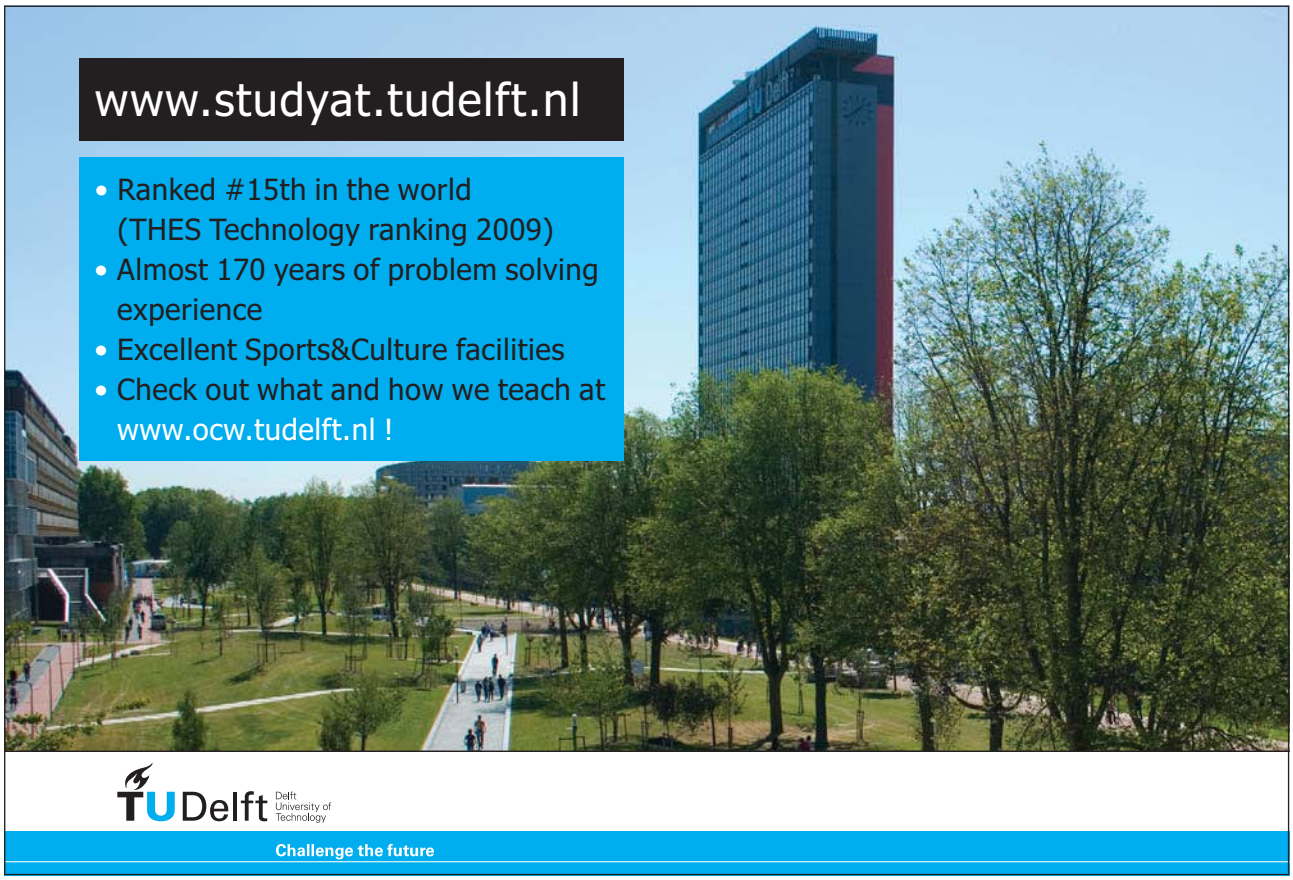
Thus:

Q = 544 W … heat transfer per unit length of pipe …. Ans.

T_interface = 198.8 C ….temp at the interface of pipe and insulation …. Ans.

Overall heat transfer coeff (based on outer area) = U_o = 8.246 [W/m^2-C] …. Ans.

Overall heat transfer coeff (based on inner area) = U_i = 19.79 [W/m^2-C] …. Ans.



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In addition:

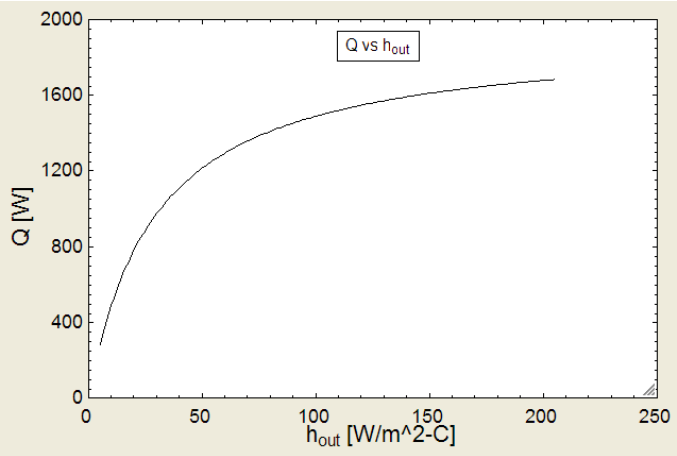
1. **Plot the variation of Q and T_interface as h_out varies from 5 to 200 W/m^2.C:**

   First, construct the parametric table:

Table 1

1..21	h_{out} [W/m2-C]	Q [W]	$T_{interface}$ [C]
Run 1	5	281.6	199.4
Run 2	15	653.4	198.5
Run 3	25	887.8	198
Run 4	35	1049	197.6
Run 5	45	1167	197.3
Run 6	55	1257	197.1
Run 7	65	1328	197
Run 8	75	1385	196.8
Run 9	85	1432	196.7
Run 10	95	1471	196.6
Run 11	105	1505	196.5
Run 12	115	1534	196.5
Run 13	125	1559	196.4
Run 14	135	1582	196.4
Run 15	145	1601	196.3
Run 16	155	1619	196.3
Run 17	165	1634	196.2
Run 18	175	1648	196.2
Run 19	185	1661	196.2
Run 20	195	1673	196.2
Run 21	205	1684	196.1

Then, plot the results:



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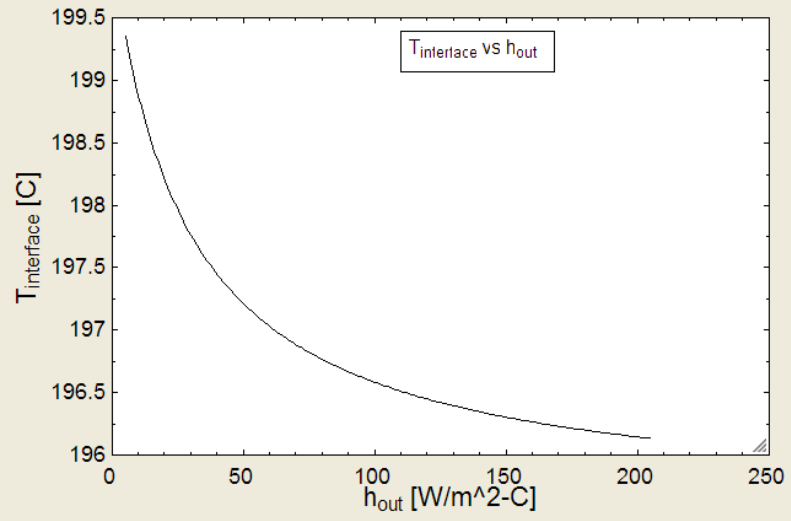

2. **Plot the variation of T_1 and T_3 as h_out varies from 5 to 200 W/m^2.C:**
   First, construct the parametric table:

1..21	1 h_{out} [W/m2-C]	2 T_1 [C]	3 T_3 [C]
Run 1	5	199.6	174.4
Run 2	15	199.1	140.5
Run 3	25	198.8	119.2
Run 4	35	198.6	104.5
Run 5	45	198.4	93.79
Run 6	55	198.3	85.62
Run 7	65	198.2	79.18
Run 8	75	198.1	73.98
Run 9	85	198	69.69
Run 10	95	198	66.09
Run 11	105	197.9	63.02
Run 12	115	197.9	60.39
Run 13	125	197.9	58.09
Run 14	135	197.8	56.07
Run 15	145	197.8	54.29
Run 16	155	197.8	52.7
Run 17	165	197.8	51.27
Run 18	175	197.7	49.99
Run 19	185	197.7	48.82
Run 20	195	197.7	47.76
Run 21	205	197.7	46.78

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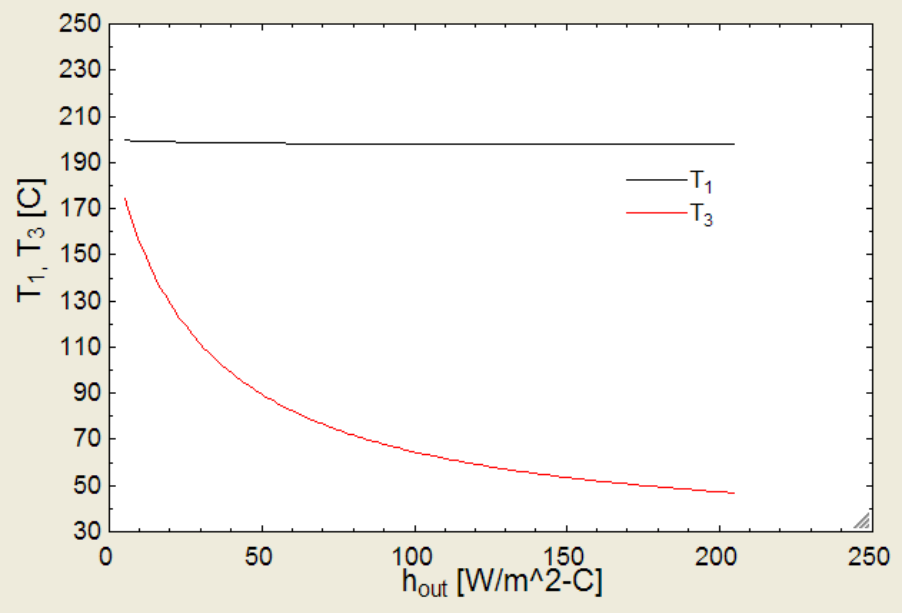
Then, plot the results:



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"**Prob. 1C.2.** A 200 mm ID pipe carries superheated steam at 210 C. The thermal cond. of pipe material is 12.5 W/m.C. The outside insulating layer has a thermal cond. of 0.2 W/m.C. The mean temp at the interface is 185 C. The heat transfer coeff between steam and pipe wall can be taken as 60 W/m^2.C and between the outer surface and ambient air as 35 W/m^2.C. Assuming the total thickness of pipe and insulation as 100 mm, and the ambient air at 30 C, calculate: (i) the required thickness of each layer, (ii) rate of heat transfer per unit length, and (iii) the inner and outer surface temperatures. [M.U.- Dec. 1999]"

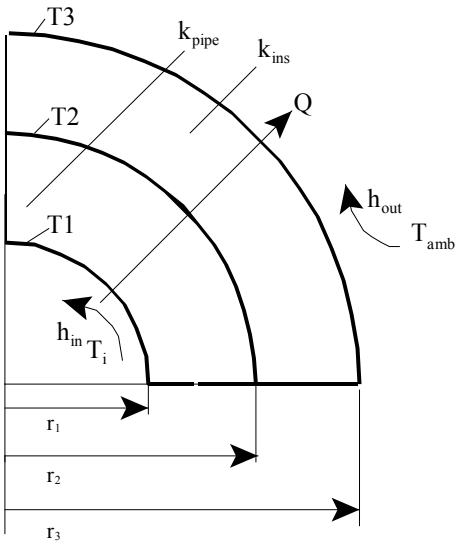

Fig.Prob.1C.2

EES Solution:

"Data:"

r_1 = 0.1 [m]
r_3 = r_1 + 0.1[m] "[m]"
k_ins = 0.2 [W/m-C]
k_pipe = 12.5 [W/m-C]
h_in = 60 [W/m^2-C]
h_out = 35 [W/m^2-C]
T_i = 210 [C]
T_amb = 30 [C]
T_2 = 185 [C] "…temp at the interface"
L = 1 [m] "…..length of pipe … assumed"

"Let T_1, T_3 be temperatures at the inside surface of pipe and outside surface of insulation"

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"Calculations:"

R_c1 = 1/(h_in * 2 * pi * r_1 * L) "[C/W] … convective resist on inside of pipe"
R_pipe = ln(r_2/r_1)/(2 * pi * k_pipe * L) "[C/W] … thermal resist of pipe material"
R_ins = ln(r_3/r_2)/(2 * pi * k_ins * L) "[C/W] … thermal resist of insulation material"
R_c2 = 1/(h_out * 2 * pi * r_3 * L) "[C/W] … convective resist on outside of insulation"
R_total = R_c1 + R_pipe + R_ins + R_c2 "[C/W]"

"Consider heat transfer per metre length of pipe, between the steam and the interface.
This should be equal to the heat transfer between the interface and the outside ambient:"

Q = (T_i – T_2)/(R_c1 + R_pipe) "[W] …. between steam and interface between pipe and insulation"
Q = (T_2 – T_amb)/(R_ins + R_c2) "[W]…between interface and ambient"

"To determine T_3 and T_1:"

Q = (T_2 – T_3)/R_ins "…determines T_3, the outside surface temp of insulation layer"
Q = (T_i – T_1)/R_c1 "…determines T_1, the inside surface temp of the pipe"

"To determine thickness of pipe and insulation:"

t_pipe = r_2 – r_1 "[m]….thickness of pipe"
t_ins = r_3 – r_2 "[m]….thickness of insulation"

Results:

Unit Settings: SI C kPa kJ mass deg

h_{in} = 60 [W/m^2-C]	h_{out} = 35 [W/m^2-C]	k_{ins} = 0.2 [W/m-C]
k_{pipe} = 12.5 [W/m-C]	L = 1 [m]	**Q = 769.4 [W]**
r_1 = 0.1 [m]	r_2 = 0.1598 [m]	r_3 = 0.2 [m]
R_{c1} = 0.02653 [C/W]	R_{c2} = 0.02274 [C/W]	R_{ins} = 0.1787 [C/W]
R_{pipe} = 0.005966 [C/W]	R_{total} = 0.2339 [C/W]	**T_1 = 189.6 [C]**
T_2 = 185 [C]	**T_3 = 47.49 [C]**	T_{amb} = 30 [C]
T_i = 210 [C]	**t_{ins} = 0.04023 [m]**	t_{pipe} = 0.05977 [m]

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Thus:

t_pipe = 0.05977 m … thickness of pipe …. Ans.
t_ins = 0.04023 m ….thickness of insulation …. Ans.
Q = 769.4 W.… Ans.
T_1 = 189.6 C …. inner surface temp. …Ans.
T_3 = 47.49 C …. outer surface temp. …Ans.

==========

Prob. 1C.3. A steam pipe of 0.12 m OD is insulated with a layer of calcium silicate (k = 0.089 W/m.K). (a) If the insulation is 20 mm thick and its inner and outer surfaces are maintained at T_s1 = 800 K and T_s2 = 490 K respectively, what is the heat loss per unit length of pipe (= Q)?

(b) Now, explore the effect of insulation thickness on heat loss Q and outer surface temp T_s2 with the inner surface temp T_s1 fixed at 800 K. The outer surface is exposed to an air flow (T_inf = 25 C) with h = 25 W/m^2.K and to a large surrounding for which T_surr = T_inf = 25 C. The surface emissivity of calcium silicate is about 0.8. Compute and plot the temp distribution in the insulation as a a function of insulation thickness, taking r_2 between 0.06 m and 0.2 m. Also plot the heat loss as a function of insulation thickness with the thickness varying from 0 to 0.14 m.[Ref. 3]

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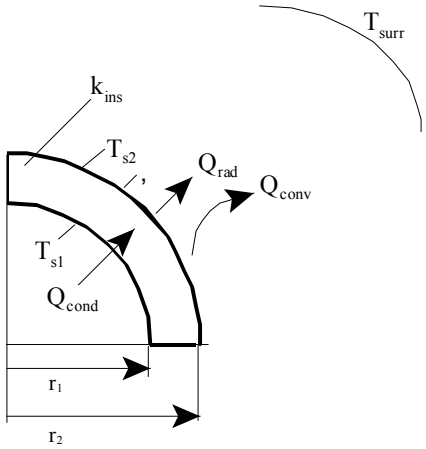

Fig.Prob.1C.3

Mathcad Solution:

Data: $r_1 := 0.06$ m....outer radius of pipe $k_{ins} := 0.089$ W/m.K

$r_2 := r_1 + 0.02$ $r_2 = 0.08$ m...outer radius of insulation

$T_{s1} := 800$ K $T_{s2} := 490$ K $L := 1$ m ... assumed

$T_{inf} := 25$ C $T_{surr} := 25$ C $h := 25$ W/m^2.K

$\varepsilon := 0.8$

Calculations:

Case 1:

$$R_{ins} := \frac{\ln\left(\frac{r_2}{r_1}\right)}{2 \cdot \pi \cdot k_{ins} \cdot L} \qquad \text{i.e.} \qquad R_{ins} = 0.514 \quad \text{C/W}$$

$$Q := \frac{\left(T_{s1} - T_{s2}\right)}{R_{ins}}$$

i.e. $Q = 602.586$ **W.....Ans.**

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Case 2:

$T_{s1} := 800$ K $\quad \sigma := 5.67 \cdot 10^{-8}$ W/m^2.K^4

$T_{inf} := 25$ C $\quad T_{surr} := 25$ C

$\varepsilon := 0.8$ ...emissivity of outer surface of insulation

By energy balance at the outer surface of insulation:

heat reaching the surface from inside by conduction = heat lost by convection + heat lost by radiation:

Use Solve Block to find T_s2: Start with a trial value of T_s2:

$T_{s2} := 500$ K...trial value

Given

$$\frac{T_{s1} - T_{s2}}{R_{ins}} = h \cdot \left(2 \cdot \pi \cdot r_2 \cdot L\right) \cdot \left[T_{s2} - \left(T_{inf} + 273\right)\right] + \sigma \cdot \varepsilon \cdot \left(2 \cdot \pi \cdot r_2 \cdot L\right) \cdot \left[T_{s2}^4 - \left(T_{surr} + 273\right)^4\right]$$

$T_{s2} := \text{Find}(T_{s2})$

$T_{s2} = 353.19$ **K....Ans.**

Case 3: To plot the graphs:

$$R_{ins}(r_2) := \frac{\ln\left(\frac{r_2}{r_1}\right)}{2 \cdot \pi \cdot k_{ins} \cdot L}$$ C/W....thermal resist of insulation is defined as a function of r_2

Again, use Solve Block to find T_s2: Start with a trial value of T_s2:

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$T_{s2} := 500$ K....trial value

Given

$$\frac{T_{s1} - T_{s2}}{R_{ins}(r_2)} = h \cdot (2 \cdot \pi \cdot r_2 \cdot L) \cdot \left[T_{s2} - (T_{inf} + 273)\right] + \sigma \cdot \varepsilon \cdot (2 \cdot \pi \cdot r_2 \cdot L) \cdot \left[T_{s2}^4 - (T_{surr} + 273)^4\right]$$

$T_{s2}(r_2) := \text{Find}(T_{s2})$

$T_{s2}(r_2) = 353.19$ **K...when r_2 = 0.08 m...Ans.**

Note that we have put T_s2 as a function of r_2 in the Solve Block…. this makes it convenient to plot T_s2 as a function of r_2 later, as shown below.

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$$Q(r_2) := \frac{T_{s1} - T_{s2}(r_2)}{R_{ins}(r_2)}$$

$Q(r_2) = 868.521$ **W.....when r_2 = 0.08 m**

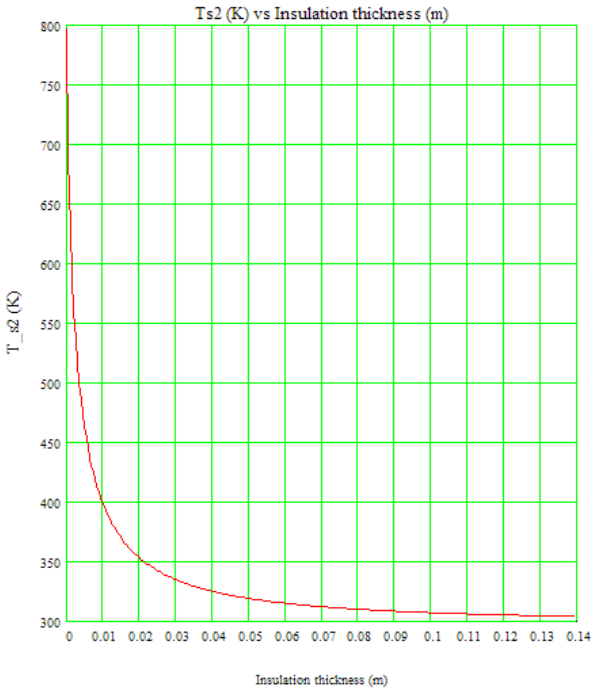
$T_{s2}(0.060001) = 799.655$ **K....almost 800K.when r_2 = r_1 = 0.06 m**

$Q(0.060001) = 1.159 \cdot 10^4$ **W.....when r_2 = r_1 = 0.06 m**

Note that in the above two eqns, to find T_s2 and Q at r_1, we used the r_2 value as 0.060001 m (i.e. almost equal to value of r_1), in the respective functions, to avoid dividing by zero.

To draw the graphs:

$r_2 := 0.06001, 0.0605 .. 0.2$ ...define a range vaiable r_2 from 0.060011 m to 0.2 m, with an increment of 0.00049 m



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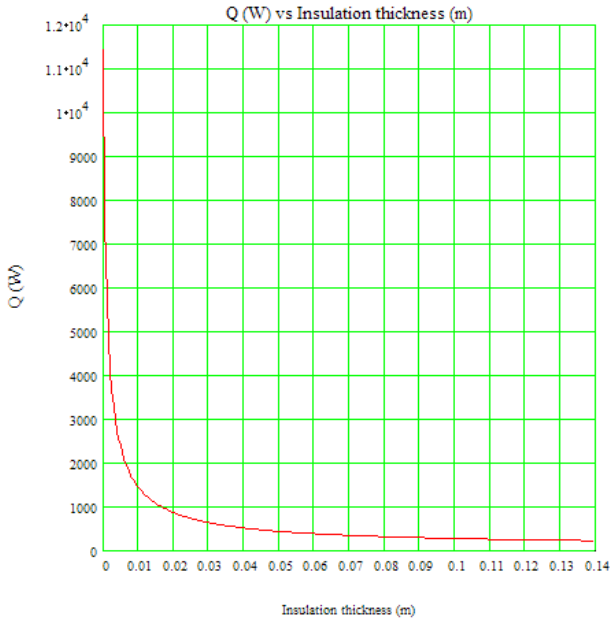

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"Prob. 1C.4. A 240 mm steam main, 210 m long is covered with 50 mm of high temp insulation (k = 0.092 W/m.C) and 40 mm of low temp insulation (k = 0.062 W/m.C). The inner and outer surface temperatures as measured are 390 C and 40 C respectively. Calculate: (i) the total heat lost per hour, (ii) heat loss per m^2 of pipe surface, (iii) heat loss per m^2 of outer surface, and (iv) the temp between two layers of insulation. Neglect heat conduction through the pipe material. [VTU-6th Sem-B.E.-July/ Aug. 2003]"

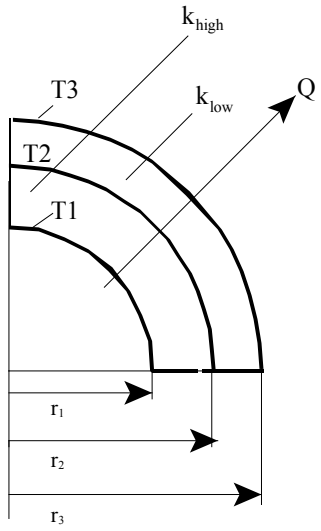

Fig.Prob.1C.4

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EES Solution:

"Data:"

r_1 = 0.12 [m] "…outer radius of pipe"
r_2 = r_1 + 0.05[m] "…outer radius of high temp insulation layer"
r_3 = r_2 + 0.04[m] "…outer radius of low temp insulation layer"
k_high = 0.092 [W/m-C]
k_low = 0.062 [W/m-C]
T_1 = 390 [C]
T_3 = 40 [C]
L = 210 [m] "…length of pipe"
"Let the interface temp between two layers of insulation be T_2"

"Calculations:"

A_1 = 2 * pi * r_1 * L "[m^2]….surface area of pipe"
A_2 = 2 * pi * r_2 * L "[m^2]….surface area of high temp ins layer"
A_3 = 2 * pi * r_3 * L "[m^2]….outer surface area of low temp ins layer"

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R_high = ln(r_2/r_1)/(2 * pi * k_high * L) "[C/W] … thermal resist. of high temp ins layer"
R_low = ln(r_3/r_2)/(2 * pi * k_low * L) "[C/W] … thermal resist. of low temp ins layer"
R_tot = R_high + R_low "[C/W] … total thermal resist."

Q_tot = (T_1 – T_3)/R_tot "[W] …. total heat transfer rate from the pipe"
Q_tot_perhour = Q_tot * 3600 [s] "[J /h]…..total heat transfer per hour"
Q_loss_persqmofpipe = Q_tot/A_1 "[W/m^2]…. heat loss per m^2 of pipe surface"
Q_loss_persqmofoutersurface = Q_tot/A_3 "[W/m^2]…. heat loss per m^2 of outer surface"

"To find temp T_2 between two layers of insulation:

Use the fact that heat transfer rate is the same through each layer in steady state:

i.e. heat transfer rate through high temp insulation = heat transfer rate through low temp insulation"

(T_1 – T_2)/R_high = (T_2 – T_3)/R_low "[W] ….

Results:

Unit Settings: SI C kPa kJ mass deg

$A_1 = 158.3$ [m^2]	$A_2 = 224.3$ [m^2]
$A_3 = 277.1$ [m^2]	$k_{high} = 0.092$ [W/m-C]
$k_{low} = 0.062$ [W/m-C]	$L = 210$ [m]
$Q_{loss,persqmofoutersurface} = 231.7$ [W/m^2]	$Q_{loss,persqmofpipe} = 405.4$ [W/m^2]
$Q_{tot} = 64193$ [W]	$Q_{tot,perhour} = 2.311E+08$ [J]
$r_1 = 0.12$ [m]	$r_2 = 0.17$ [m]
$r_3 = 0.21$ [m]	$R_{high} = 0.002869$ [C/W]
$R_{low} = 0.002583$ [C/W]	$R_{tot} = 0.005452$ [C/W]
$T_1 = 390$ [C]	$T_2 = 205.8$ [C]
$T_3 = 40$ [C]	

Thus:

Q_tot = 64193 W … . Ans.
Q_tot_perhour = 2.311E08 J …. Ans.
Q_tot_persqmof pipe surface = 405.4 W/m^2…. Ans.
Q_tot_persqmof outer surface = 231.7 W/m^2…. Ans.

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"Prob. 1C.5. ..A saturated refrigerant at -30 C flows through a copper pipe of 12 mm ID and 4 mm wall thickness. Layer of 40 mm thick thermocole is provided on the outer surface of the pipe to reduce the heat flow. Determine the heat leakage into the refrigerant per metre length of pipe. Ambient temp is 35 C. Assume internal and external heat transfer coefficients to be 450 and 6 W/m^2.K respectively. k_copper 410 W/m.K; k_thermocole = 0.0295 W/m.K. Find the amount of refrigerant vapourised per hour per metre length of pipe when the pipe is covered and when the pipe is bare. Take latent heat of vapourisation at -30 C = 267 kJ/kg. [VTU-6th Sem-B.E.-Jan./Feb. 2005]"

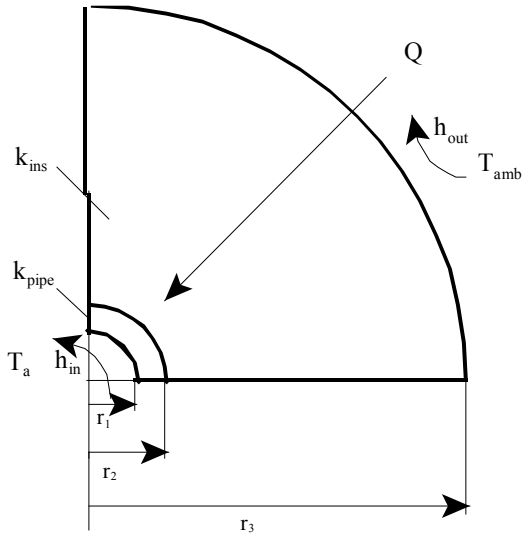

Fig.Prob.1C.5

Mathcad Solution:

Data: $r_1 := 0.006$ m....inner radius of pipe

$r_2 := r_1 + 0.004$ $r_2 = 0.01$ m...outer radius of pipe

$r_3 := r_2 + 0.04$ $r_3 = 0.05$ m...outer radius of insulation

$k_{ins} := 0.0295$ W/m.K $k_{pipe} := 410$ W/m.K

$T_a := -30$ C $T_{amb} := 35$ C L := 1 m ... assumed

$h_{in} := 450$ W/m^2.C $h_{out} := 6$ W/m^2.K

$h_{fg} := 267 \cdot 10^3$ J/kg

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Calculations:

Case 1: When the pipe is insulated:

$$R_{pipe} := \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\cdot\pi\cdot k_{pipe}\cdot L} \quad \text{i.e.} \quad R_{pipe} = 1.983\cdot 10^{-4} \quad \text{C/W...cond. resist of pipe}$$

$$R_{ins} := \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\cdot\pi\cdot k_{ins}\cdot L} \quad \text{i.e.} \quad R_{ins} = 8.683 \quad \text{C/W...cond. resist of ins}$$

$$R_{conv1} := \frac{1}{h_{in}\cdot\left(2\cdot\pi\cdot r_1\cdot L\right)} \quad R_{conv1} = 0.059 \quad \text{C/W....convective resist on the inside}$$

$$R_{conv2} := \frac{1}{h_{out}\cdot\left(2\cdot\pi\cdot r_3\cdot L\right)} \quad R_{conv2} = 0.531 \quad \text{C/W....convective resist on the outside}$$

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$R_{tot} := R_{conv1} + R_{pipe} + R_{ins} + R_{conv2}$

$R_{tot} = 9.273$ C/W...total thermal resistance

Therefore, $Q := \frac{T_{amb} - T_a}{R_{tot}}$ i.e. $Q = 7.01$ **W.....heat loss per metre length when insulation is applied....Ans.**

$m_{refrig} := \frac{Q}{h_{fg}}$ i.e. $m_{refrig} = 2.625 \cdot 10^{-5}$ **kg/s....refrig. vapourised....Ans.**

Now: $m_{refrigperhour} := m_{refrig} \cdot 3600$

i.e. $m_{refrigperhour} = 0.095$ **kg/h....refrig. vapourised....Ans.**

Case 2: When the pipe is bare:

$Q_{bare} := \frac{T_{amb} - T_a}{R_{conv1} + R_{pipe} + \frac{1}{h_{out} \cdot (2 \cdot \pi \cdot r_2 \cdot L)}}$ ...assuming inside and outside convection coeffs to remain the same

i.e. $Q_{bare} = 23.969965$ **W.....heat loss per metre length when pipe is bare....Ans.**

And, $m_{refrigbare} := \frac{Q_{bare}}{h_{fg}} \cdot 3600$ kg/h

i.e. $m_{refrigbare} = 0.323$ **kg/h....refrig. vapourised when pipe is bare....Ans.**

To find the variation of refrigerant evaporation rate (kg/s) and the outside surface temp of insulation as the insulation thickness is varied:

i.e. vary the radius r_3.

Now, note that R_conv1 and R_pipe do not depend on r_3; only R_ins and R_conv2 depend on r_3.

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So, write R_ins and R_conv2 as functions of r_3; then R_tot and Q_tot and m_refrig, and outside surface temp (T_3) are also written as functions of r_3, and the plot is easily drawn:

$r_3 := r_2 + 0.04 \qquad r_3 = 0.05$ m...outer radius of insulation

$$R_{conv1} := \frac{1}{h_{in} \cdot (2 \cdot \pi \cdot r_1 \cdot L)} \qquad R_{pipe} := \frac{\ln\left(\frac{r_2}{r_1}\right)}{2 \cdot \pi \cdot k_{pipe} \cdot L}$$

$$R_{ins}(r_3) := \frac{\ln\left(\frac{r_3}{r_2}\right)}{2 \cdot \pi \cdot k_{ins} \cdot L} \qquad R_{conv2}(r_3) := \frac{1}{h_{out} \cdot (2 \cdot \pi \cdot r_3 \cdot L)}$$

Then,

$$R_{tot}(r_3) := \begin{cases} 0.0591446 & \text{if } r_3 = r_2 \\ 0.0591446 + R_{ins}(r_3) + R_{conv2}(r_3) & \text{otherwise} \end{cases}$$

C/W...total resist as a function of r_3

$$Q(r_3) := \begin{cases} 23.97 & \text{if } r_3 = r_2 \\ \frac{T_{amb} - T_a}{R_{tot}(r_3)} & \text{otherwise} \end{cases}$$

W...total heat loss as a function of r_3

$$m_{refrig}(r_3) := \frac{Q(r_3)}{h_{fg}}$$

kg/s...evapn. rate of refrigerant as a function of r_3

$m_{refrig}(r_3) = 2.625 \cdot 10^{-5}$ kg/s...evapn. rate of refrigerant for r_3 = 0.05 m, as obtained earlier.

To find T_3, outer surface temp:

Apply the fact that in steady state, heat transfer through each layer is the same.

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Considering the outer convection layer:

$Q = h_{out} \cdot (2 \cdot \pi \cdot r_3 \cdot L) \cdot (T_{amb} - T_3)$ ...applying the Newton's Law of cooling

i.e. $T_3(r_3) := \begin{cases} T_{amb} - \dfrac{23.97}{2 \cdot \pi \cdot 0.01 \cdot L \cdot h_{out}} & \text{if } r_3 = r_2 \\ T_{amb} - \dfrac{Q(r_3)}{2 \cdot \pi \cdot r_3 \cdot L \cdot h_{out}} & \text{otherwise} \end{cases}$ C.....T_3 written as a function of r_3

$T_3(r_3) = 31.281$ C...outer surface temp for r_3 = 0.05 m

$T_3(0.01) = -28.582$ C...temp on outer surface of bare pipe

Now, draw the graphs:

$r_3 := 0.01, 0.011 .. 0.1$ ....define the range variable. First value of 0.01 represents the condition of 'no insulation', i.e. bare pipe.

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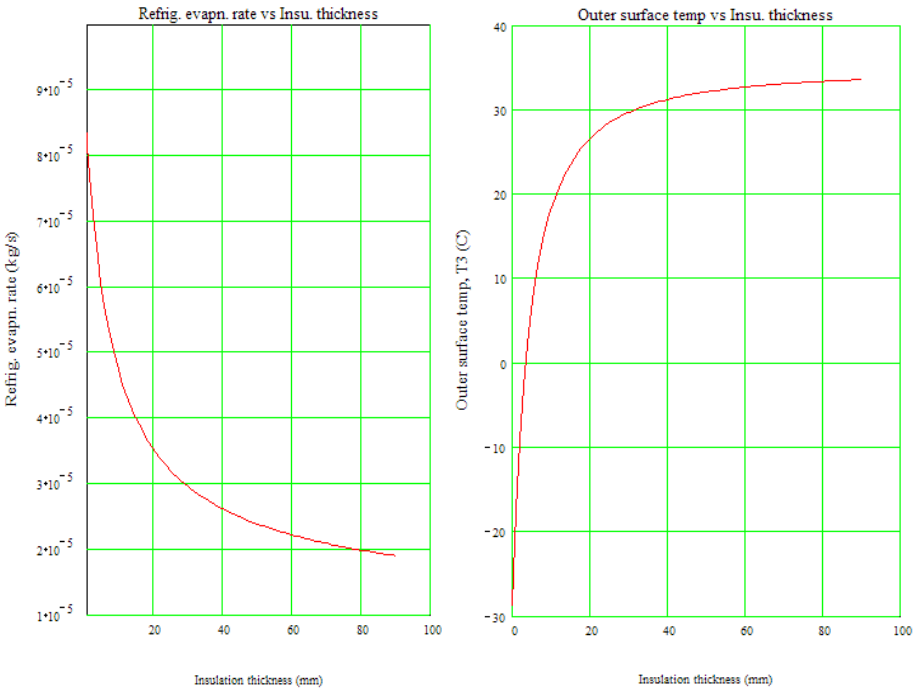
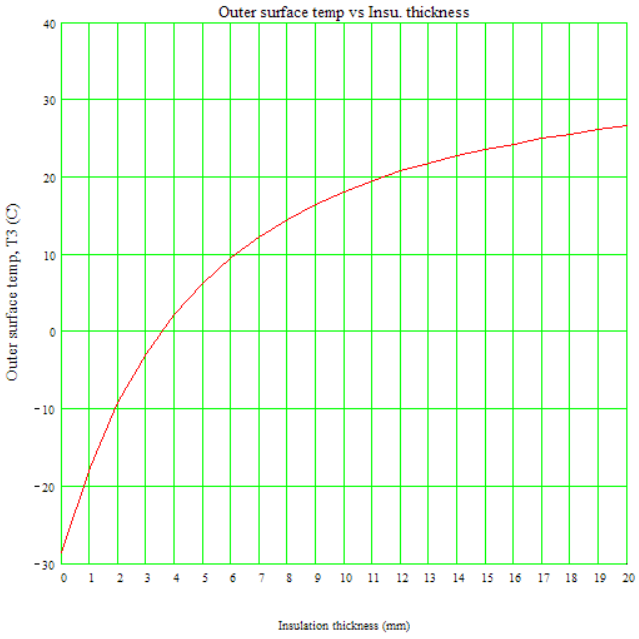


In addition:

What should be the min. thickness of insulation so as to avoid condensation on the outer surface of insulation?

Note from the above graph the insulation thickness corresponding to a value of T_3 = 0 deg.C.

Draw the above graph with the x-axis range from 0 to 0.02 m, so that we can read more accurately:



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Observe from the graph that an insulation thickness of about 3.5 mm is enough to prevent condensation on the surface.

Also, increasing the thickness beyond 5 cm is not much beneficial.

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"**Prob. 1C.6.** An insulated steam pipe having OD of 30 mm is to be covered with two layers of insulation, each having a thickness of 20 mm. The thermal cond. of one material is 3 times that of the other. Assuming that the inner and outer surface temperatures of composite insulation are fixed, how much heat transfer will be increased when the better insulation material is next to the pipe than when it is at the outer layer? [VTU-6th Sem-B.E.-Dec. 2010]"

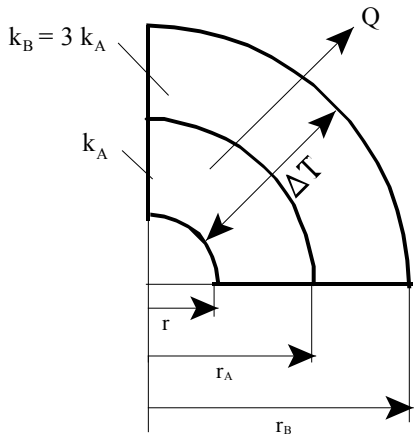

Fig.Prob.1C.6

EES Soluion:

"Data:"

r = 0.015[m]

r_A = 0.035[m]

r_B = 0.055[m]

L = 1 [m] "….assumed"

"Calculations:"

"Let k_B = 3*k_A … i.e. A is better insulation, since k_A < k_B;

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Overall temp. difference DELTAT being the same, two cases are considered:

(i) better insulation i.e. insulation A is applied next to the pipe: then, Q1 = DELTAT/ R_tot1 where R_tot1 is the total thermal resistance

(ii) other insulation i.e. insulation B is applied next to the pipe: then, Q2 = DELTAT/ R_tot2 where R_tot2 is the total thermal resistance

Then, ratio of Q2/Q1 is equal to R_tot1 / R_tot2.

Note that while determining the ratio Q2/Q1, k_A and L cancel from the numerator and denominator, so value of k_A is not required to be known. So, we get:

$$Q2byQ1 = \frac{\frac{\ln\left[\frac{r_A}{r}\right]}{2\cdot\pi} + \frac{\ln\left[\frac{r_B}{r_A}\right]}{2\cdot\pi\cdot 3}}{\frac{\ln\left[\frac{r_A}{r}\right]}{2\cdot\pi\cdot 3} + \frac{\ln\left[\frac{r_B}{r_A}\right]}{2\cdot\pi}}$$

”

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```
{
R_tot1 = ln(r_A/r)/(2*pi*k_A*L) + ln(r_B/r_A)/(2*pi*3*k_A*L) "…total thermal resist. in case (i)
R_tot2 = ln(r_A/r)/(2*pi*3*k_A*L) + ln(r_B/r_A)/(2*pi*k_A*L) "…total thermal resist. in case (ii)
}
Q2byQ1 = (ln(r_A/r)/(2*pi) + ln(r_B/r_A)/(2*pi*3)) / (ln(r_A/r)/(2*pi*3) + ln(r_B/r_A)/(2*pi))
```

Results:

Unit Settings: SI C kPa kJ mass deg

L = 1 [m] | Q2byQ1 = 1.359 | r = 0.015 [m] | r_A = 0.035 [m] | r_B = 0.055 [m]

Thus:

Q2 is greater from Q1 by 35.9% ……Ans.

==========

"**Prob. 1C.7.** A steam pipe with internal and external diameters of 18 cm and 21 cm is covered with two layers of insulation each 30 mm thick with thermal conductivities 0.18 and 0.09 W/m.K. The difference in temp between inside and outside surfaces is 250 C. Calculate the quantity of heat lost per metre length of the pipe if its thermal cond. is 60 W/m.K. What is the percentage error if the calculation is carried out considering the pipe as a plane wall?[VTU-6th Sem-B.E.-June/July 2011]"

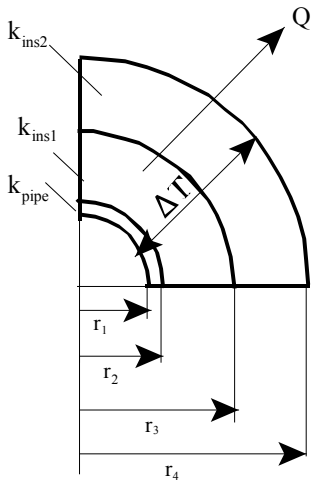

Fig.Prob.1C.7

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EES Solution:

"Data:"

r_1 = 0.09[m]
r_2 = 0.105[m]
r_3 = 0.135[m]
r_4 = 0.165 [m]
k_pipe = 60 [W/m-C]
k_ins1 = 0.18 [W/m-C]
k_ins2 = 0.09 [W/m-C]
DELTAT = 250 [C]

L = 1 [m] "….assumed"

"Calculations:"

R_pipe = ln(r_2/r_1) / (2 * pi * k_pipe * L) "[C/W] ….thermal resistance of pipe wall"
R_ins1 = ln(r_3/r_2) / (2 * pi * k_ins1 * L) "[C/W] ….thermal resistance of first insulation layer"
R_ins2 = ln(r_4/r_3) / (2 * pi * k_ins2 * L) "[C/W] ….thermal resistance of second insulation layer"

R_tot = R_pipe + R_ins1 + R_ins2 "[C/W] … total thermal resistance"

Q_cyl = DELTAT / R_tot "[W] …total heat loss for the cylindrical system"

"When the system is considered as a plane wall:"

"Distances as measured from left:"

L_1 = 0.09[m]
L_2 = 0.105[m]
L_3 = 0.135[m]
L_4 = 0.165 [m]
A = 1 [m^2] "….area of wall… assumed"

"Now, the resistances are re-calculated as for a plane wall:"

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"Resistances:"

R_wall = (L_2 – L_1) / (k_pipe*A) "[C/W] ….thermal resistance of pipe wall"
R_1ins = (L_3 – L_2) / (k_ins1 * A) "[C/W] ….thermal resistance of first insulation layer as a plane wall"
R_2ins = (L_4 – L_3) / (k_ins2 * A) "[C/W] ….thermal resistance of second insulation layer as a plane wall"
R_tot_wall = R_wall + R_1ins + R_2ins "[C/W] … total thermal resistance"

Q_wall = DELTAT / R_tot_wall "[W] …total heat loss for the plane wall system"

Results:

Unit Settings: SI C kPa kJ mass deg

$A = 1$ [m^2]	$\Delta T = 250$ [C]	$k_{ins1} = 0.18$ [W/m-C]
$k_{ins2} = 0.09$ [W/m-C]	$k_{pipe} = 60$ [W/m-C]	$L = 1$ [m]
$L_1 = 0.09$ [m]	$L_2 = 0.105$ [m]	$L_3 = 0.135$ [m]
$L_4 = 0.165$ [m]	$Percent_{error} = 15.44$	$Q_{cyl} = 432.9$ [W]
$Q_{wall} = 499.8$ [W]	$r_1 = 0.09$ [m]	$R_{1ins} = 0.1667$ [C/W]
$r_2 = 0.105$ [m]	$R_{2ins} = 0.3333$ [C/W]	$r_3 = 0.135$ [m]
$r_4 = 0.165$ [m]	$R_{ins1} = 0.2222$ [C/W]	$R_{ins2} = 0.3549$ [C/W]
$R_{pipe} = 0.0004089$ [C/W]	$R_{tot} = 0.5775$ [C/W]	$R_{tot,wall} = 0.5003$ [C/W]
$R_{wall} = 0.00025$ [C/W]		

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Thus:

Q_cyl = 432.9 W ….heat loss for the cyl. System….Ans.

Q_wall = 499.8 W ….heat loss for the plane wall System….Ans.

Percent_error = 15.44 % ….percent error in considering the system as plane wall …Ans.

==========

"**Prob. 1C.8.** A steel pipe of 220 mm OD is carrying steam at 280 C. It is insulated with a material of k = 0.06. [1 + 0.0018.T] where k is in W/m.C. Thickness of insulation is 50 mm and the outer surface temp is 50 C. Determine the heat flow per metre length of the pipe and the temp at the mid-thickness of pipe. [VTU-6th Sem-B.E.-June/July 2009]"

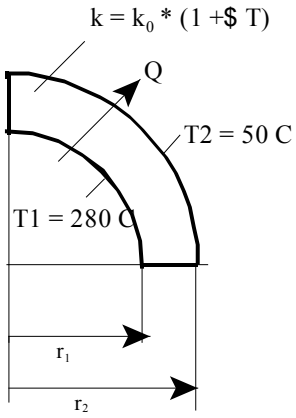

Fig.Prob.1C.8

EES Solution:

"Data:"

r_1 = 0.11 [m]
T_1 = 280 [C]
r_2 = 0.16 [m]
"Th. conductivity k is linearly varying: of the form k = k_0 (1 + beta.T), where:"
k_0 =0.06
beta = 0.0018
T_2 = 50 [C]
L = 1 [m] "…length of pipe … assumed"

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"Calculations:"

T_m = (T_1+T_2)/2 "[C] … mean temp of insulation"
k_m = k_0*(1+beta*T_m) "[W/m.C]] … mean th. conductivity of insulation"
R_ins = ln(r_2/r_1)/(2 * pi * k_m * L) "[C/W] … thermal resist of cyl. layer of insulation"
Q = (T_1-T_2)/R_ins "..finds Q (W), the heat transfer rate"

"To find temp T(r) at any radius r:"

r = 0.135 [m] "…starting with a value of r, this is the mid-thickness of insulation, but this is a variable to draw graph:"

"Let temp be Tr at radius r:"

T_m_r = (T_1 + Tr)/2 "[C]….mean temp between pipe OD surface and mid-thickness of insulation"
k_m_r = k_0*(1+beta*T_m_r) " [W/m-C]…mean th. cond. up to mid-thickness of insulation"

"Remember that in steady state, Q (already calculated = 300.1 W) is the same through each layer:"

Q = (2*pi*k_m_r*L)*(T_1-Tr)/ln(r/r_1) "..finds Tr (C) at r"

"To draw the plot of variation of temp in the insulation with the radius:"

"First, construct a parametric table, and then draw the graph:"

Results:

Unit Settings: SI C kPa kJ mass deg

$\beta = 0.0018$ [1/C]	$k_0 = 0.06$ [W/m-C]	$k_m = 0.07782$ [W/m-C]
$k_{m,r} = 0.08395$ [W/m-C]	$L = 1$ [m]	$Q = 300.1$ [W]
$r = 0.135$ [m]	$r_1 = 0.11$ [m]	$r_2 = 0.16$ [m]
$R_{ins} = 0.7663$ [C/W]	$Tr = 163.5$ [C]	$T_1 = 280$ [C]
$T_2 = 50$ [C]	$T_m = 165$ [C]	$T_{m,r} = 221.7$ [C]

Thus:

Q = 300.1 W ….heat transfer rate … Ans.
Tr = 163.5 C ….temp at mid-thickness of insulation … Ans.

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Table of Tr vs. r:

1..10	1 r [m]	2 Tr [C]
Run 1	0.11	280
Run 2	0.12	232.6
Run 3	0.125	209.3
Run 4	0.13	186.3
Run 5	0.135	163.5
Run 6	0.14	140.7
Run 7	0.145	118.1
Run 8	0.15	95.44
Run 9	0.155	72.76
Run 10	0.16	50

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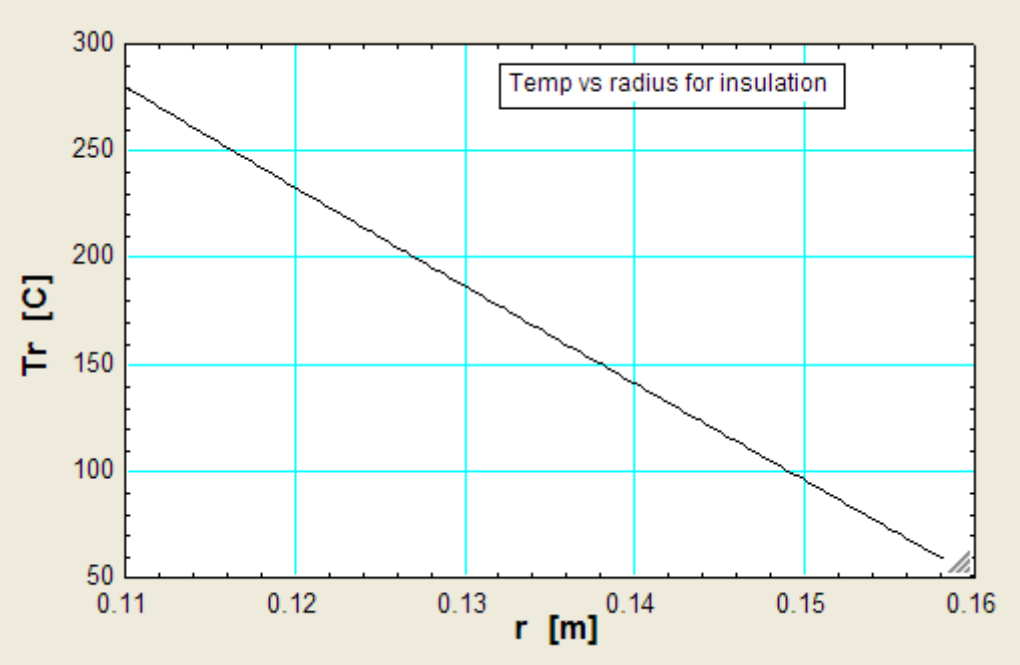
Plot of Tr vs. r:



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Prob. 1C.9. A long, hollow cylinder is constructed from a material whose k varies with temp as: k = 0.01 + 0.001.T, where k is in W/m.K and T is in deg.C. The inner and outer radii of the cylinder are 125 mm and 250 mm respectively. Under steady state conditions, the inner and outer surface temperatures are 698 K and 363 K respectively. Determine: (i) the rate of heat flow per metre length, (ii) temp of air on the outside of cylinder, if the surface heat transfer coeff on the exterior surface is 14.5 W/m^2.K [VTU – VI Sem. B.E. – Feb. 2002]

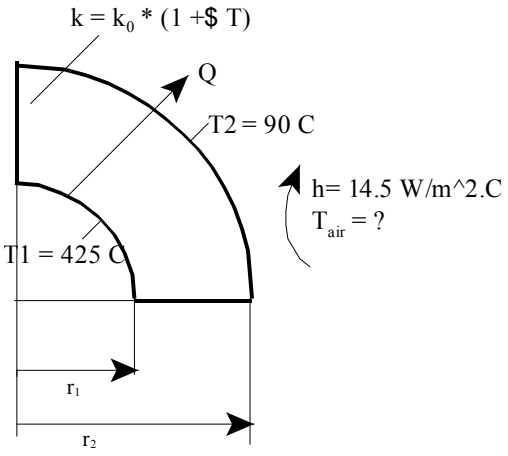

Fig.Prob.1C.9

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Mathcad Solution:

Data:

$r_1 := 0.125$ m $r_2 := 0.25$ m $L := 1$ m $h := 14.5$ W/m^2.K

k varies linearly, with the form: k = k0 (1 + β.T), where T is in deg.C, and:

$k_0 := 0.01$ $\beta := \frac{0.001}{0.01}$ $\beta = 0.1$

$T_1 := 698 - 273$ $T_1 = 425$ C

$T_2 := 363 - 273$ $T_2 = 90$ C

Calculations:

$T_m := \frac{(T_1 + T_2)}{2}$ i.e. $T_m = 257.5$ C....mean temp.

$k_m := k_0 \cdot (1 + \beta \cdot T_m)$ i.e. $k_m = 0.268$ W/m.K....mean th. cond.

$R_{cyl} := \frac{\ln\left(\frac{r_2}{r_1}\right)}{2 \cdot \pi \cdot k_m \cdot L}$ C/W....thermal resist of cyl

i.e. $R_{cyl} = 0.412$ C/W

$Q := \frac{T_1 - T_2}{R_{cyl}}$

i.e. $Q = 812.312$ **W.....heat transfer rate per metre length.....Ans.**

Temp of outside air:

In steady state:

Q = h A (T2 - Tair) where A = outside surface area

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$A := 2 \cdot \pi \cdot r_2 \cdot L$ $A = 1.571$ m^2

$T_{air} := T_2 - \frac{Q}{h \cdot A}$ $T_{air} = 54.336$ **C....temp of outside air .... Ans.**

Now, consider the following extension of this problem:

Inside surface temp is fixed at 425 deg.C. Ambient temp T_amb is 35 deg. C.

Calculate the outside surface temp T2 as the heat transfer coeff. h varies from 4 W/m^2.C to 200 W/m^2.C. Other data remain the same.:

To get T2, apply the heat balance on the outer surface;

i.e. heat reaching the surface from inside by conduction = heat lost to ambient by convection.

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Use the Solve Block of Mathcad. Start with a trial value for T2:

$T_1 = 425$ C $T_{amb} := 35$ C $h = 14.5$ W/m^2.C $r_2 = 0.25$ m

$T_2 := 400$ C..... trial value of T2

Given

$$\frac{T_1 - T_2}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{2\cdot\pi\cdot L\cdot k_0\cdot\left[1+\beta\cdot\left(\frac{T_1+T_2}{2}\right)\right]}} = h\cdot\left(2\cdot\pi\cdot r_2\cdot L\right)\cdot\left(T_2 - T_{amb}\right)$$

...LHS is conduction in cyl. shell of variable k; RHS is convection to ambient.

$T_2(r_2, h) := \text{Find}(T_2)$ **Note: T2 is defined as function of r2 and h. This will be very useful to draw graphs for various values of r2 and h.**

Also find Q as a function of r2 and h:

$Q(r_2, h) := h\cdot\left(2\cdot\pi\cdot r_2\cdot L\right)\cdot\left(T_2(r_2, h) - T_{amb}\right)$ **W....Q as a function of r2 and h**

Examples:

$T_2(r_2, h) = 71.338$ C... T2 at r2 = 0.25 m and h = 14.5 W/m^2.C, with Tamb = 35 C

$Q(r_2, h) = 827.65$ W... Q at r2 = 0.25 m and h = 14.5 W/m^2.C, with Tamb = 35 C

$T_2(0.2, 25) = 73.767$ C... T2 at r2 = 0.2 m and h = 25 W/m^2.C, with Tamb = 35 C

$Q(0.2, 25) = 1.218\cdot10^3$ W... Q at r2 = 0.2 m and h = 25 W/m^2.C, with Tamb = 35 C

To plot T2 as a function of h for different values of r2:

$h := 4, 6 .. 200$ ...define a range variable h from 4 to 200 W.m^2.C, with an increment of 2

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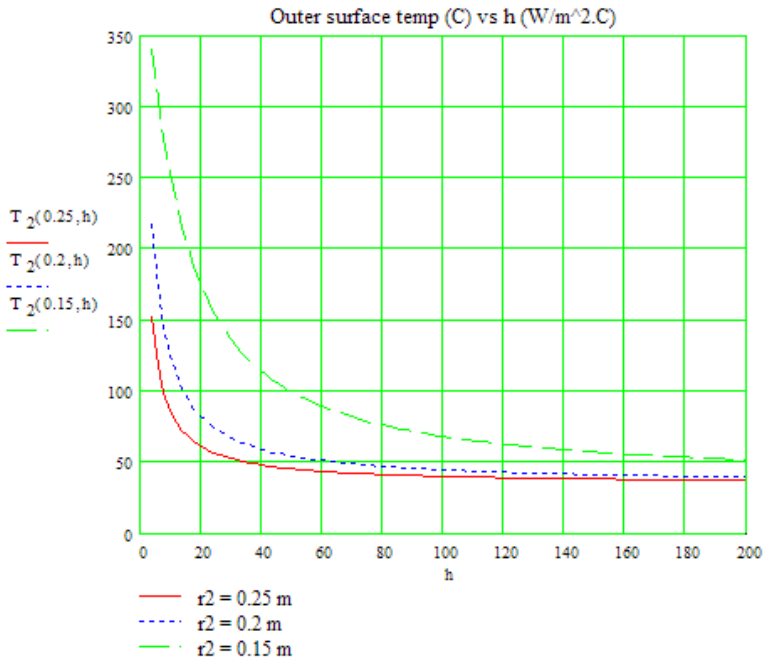
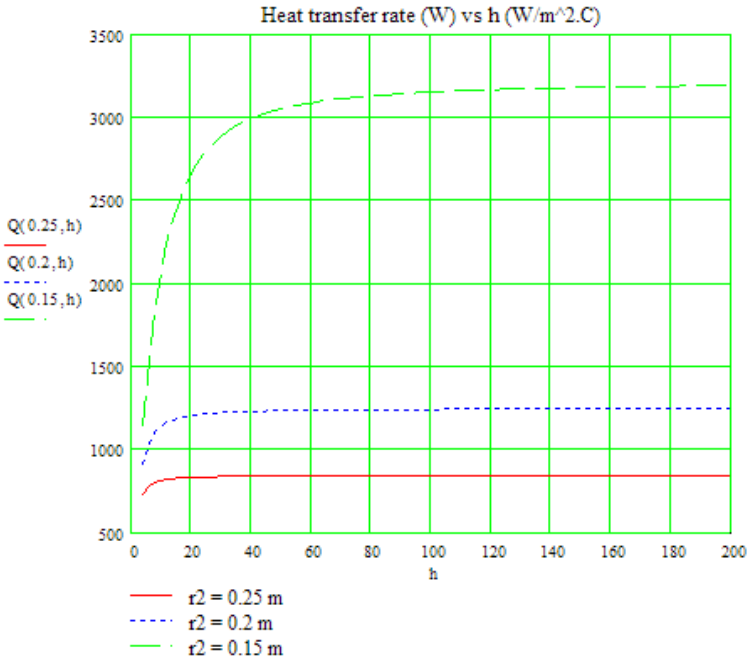


To plot Q as a function of h for different values of r2:



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"**Prob. 1C.10**. A hollow sphere of pure iron contains a liquid mixture which releases 8000 W. If inside dia of sphere is 120 mm and outside dia is 240 mm, steady state conditions prevail and outside surface temp of the sphere is 60 C, determine the temp at a location 30 mm from the outside surface of the sphere. Assume material of the sphere has k = 75 W/m.K and heat release by the chemical mixture is constant. [VTU-6th Sem-B.E.-Jan./Feb. 2005]"

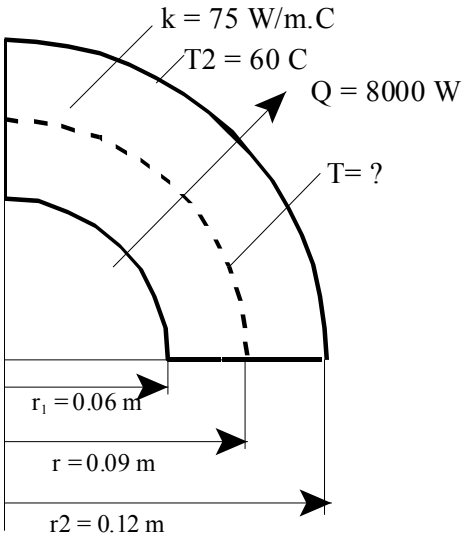

Fig. Prob.1C.10

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EES Solution:

"Data:"

r_1 = 0.06 [m]
r_2 = 0.12 [m]
T_2 = 60 [C]
k = 75 [W/m-C]
Q = 8000 [W]

"Calculations:"

"Let the inner surface temp of the sphere be T_1"

R_sph = (r_2 – r_1)/(4 * pi * k * r_1 * r_2) "[C/W] … thermal resist of spherical layer"

Q = (T_1-T_2)/R_sph "..finds T_1 (C), the inner surface temp."

"Temp. at a radius r = (r_2 – 0.03) = 0.09 m"

r = 0.09 [m]

"Temp. 'T' at radius' r 'for a spherical layer is given by:"

(T-T_1) / (T_2 – T_1) = (1/r – 1/r_1) / (1/r_2 – 1/ r_1) "….finds T at given r"

Results:

Unit Settings: SI C kPa kJ mass deg

$k = 75$ [W/m-C]	$Q = 8000$ [W]	$r = 0.09$ [m]	$r_1 = 0.06$ [m]
$r_2 = 0.12$ [m]	$R_{sph} = 0.008842$ [C/W]	$T = 83.58$ [C]	$T_1 = 130.7$ [C]
$T_2 = 60$ [C]			

Thus:

T_1 = 130.7 C …. Temp at the inside surface of sphere ….. Ans.

T = 83.58 C ……. Temp at a location 30 mm from outside surface, i.e. at r = 0.09 m …. Ans.

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"**Prob. 1C.11.** A 600 mm OD sphere storing liquid is provided with two insulating layers, a high temp insulation of k_1 = 0.35 W/m.K and low temp insulation of k_2 = 0.07 W/m.K. The thickness of the former is 100 mm. The temp drop across the high temp insulation is required to be 2.5 times that across the low temp insulation. What should be the thickness of the latter? [VTU-6th Sem-B.E.- Feb. 2002]"

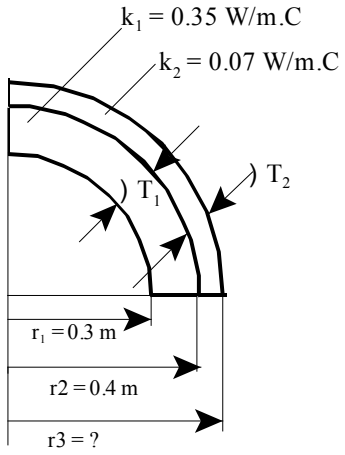

Fig.Prob.1C.11

"EES Solution:"

"Data:"

"Let:
t_ins1 = thickness of high temp insulation
t_ins2 = thickness of low temp insulation layer
DELTAT_1 = temp drop in high temp insulation layer, and
DELTAT_2 = temp drop in low temp insulation layer"

r_1 = 0.3 [m]
t_ins1 = 0.1[m]
r_2 = r_1 + t_ins1 "[m]"
r_3 = r_2 + t_ins2 "[m]"
k_1 = 0.35 [W/m-C]
k_2 = 0.07 [W/m-C]

"Calculations:"

R_ins1 = (r_2 – r_1)/(4 * pi * k_1 * r_1 * r_2) "[C/W] … thermal resist of first, high temp insulation layer"
R_ins2 = (r_3 – r_2)/(4 * pi * k_2 * r_2 * r_3) "[C/W] … thermal resist of next low temp insulation layer"

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"In steady state, Q through each layer is same:

Q = DELTAT_1/R_ins1

Q = DELTAT_2/R_ins2"

"DELTAT_1 = 2.5 * DELTAT_2 …. by data"

"Therefore:"

"2.5 * DELTAT_2/R_ins1 = DELTAT_2/R_ins2"

2.5/R_ins1 = 1/R_ins2 "….finds r_3"

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Results:

Unit Settings: SI C kPa kJ mass deg

k_1 = 0.35 [W/m-C]	k_2 = 0.07 [W/m-C]	r_1 = 0.3 [m]
r_2 = 0.4 [m]	r_3 = 0.411 [m]	R_{ins1} = 0.1895 [C/W]
R_{ins2} = 0.07579 [C/W]	t_{ins1} = 0.1 [m]	t_{ins2} = 0.01096 [m]

Thus:

t_ins2 = 0.01096 m ….i.e. thickness of low temp insulation = 10.96 mm … Ans.

==========

Prob. 1C.12. Consider a spherical container to store liquid oxygen (LOX). Its OD is 500 mm and the outer surface temp is -183 C. Container surface has an emissivity of 0.2 and is placed in an ambient of 30 C. If convection heat transfer coeff on the outer surface is 12 W/m^2.C what is the evaporation rate of liquid oxygen from the container? Take latent heat of vaporization of oxygen as 214 kJ/kg.

(ii) Now, to reduce the evaporation loss, if the container is covered with an insulation (k_ins = 0.00016 W/m.C) of 10 mm thickness with surface emissivity = 0.2, what is the percentage reduction in evaporation rate as compared to the un-insulated container?

(iii) Plot the evaporation rate as a function of insulation thickness for t_ins = 0 to 50 mm.

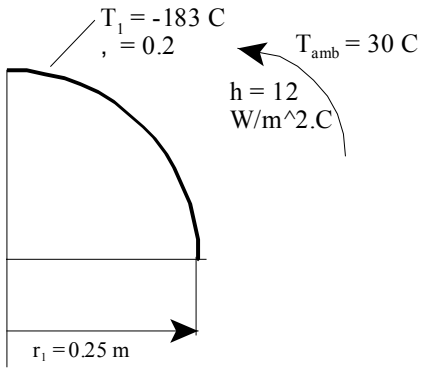

Fig. Prob.1C.12,a.

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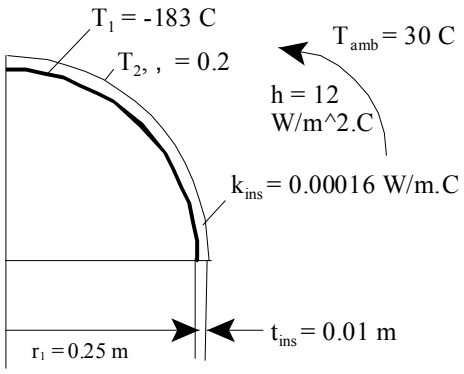

Fig. Prob.1C.12,b.

Mathcad Solution:

Data:

$r_1 := 0.25$ m $\quad T_1 := -183$ C $\quad \varepsilon := 0.2$ $\quad T_{amb} := 30$ C $\quad h := 12$ W/m^2.C

$h_{fg} := 214 \cdot 10^3$ J/kg $\quad k_{ins} := 0.00016$ W/m.C $\quad t_{ins} := 0.01$ m

$\sigma := 5.67 \cdot 10^{-8}$ W/m^2.K^4.....Stefan-Boltzmann constant

Calculations:

Case 1: Spherical container with no insulation:

Now, the heat transfer to the container is by convection and radiation:

$A := 4 \cdot \pi \cdot r_1^2$

i.e. $A = 0.785$ m^2..... surface area of bare container

$Q_{conv} := h \cdot A \cdot (T_{amb} - T_1)$

i.e. $Q_{conv} = 2.007 \cdot 10^3$ W

$Q_{rad} := \sigma \cdot \varepsilon \cdot A \cdot \left[(T_{amb} + 273)^4 - (T_1 + 273)^4 \right]$

i.e. $Q_{rad} = 74.487$ W

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$$Q_{tot} := Q_{conv} + Q_{rad}$$

i.e. $Q_{tot} = 2.082 \cdot 10^{3}$ W

Therefore: $m_{LOX} := \frac{Q_{tot}}{h_{fg}}$

i.e. $m_{LOX} = 9.729 \cdot 10^{-3}$ **kg/s... evapn rate of LOX in un-insulated container.... Ans.**

Case 2: When the container is insulated:

Now, $r_2 := r_1 + t_{ins}$ $r_2 = 0.26$ m

Heat is transferred to outer surface from ambient by convection and radiation and this is transferred to LOX by conduction through the insulation layer.

Let the outer insulation surface temp be T2. Now, T2 is obtained from heat balance at the outer surface.

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Use the Solve Block of Mathcad. Start with a trial value of T2:

$T_2 := 10$ C... trial value of T2

Given

$$\frac{T_2 - T_1}{\frac{r_2 - r_1}{4\cdot\pi\cdot k_{ins}\cdot r_1\cdot r_2}} = \left[h\cdot\left(4\cdot\pi\cdot r_2^2\right)\cdot\left(T_{amb} - T_2\right)\right] + \sigma\cdot\varepsilon\cdot\left(4\cdot\pi\cdot r_2^2\right)\cdot\left[\left(T_{amb} + 273\right)^4 - \left(T_2 + 273\right)^4\right]$$

In the above, LHS is the heat transfer into the LOX through the insulation by conduction from the outer surface and the RHS is heat transfer by convection and radiation from the ambient to the outer surface of insulation.

$T_2(r_2) := \text{Find}(T_2)$ Note: T2 is written as a function of r2, so that it will be convenient to draw the graph.

$T_2(r_2) = 29.753$ **C.... surface temp. T2 at r2 = 0.26 m**

To find heat transfer into LOX:

$$Q(r_2) := \frac{T_2(r_2) - T_1}{\frac{r_2 - r_1}{4\cdot\pi\cdot k_{ins}\cdot r_1\cdot r_2}}$$

i.e. $Q(r_2) = 2.78$ W...heat transferred when r2 = 0.26 m, i.e. with 10 mm thick insulation

And, evapn. rate of LOX:

$$m_{evap}(r_2) := \frac{Q(r_2)}{h_{fg}}$$

i.e. $m_{evap}(r_2) = 1.299\cdot10^{-5}$ **kg/s...evapn. rate of LOX when r2 = 0.26 m, i.e. with 10 mm thick insulation ... Ans.**

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Therefore, % reduction in evapn. rate by using insulation:

$$\text{Percent_reduction} := \frac{m_{LOX} - m_{evap}(r_2)}{m_{LOX}} \cdot 100$$

i.e. Percent_reduction = 99.866 **% reduction in evapn. loss....Ans.**

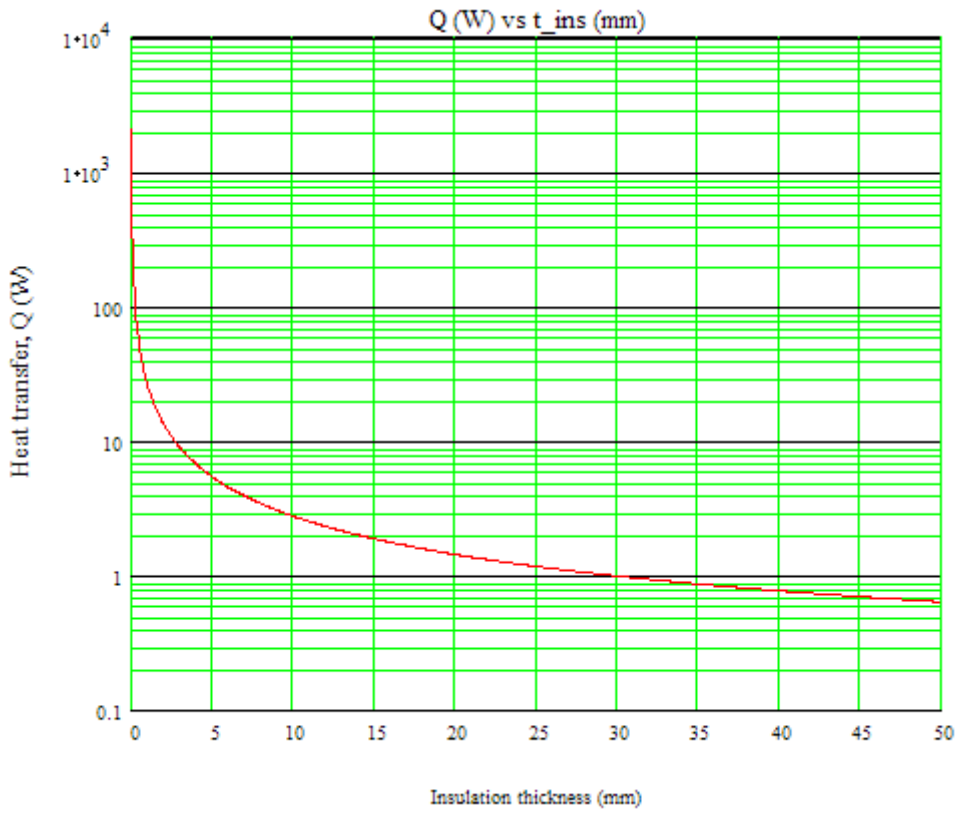
To plot Q and m_evap as a function of insulation thickness:

Remember that insulation thickness =(r2 - r1) * 1000 mm

$r_2 := 0.250000001, 0.25005 .. 0.3$

....define the range variable r2, starting from 0.250000001 to 0.3 m

Note: first value of r2 is slightly above value of r1, to avoid division by zero.



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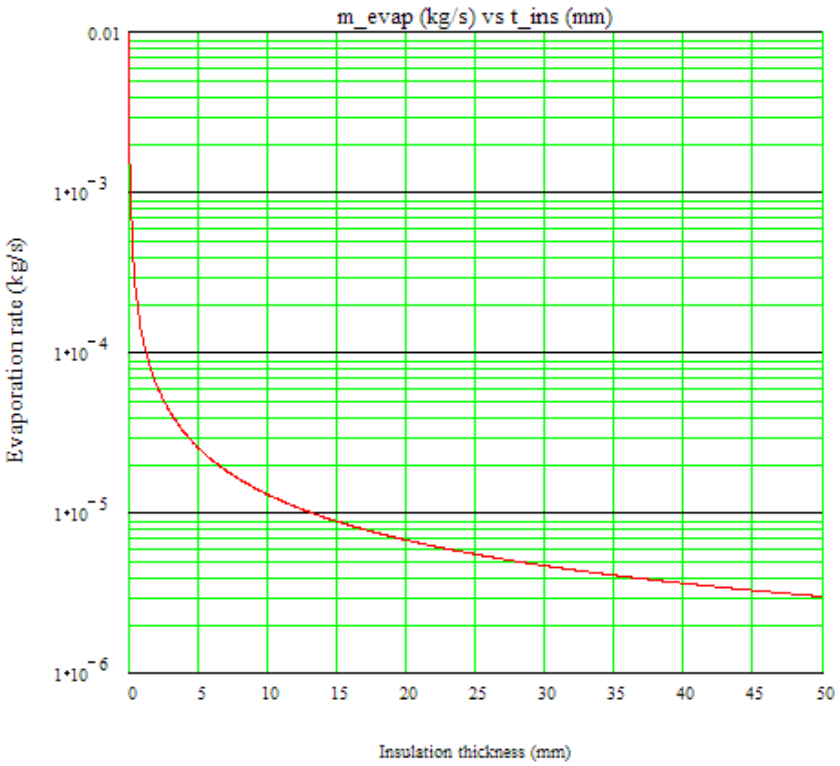

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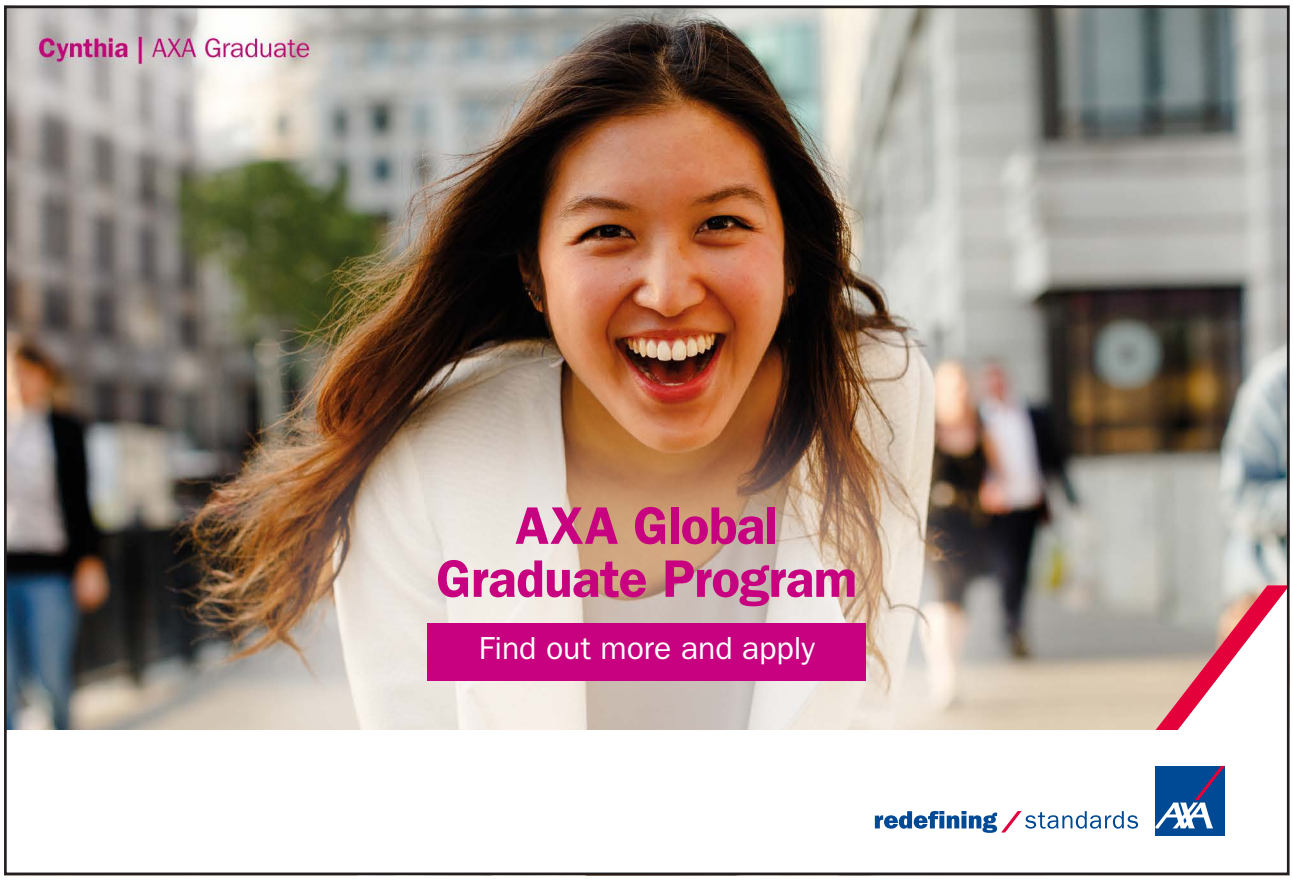

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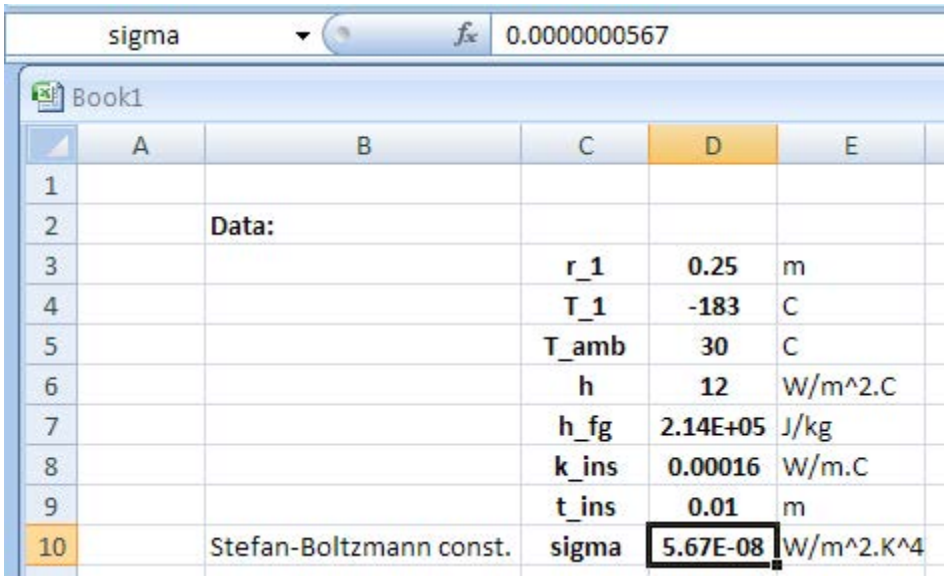
Solve the above problem in EXCEL:

Following are the steps:

1. Set up the EXCEL worksheet, enter data and name the cells:

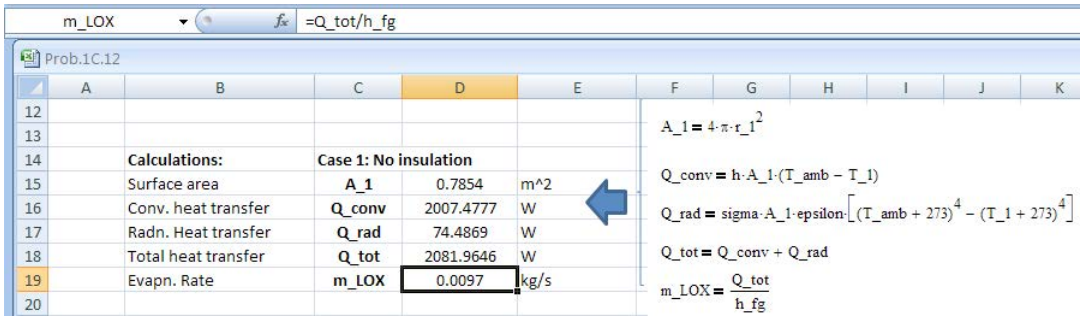


sigma | 0.0000000567

Book1

	A	B	C	D	E
1					
2		Data:			
3			r_1	0.25	m
4			T_1	-183	C
5			T_amb	30	C
6			h	12	W/m^2.C
7			h_fg	2.14E+05	J/kg
8			k_ins	0.00016	W/m.C
9			t_ins	0.01	m
10		Stefan-Boltzmann const.	sigma	5.67E-08	W/m^2.K^4

2. Do the preliminary calculations for case 1, i.e. with no insulation. Formulas used are shown in the worksheet.



m_LOX | =Q_tot/h_fg

Prob.1C.12

	A	B	C	D	E
12					
13					
14		Calculations:	Case 1: No insulation		
15		Surface area	A_1	0.7854	m^2
16		Conv. heat transfer	Q_conv	2007.4777	W
17		Radn. Heat transfer	Q_rad	74.4869	W
18		Total heat transfer	Q_tot	2081.9646	W
19		Evapn. Rate	m_LOX	0.0097	kg/s
20					

$A_1 = 4 \cdot \pi \cdot r_1^2$

$Q_conv = h \cdot A_1 \cdot (T_amb - T_1)$

$Q_rad = sigma \cdot A_1 \cdot epsilon \cdot \left[(T_amb + 273)^4 - (T_1 + 273)^4 \right]$

$Q_tot = Q_conv + Q_rad$

$m_LOX = \frac{Q_tot}{h_fg}$

Thus, evapn. Rate of LOX, when there is no insulation is 0.0097 kg/s …. Ans.

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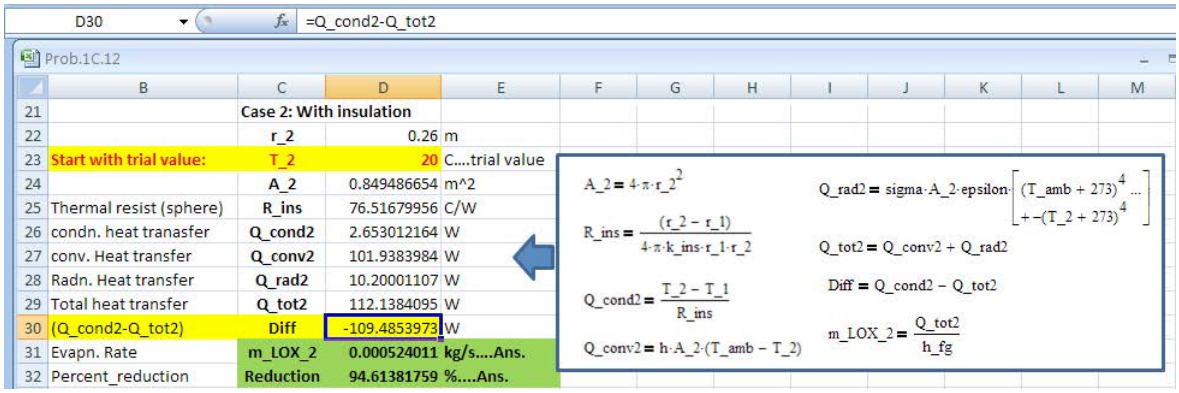
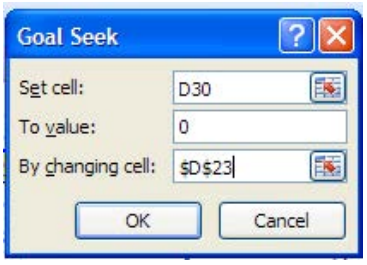
3. Next, let us do the calculations when there is insulation on the container. Here, t_ins = 0.01 m, and therefore r_2 = 0.26 m. To get the temp of the outer surface of insulation, we make a heat balance on that surface, i.e. heat transferred to the outer surface by convection and radiation must be equal to the heat conducted into the container through the insulation layer. In EXCEL, we first assume a value for the surface temp, T_2, and do the calculations, and then apply 'Goal seek' to make the *difference* between Conduction heat transfer and the sum of (Convection + Radiation heat transfer) to zero, by varying T_2. See the following part of worksheet:



Note that in the above worksheet, we have started with a trial value of 20 deg.C for T_2. So, the difference, Diff = (Q_cond2-Q_tot2), (i.e. cell D30) is not equal to zero.

4. Now, we use Goal seek to make cell D30 equal to zero, by changing T_2, i.e. cell D23. Click on Data-What-If Analysis-Goal seek. we get:



Fill up the values: Set_cell = D30, To_value = 0, By changing cell = D23. Click OK:

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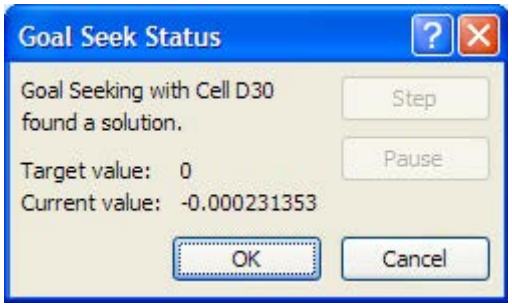
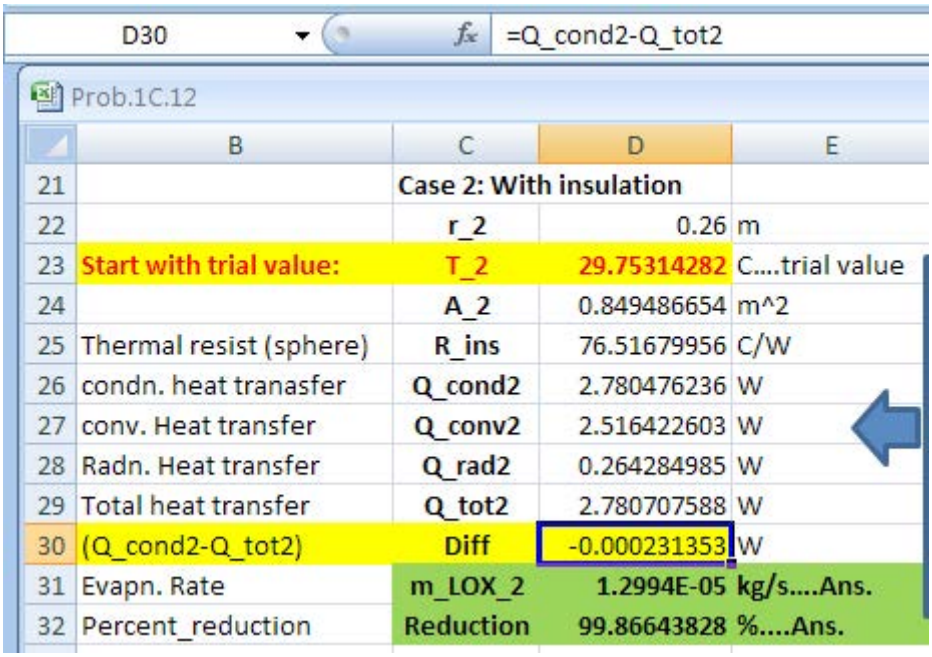
We get the message:



Click OK and *see that T_2 has changed* to 29.95715, and Diff = almost zero. See the worksheet below:



	B	C	D	E
21		Case 2: With insulation		
22		r_2	0.26	m
23	Start with trial value:	T_2	29.75314282	C....trial value
24		A_2	0.849486654	m^2
25	Thermal resist (sphere)	R_ins	76.51679956	C/W
26	condn. heat tranasfer	Q_cond2	2.780476236	W
27	conv. Heat transfer	Q_conv2	2.516422603	W
28	Radn. Heat transfer	Q_rad2	0.264284985	W
29	Total heat transfer	Q_tot2	2.780707588	W
30	(Q_cond2-Q_tot2)	Diff	-0.000231353	W
31	Evapn. Rate	m_LOX_2	1.2994E-05	kg/s....Ans.
32	Percent_reduction	Reduction	99.86643828	%....Ans.

Thus, Evapn. rate of LOX = 1.2994E-06 kg/s and Percent_reduction (as compared to the case with no insulation) is 99.866 %…..Ans.

Note the advantage of EXCEL: all other related values such as Q_cond2, Q_conv2, Q_rad2, Q_tot2 etc. have also changed.

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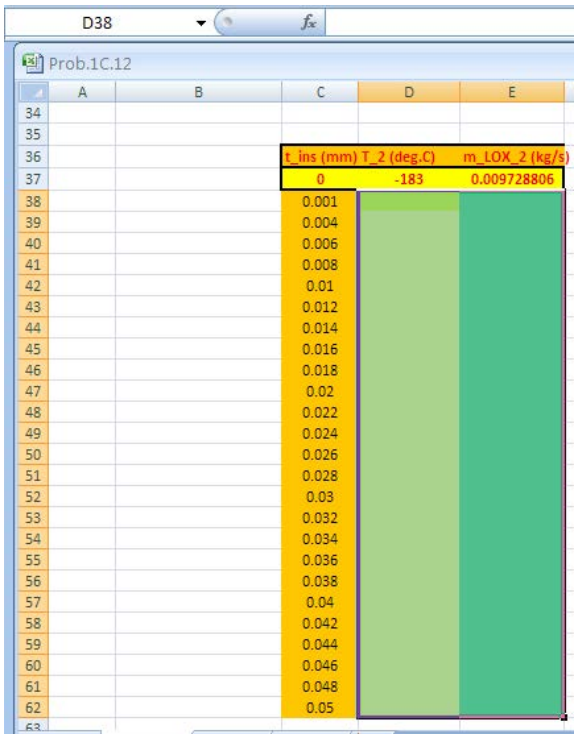
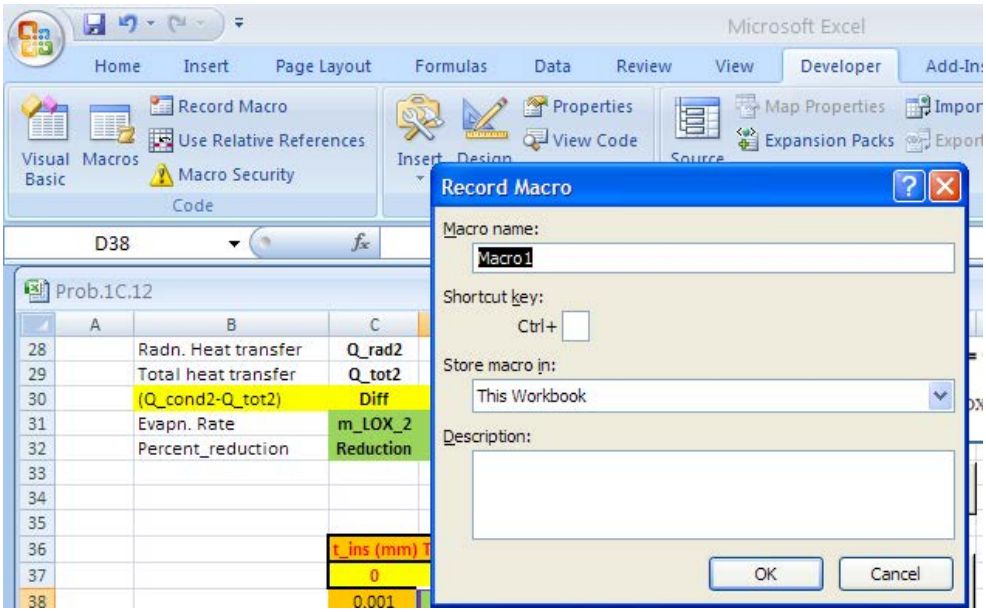
5. Now, let us draw a plot of T_2 and m_LOX_2 as h varies from 0 to 50 mm. When we vary t_ins, r_2 varies and we will find T_2 by Goal seek, starting with a trial value for T_2, and note the up dated values of T_2 and m_LOX_2. And, we repeat the process for other values of t_ins. Easiest way to do this is to get the basic goal seek cpode by the 'Record acro' process and then modify it. *Start with* a ready Table of t_ins, T_2 and m_LOX_2:



Now, record a Macro to go through the Goal seek procedure: Click on Developer – Record Macro: We get:



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Fill up the short cut key, Description as you like: Click OK: Following is the screen shot of the recorded Macro. You can view (and modify, if required) the Macro code by going to: Developer – Visual Basic (first left button in Developer tab):

```
Sub Macro3()
'
' Macro3 Macro
' Finds T_2 and m_LOX_2 as t_ins is varied
'
' Keyboard Shortcut: Ctrl+Shift+R
'


    Range("D30").Select
    Range("D30").GoalSeek Goal:=0, ChangingCell:=Range("D23")
    Range("E34").Select


End Sub
```

6. Now, we will modify this program to: read values of t_ins, one by one, from the Table, do calculations including Goal seek for each value of t_ins, and also draw a plot of m_LOX_2 vs t_ins: Following is the modified code: (Read the comments in the code, for clarity).

```
Sub Macro3()
'
' Macro3 Macro
' Finds T_2 and m_LOX_2 as t_ins is varied
'
' Keyboard Shortcut: Ctrl+Shift+R
'

   Dim i As Integer


   For i = 0 To 24    'Start of For...Next loop

    Range("D10") = Cells(38 + i, 3)  'sets the cell D10 in the worksheet to value in cell C38

   'Following is the code produced by the recorded Macro to apply Goalseek:

    Range("D30").Select
    Range("D30").GoalSeek Goal:=0, ChangingCell:=Range("D23")
    Range("E34").Select

   'copy the values of T_2 and m_LOX_2 fro cells D23 and D31 to the respective cells in the Table:

    Cells(38 + i, 4) = Range("D23")
    Cells(38 + i, 5) = Range("D31")

   Next i 'Repeat the procedure for next value of t_ins in the Table

End Sub
```


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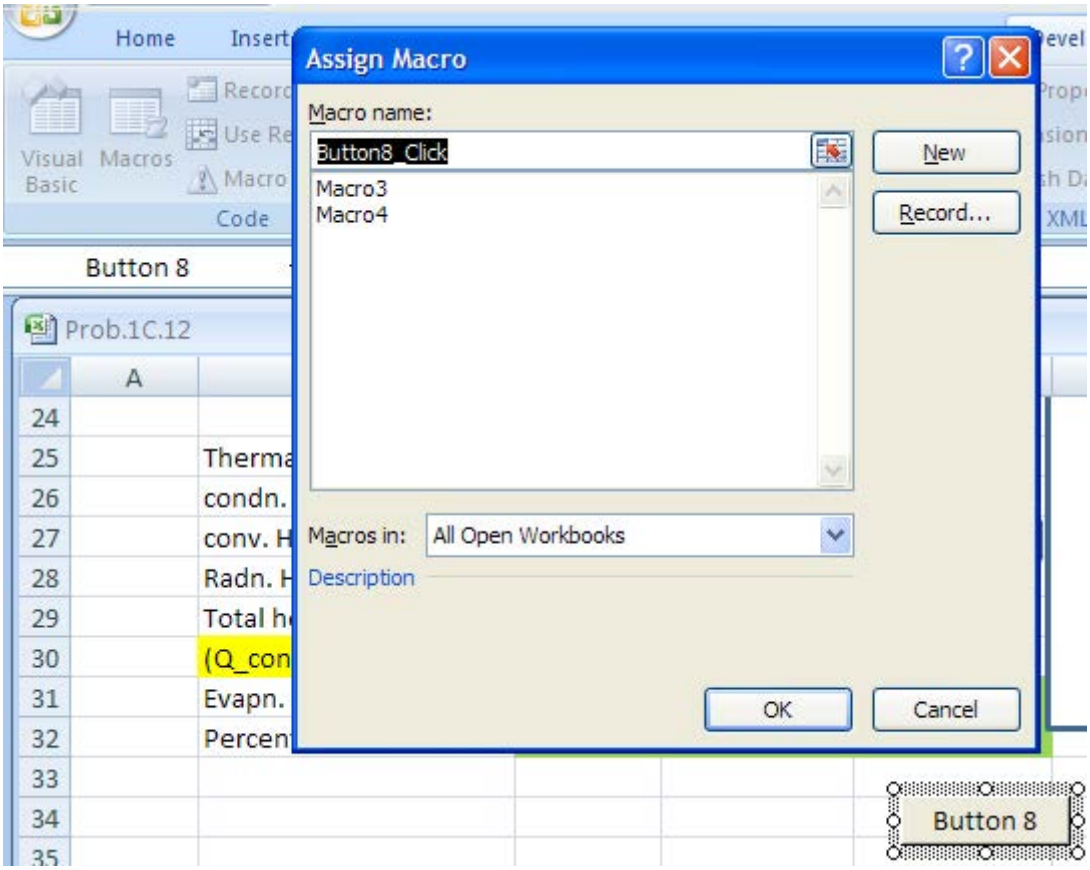
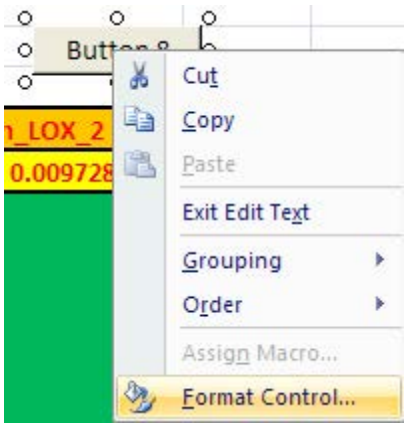
7. Instead of using the short cut key Ctrl+Shift+R, we would like to use a Form control button, which is more convenient. To do this, go to: Developer-Insert_Form controls and click on first item on the left in top row. We get:



Select Macro 3, click OK. Now, the button is coupled to Macro3. Select the Button 8, type RUN and format it by right clicking on the button:



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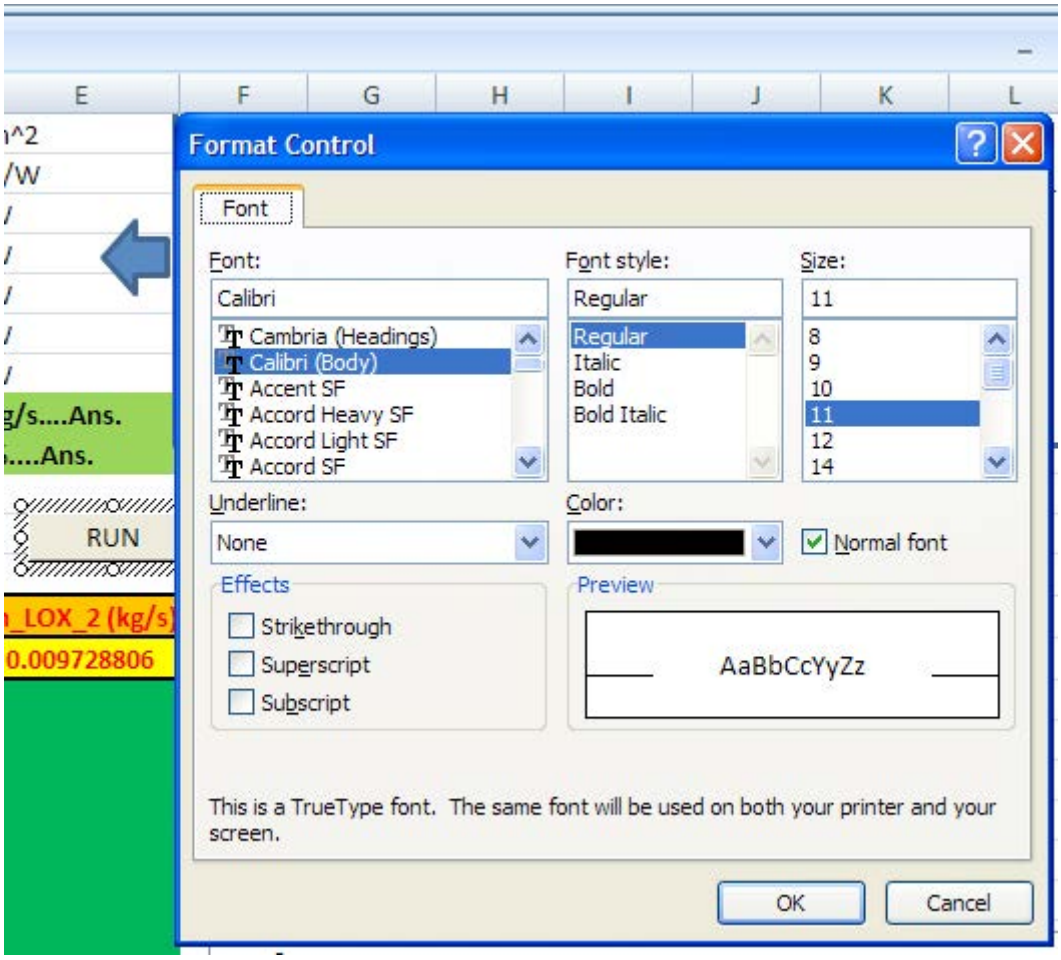
Click on Format control:



Make the choices of font, color etc and click OK. Also, we need to re-set the Table in the worksheet if we desire to run the code again after changing any of the variables. i.e. we have to delete the values in columns D and E. This is shown in another Macro:

```
Sub Macro4()
'
' Macro4 Macro
' Resets the Table
'
' Keyboard Shortcut: Ctrl+Shift+S
'
    Range("D38:E62").Select
    Selection.ClearContents
    Range("E34").Select
End Sub
```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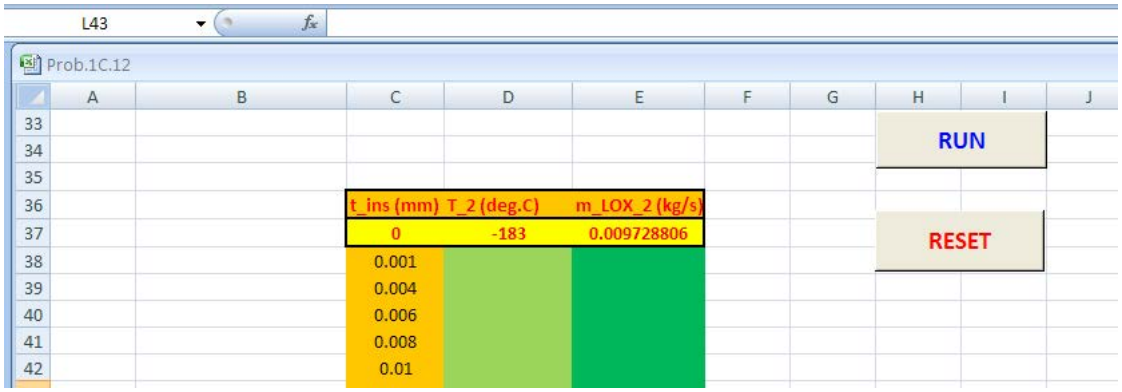
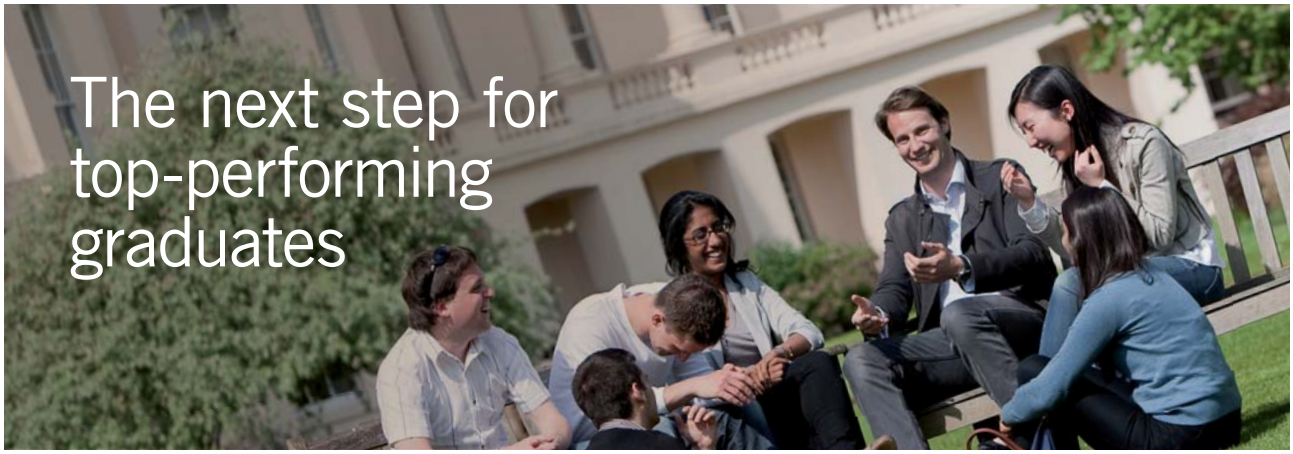
This is also connected to another Form control button named as RESET, as described earlier:





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* Figures taken from London Business School's Masters in Management 2010 employment report

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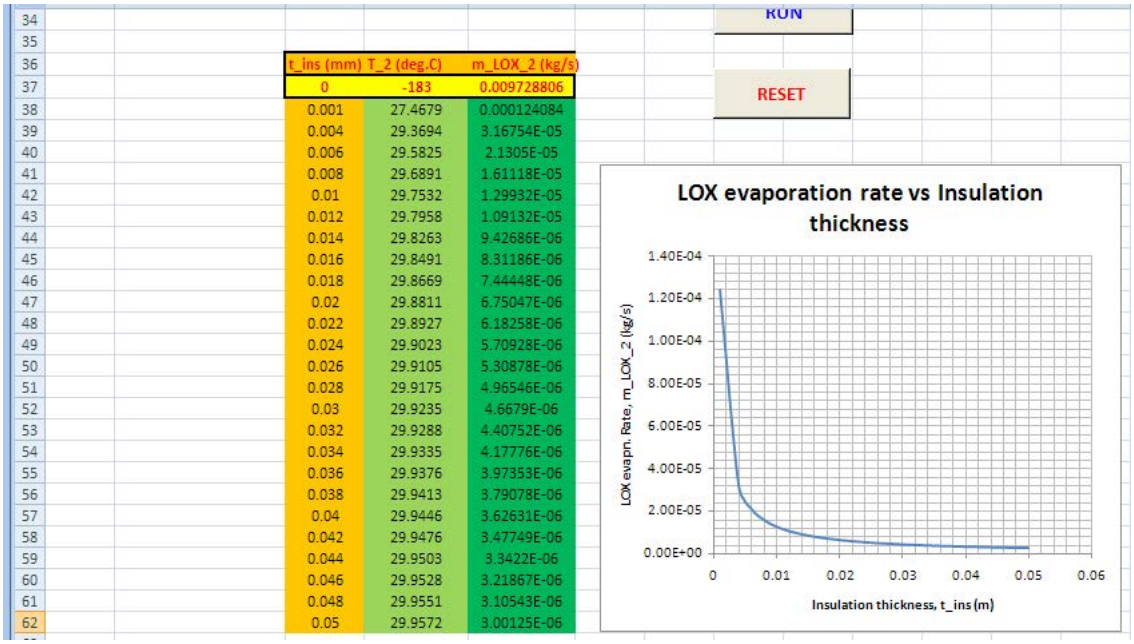
8. Now, click on the button RUN. Immediately, the Table is filled up:

t_ins (mm)	T_2 (deg.C)	m_LOX_2 (kg/s)
0	-183	0.009728806
0.001	27.4679	0.000124084
0.004	29.3694	3.16754E-05
0.006	29.5825	2.1305E-05
0.008	29.6891	1.61118E-05
0.01	29.7532	1.29932E-05
0.012	29.7958	1.09132E-05
0.014	29.8263	9.42686E-06
0.016	29.8491	8.31186E-06
0.018	29.8669	7.44448E-06
0.02	29.8811	6.75047E-06
0.022	29.8927	6.18258E-06
0.024	29.9023	5.70928E-06
0.026	29.9105	5.30878E-06
0.028	29.9175	4.96546E-06
0.03	29.9235	4.6679E-06
0.032	29.9288	4.40752E-06
0.034	29.9335	4.17776E-06
0.036	29.9376	3.97353E-06
0.038	29.9413	3.79078E-06
0.04	29.9446	3.62631E-06
0.042	29.9476	3.47749E-06
0.044	29.9503	3.3422E-06
0.046	29.9528	3.21867E-06
0.048	29.9551	3.10543E-06
0.05	29.9572	3.00125E-06

RUN

RESET

9. Now, draw and format the plot of m_LOX_2 vs t_ins:



Now, if we change the values in Table, the plot also will change accordingly.

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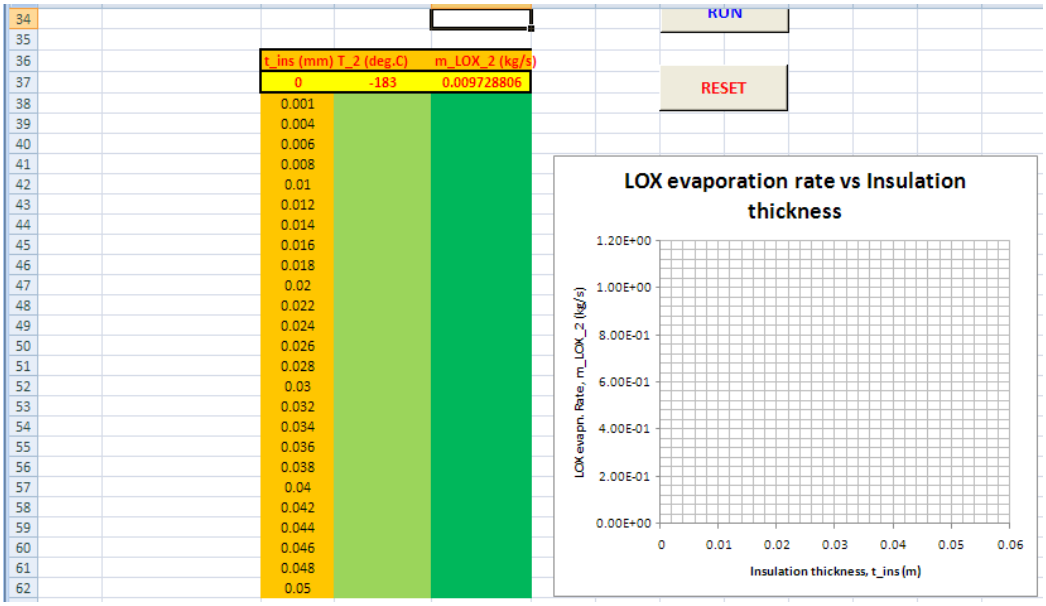
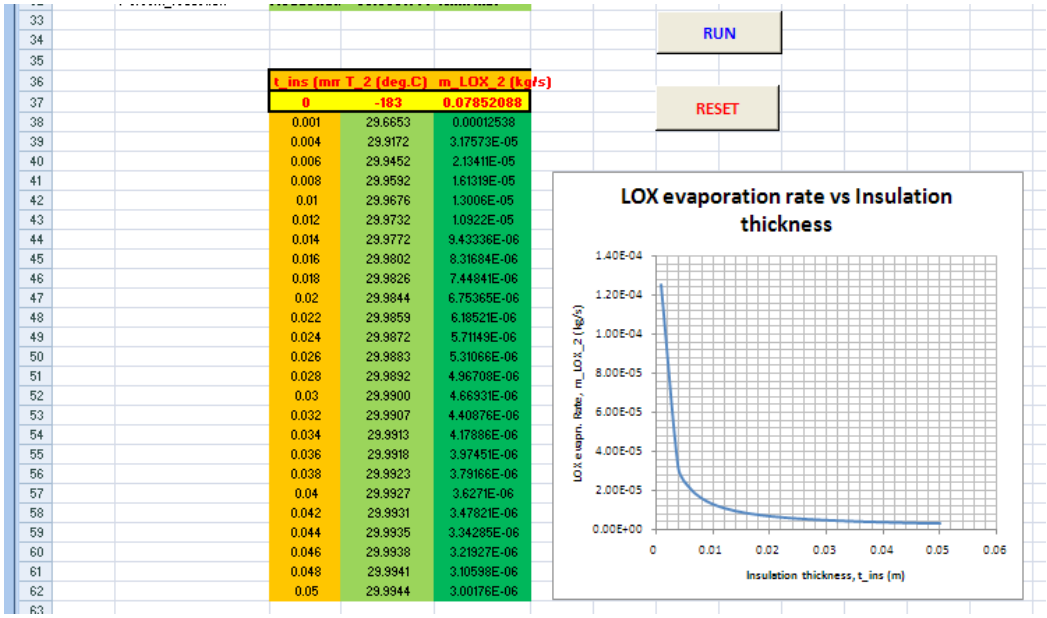
10. If we now click on RESET, we get:



Note that the Table is reset, and the plot is also empty.

11. Now, let us say, the h value (in cell D7) has changed to 100 W/m^2.C. Obviously, all connected calculations will change in other cells. Now, if we click RUN, we get the Table and Plot for this situation:



Thus, EXCEL is very useful in parametric calculations, drawing plots etc.

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Prob. 1C.13. A hollow sphere of 10 cm ID, 30 cm OD of material k = 35 W/m.K contains a liquid chemical. Inner and outer surface temp. are 400 C and 150 C. Determine the heat flow rate through the sphere. Also estimate the temp at a point quarter of the way between the inner and outer surfaces.

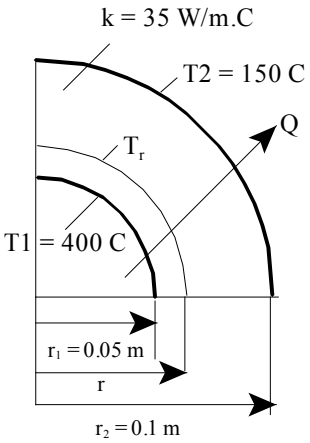

Fig. Prob.1C.13

EES Solution:

"Data:"

r_1 = 0.05 [m]
r_2 = 0.1 [m]
k = 35 [W/m-C]
T_1 = 400[C]
T_2 = 150[C]

"Calculations:"

R_sph = (r_2 – r_1)/(4 * pi * k * r_1 * r_2) "[C/W] … thermal resist of spherical layer"

Q = (T_1 – T_2)/ R_sph "[W] … heat transfer rate"

"In steady state, Q through each layer is same:

At a point quarter way between inner and outer surfaces, radius r = r_1 + (r_2 – r_1)/4 :"

r = r_1 + (r_2 – r_1)/4 "[m]….radius at which temp is reqd. Let the temp be T_r"

"Then, thermal resistance of spherical shell between the inner surface and this new r:"

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R_shell = (r – r_1)/(4 * pi * k * r_1 * r) "[C/W] … thermal resist of spherical shell between r_1 and r"

Q = (T_1 – T_r)/ R_shell "determines T_r, the temp at radius r, since Q, which is already determined, is the same through each layer"

Results:

Unit Settings: SI C kPa kJ mass deg

k = 35 [W/m-C]	Q = 10996 [W]	r = 0.0625 [m]
r_1 = 0.05 [m]	r_2 = 0.1 [m]	R_{shell} = 0.009095 [C/W]
R_{sph} = 0.02274 [C/W]	T_1 = 400 [C]	T_2 = 150 [C]
T_r = 300 [C]		

Thus:

Q = 10996 W …. Heat transfer rate …. Ans.

T_r = 300 C …. Temp at a point quarter way between inner and outer surfaces of spherical shell …. Ans.

==========

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Prob. 1C.14. A spherical tank 1m in dia is maintained at temp. of 120°C and is exposed to a convection environment with h = 25 W/m²K and T_ambient is 15°C. What thickness of urethane foam (k=20 mW/m.K) should be added to ensure that the outer temp of the insulation does not exceed 40°C? What % of reduction in heat loss results from installing the insulation.?

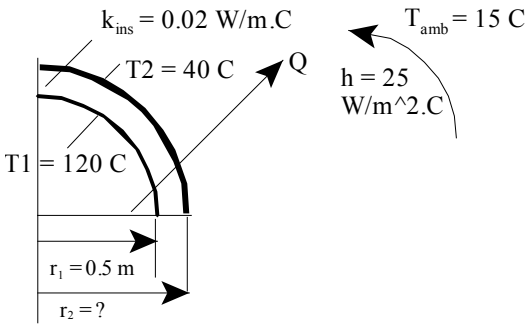

Fig. Prob.1C.14

EES Solution:

"Data:"

r_1 = 0.5 [m]
k_ins = 20e-03 [W/m-C]
T_1 = 120[C]
T_2 = 40[C]
T_amb = 15 [C]
h = 25 [W/m^2-C]

"Calculations:"

"Let the radius after installing the insulation be r_2"

R_ins = (r_2 – r_1)/(4 * pi * k_ins * r_1 * r_2) "[C/W] … thermal resist of spherical layer of insulation"

Q = (T_1 – T_2) / R_ins "[W] … heat transfer, considering the insulation layer only"

"But, in steady state, heat transfer through each layer is same;

i.e. Q should also be equal to heat transfer by convection from the outer surface of insulation to the ambient:"

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R_conv = 1 / (h * 4 * pi * r_2^2) "[C/W]… convection resistance from the outer surface of insulation to ambient"

Q = (T_2 – T_amb)/ R_conv "… determines r_2"

"Therefore: thickness of insulation is: (r_2 – r_1):"

t_insulation = r_2 – r_1 "[m]…. thickness of insulation"

"What is the percentage reduction in heat transfer compared to un-insulated tank?"

Q_bare = (T_1 – T_amb) / (1 / (h * 4 * pi * r_1^2)) "[W] … heat transfer for the un-insulated tank …. only convection from the outer surface of tank"

Percent_reduction = (Q_bare – Q) * 100 /Q_bare "[%]"

Results:

Unit Settings: SI C kPa kJ mass deg

$h = 25$ [W/m^2-C]	$k_{ins} = 0.02$ [W/m-C]
$Percent_{reduction} = 75.95$ [%]	$Q = 1984$ [W]
$Q_{bare} = 8247$ [W]	$r_1 = 0.5$ [m]
$r_2 = 0.5025$ [m]	$R_{conv} = 0.0126$ [C/W]
$R_{ins} = 0.04033$ [C/W]	$T_1 = 120$ [C]
$T_2 = 40$ [C]	$T_{amb} = 15$ [C]
$t_{insulation} = 0.002547$ [m]	

Thus:

t_insulation = 0.002547 m = 2.547 mm … thickness of insulation required to obtain surface temp = 40 C….Ans.

Percent_reduction = 75.95 % … reduction in heat transfer as a result of applying the insulation … Ans.

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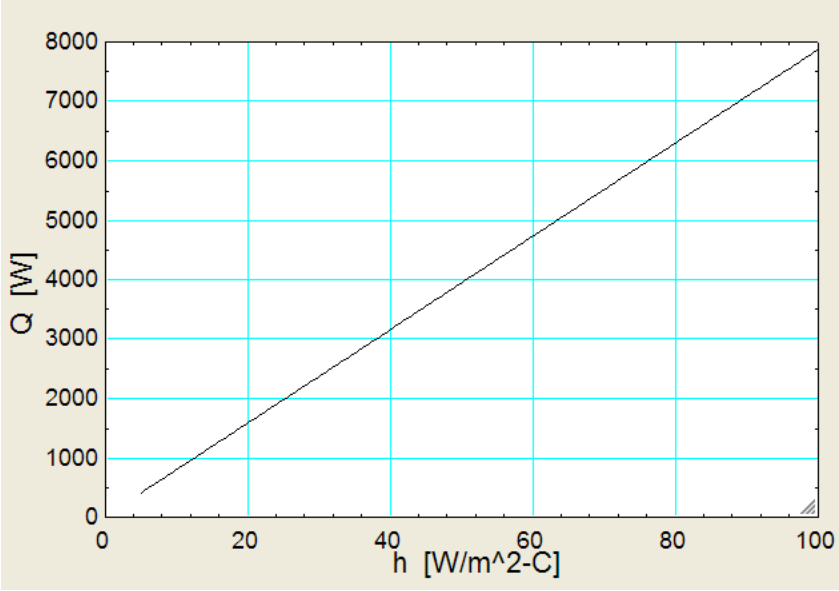
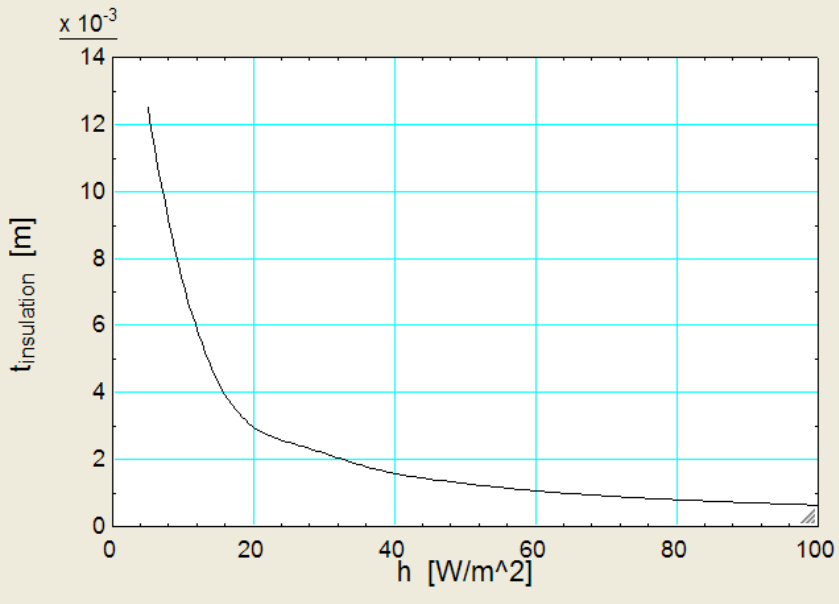
In addition:

Find the variation in Q and t_ins as h varies from 5 to 100 W/m^2/C, with other parameters remaining unaltered:





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Prob. 1C.15. A 3.3 cm OD steel pipe, outside surface of which is at 500 K, is surrounded by still air at 300 K. The heat transfer coefficient by natural convection is 10 W/(m^2.K). It is proposed to reduce the heat loss to half by applying magnesia insulation (k = 0.07 W/(m.K) on the outside surface of the pipe. Determine the thickness of the insulation. Assume pipe surface temperature and convective heat transfer coefficients remain the same.[M.U.]

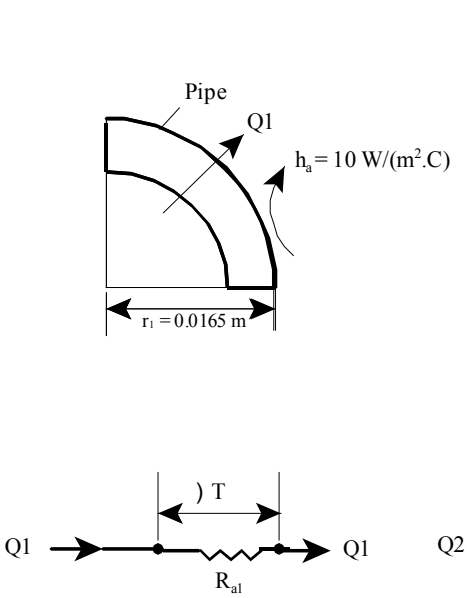

Fig.Prob.1C.15 (a)

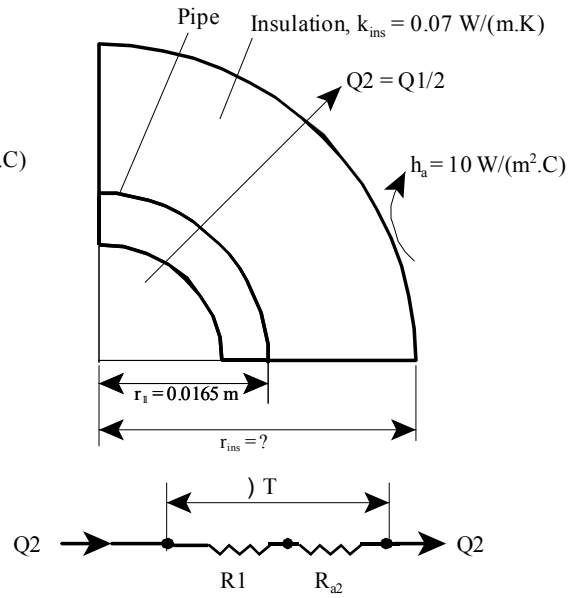

Fig.Prob.1C.15 (b)

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EXCEL Solution:

We apply Thermal resistance concept since it is a case of steady state, one dimensional conduction, with no internal heat generation.

There are two cases:

Case (i): Without insulation i.e. bare pipe – now, the heat transfer occurs only by natural convection on the pipe surface and the heat transfer rate, Q1 is given by Newton's Law of cooling,
viz. $Q1 = h\,(2\pi.r1.\,L).\Delta T$, Or, $Q1 = \Delta T/Ra_1$, where Ra_1 is the convective resistance and
$\Delta T = (500 - 300)$ deg.

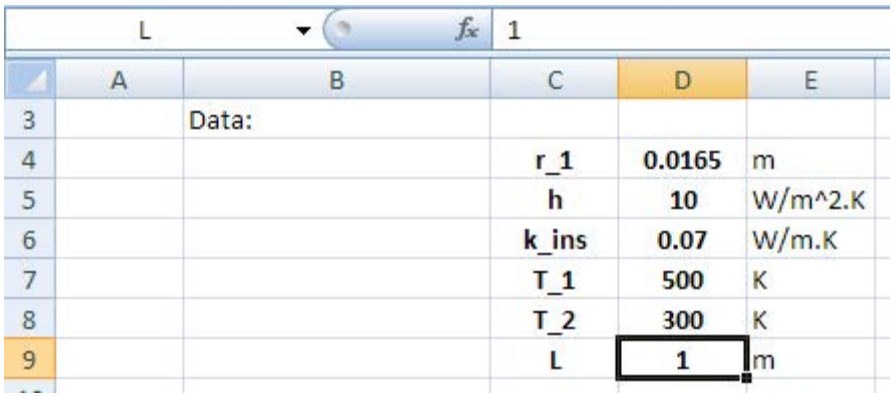
Case (ii): With insulation: Now, the heat transfer rate, Q2 is given to be one-half of Q1. Thermal resistances involved are: the conductive resistance of the cylindrical insulation layer (= R1) and the convective resistance over the insulation surface (= Ra_2) .i.e. $Q2 = \Delta T/(R1 + Ra_2)$.

Write the expression for Q2 and solve the resulting transcendental equation by trial and error, using GoalSeek in EXCEL, to get the outer radius of insulation.

Situations of case (i) and (ii) are depicted in Fig (a) and (b) above.

Following are the steps in EXCEL Solution:

1. Start EXCEL, enter the data and name the cells:



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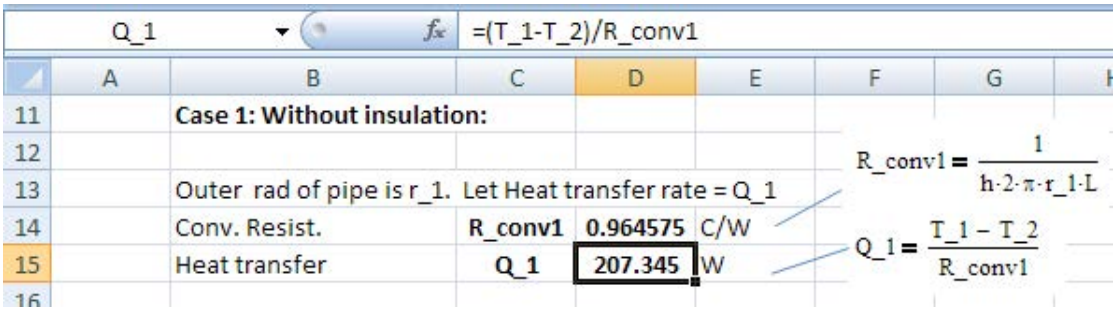
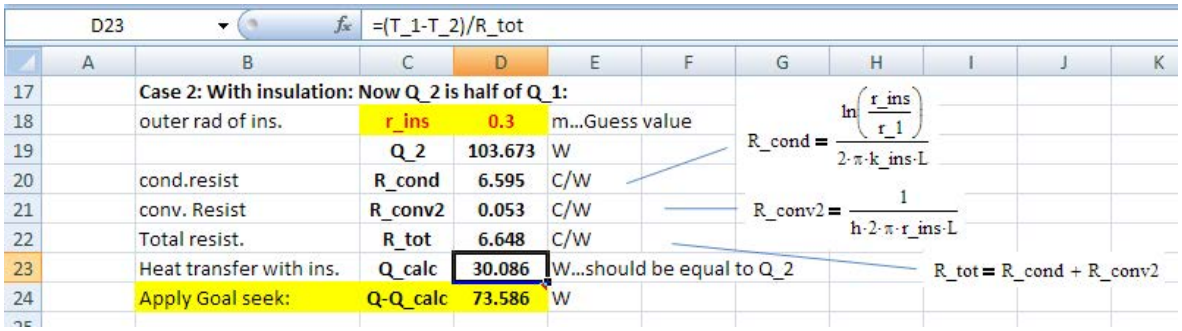
2. Do calculations foe case 1, i.e. for bare pipe, and get Q_1:

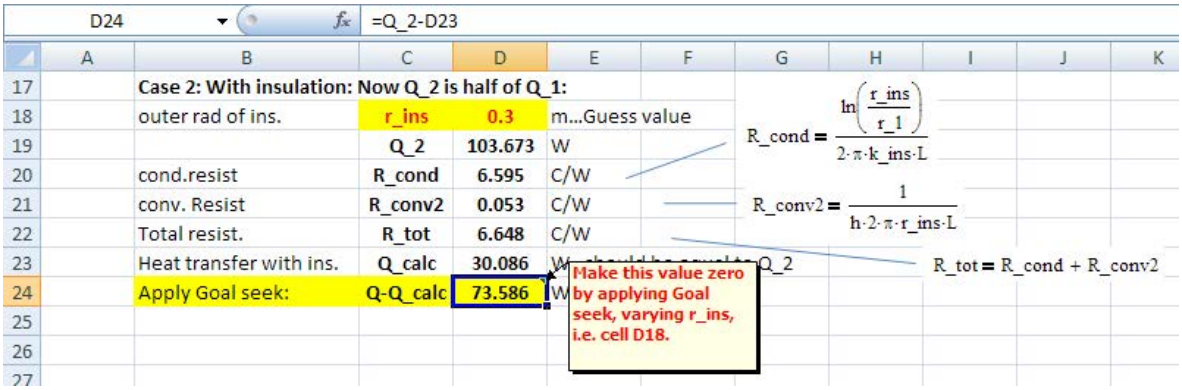


In the above fig. the formulas used are also shown for ready reference.

3. Next, do calculations for case 2, i.e. Q_2 = (0.5 * Q_1), with insulation. Start with a guess value for outer radius of insulation, r_ins:



4. Now, apply Goal Seek to make cell D23 zero by changing cell D18 (i.e. r_ins): See the cell comment below:



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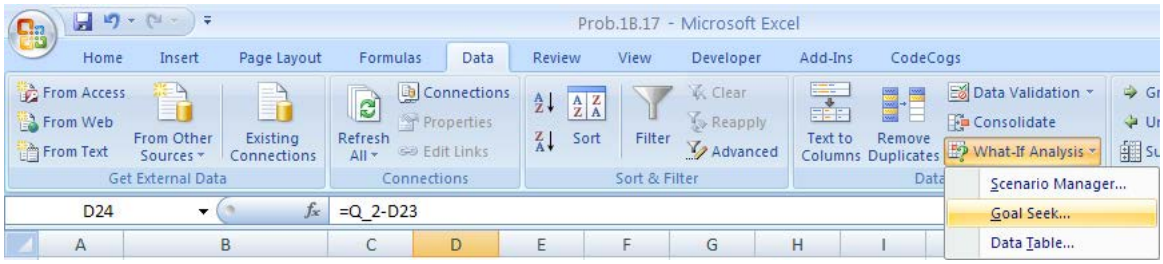
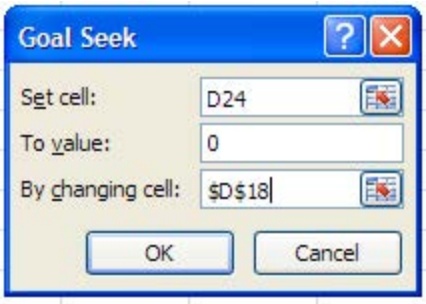
5. Now, apply Goal Seek: Go to Data-What If Analysis-Goal Seek:



And click on Goal Seek: We get:



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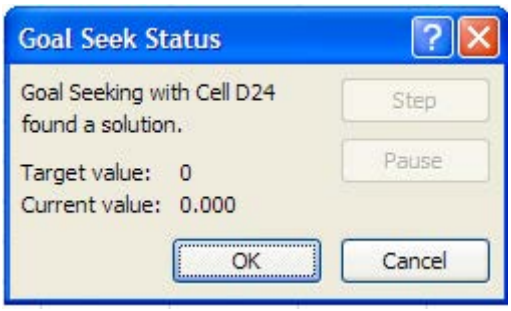
We have: Set cell: D24

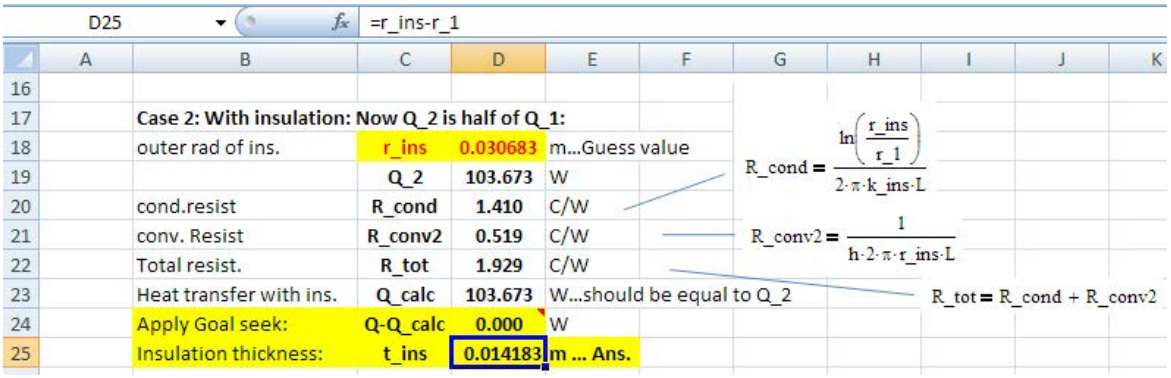
To value: zero

By changing cell: D18

Press OK: We get:



Goal Seek has found a solution. Press OK to get final results:



Thus: r_ins = 0.030683 m … Ans.

And, thickness of insulation = (r_ins – r_1) = 0.014183 = 14.18 mm … Ans.

Note that other values such as thermal resistances, Q_calc etc. have also got updated.

==========

Prob.1C.16. The inner and outer radii of a hollow cylinder are 5 and 10 cm respectively. The inside surface is maintained at 300 C and the outside surface at 100 C. The thermal conductivity varies with temperature over this temperature range as: $k(T) = 0.5 \times (1 + 10^{-3} T)$, where T is in deg. C and k(T) is in W/(m.C). Determine:

1) heat flow rate per metre length of cylinder
2) temperature at mid-thickness of shell, and
3) sketch the temperature profile within the shell

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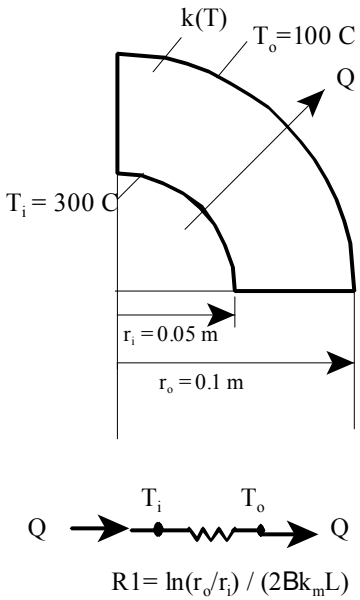

Fig. Prob.1C.16

EXCEL Solution:

From Ref.[1], the relations for T(r) and Q for a cylindrical shell with *linearly varying* k are:

$$Q = \frac{2\pi k_m L (T_i - T_o)}{\ln(\frac{r_o}{r_i})} \cdots\cdots (4.70)$$

where

$k_m = k_o (1 + \beta T_m)$ = mean value of thermal cond. and,

$T_m = (T_i + T_o)/2$ = mean value of temperature

Thermal resistance is given by:

$$R_{cyl} = \frac{\ln(\frac{r_o}{r_i})}{2\pi k_m L} \cdots\cdots (4.71)$$

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And, temp distribution is given by:

$$T(r) = \frac{-1}{\beta} + \sqrt{\left(\frac{1}{\beta} + T_i\right)^2 - \frac{2}{\beta} \times \frac{\ln(\frac{r}{r_i})}{\ln(\frac{r_o}{r_i})}(T_i - T_o)[1 + \beta \times T_m]} \cdots\cdots (4.72)$$

Now, since theeqn for Tr is rather complicated, we will write VBA Functions for Q, Tr and R_cyl, which can be used in the worksheet whenever we need them. These Functions will be like any other built-in Functions of EXCEL.

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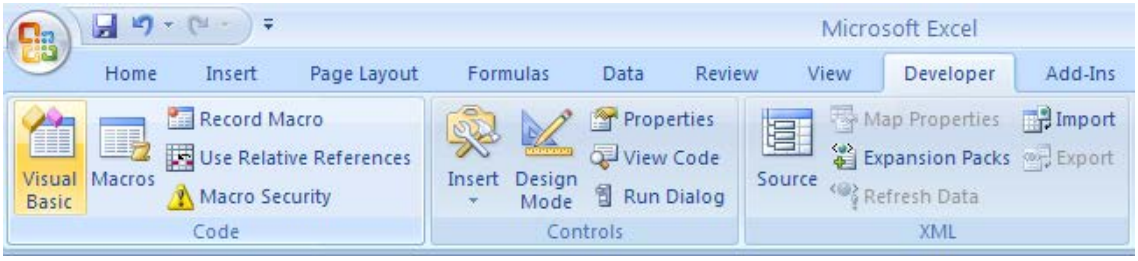
Following are the steps in EXCEL solution:

1. Set up the worksheet, enter data and name the cells:

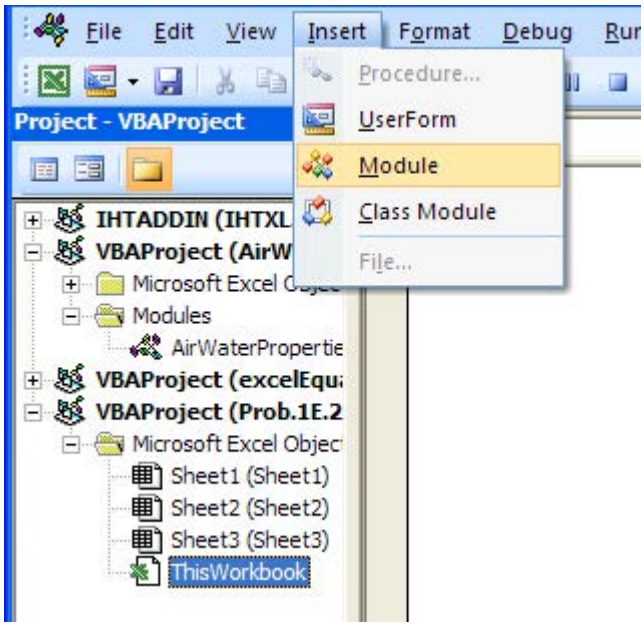
2.

	A	B	C	D	E	F	G
1							
2							
3		Data:					
4			r_i	0.05	m		
5			r_0	0.1	m		
6			T_i	300	C		
7			T_0	100	C		
8		k(T)=0.5 * (1 + 0.001 * T), W/m.C, where T is in deg.C					
9			k_0	0.5			
10			beta	0.001			

3. Now, write the VBA Functions: To do this, go to Developer – Visual Basic. We get:



Click on Visual Basic to get:



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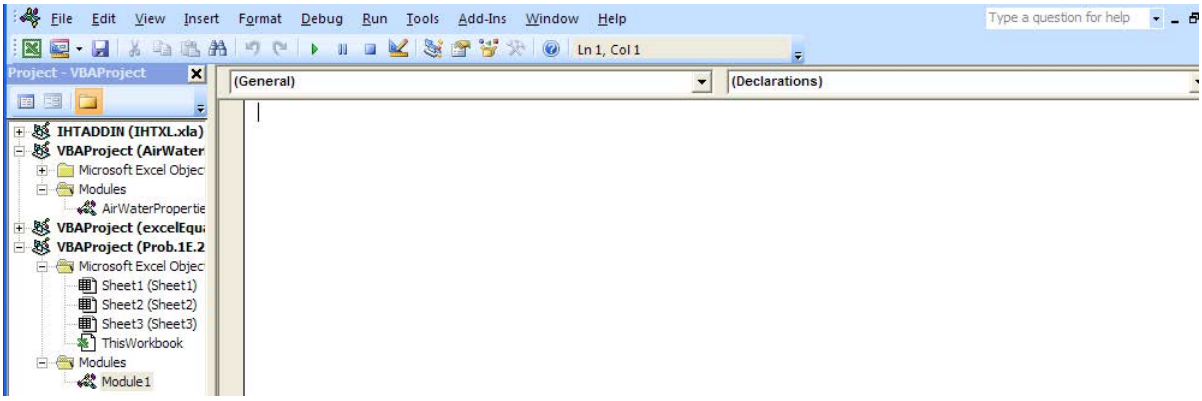
Click on Insert-Module in the above. We get:



4. Now, we can write the code in blank space:

```
Option Explicit

Function OneD_condn_variable_k_cyl_Q(k_0 As Double, beta As Double, L As Double, T_i As Double, _
T_o As Double, r_o As Double, r_i As Double) As Double

'gives heat transfer rate in a cyl, k varying linearly, k = k0 * (1 + beta* T)
'Mean thermal cond, k_m = k_0 * (1+beta * T_m), Mean temp, T_m = (T_i + T_0)/2

    Dim T_m As Double
    Dim k_m As Double

    T_m = (T_i + T_o) / 2
    k_m = k_0 * (1 + beta * T_m)

    OneD_condn_variable_k_cyl_Q = 2 * Application.Pi() * k_m * L * (T_i - T_o) / _
    Application.Ln(r_o / r_i)

End Function

Function OneD_condn_variable_k_cyl_Tr(r As Double, T_i As Double, T_o As Double, r_i As Double, _
r_o As Double, beta As Double) As Double

'gives temp distribn along radius

Dim T_m As Double, AA As Double, BB As Double

T_m = (T_i + T_o) / 2
AA = (1 / beta + T_i) ^ 2
BB = (2 / beta) * Application.Ln(r / r_i) * (T_i - T_o) * (1 + beta * T_m) / Application.Ln(r_o / r_i)
    OneD_condn_variable_k_cyl_Tr = -1 / beta + Sqr(AA - BB)
End Function
Function OneD_condn_variable_k_cyl_Rcyl(k_m As Double, L As Double, r_o As Double, _
r_i As Double) As Double
'gives thermal resist of cyl, variable k
    OneD_condn_variable_k_cyl_Rcyl = Application.Ln(r_o / r_i) / (2 * Application.Pi() * k_m * L)
End Function
```

There are 3 Functions for cyl. system in the above screen shot: One for Q, another one for Tr and the other one for R_cyl in 1D conduction, variable k.

Starting from top:

Line 1: Declares that all variables should be explicitly declared. This is recommended as a good programming practice, which will be useful in de-bugging the code.

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Line 2, 3: Declares the Function name. Note that all variables involved in calculation are shown and declared inside the brackets). Also to continue the code to the next line, put an under-score i.e. _) at the end of the previous line, after a space.

Line 4, 5: comments

Line 6, 7: Dimensions of two variables, T_m and k_m, are declared. These variables are used only within this Function

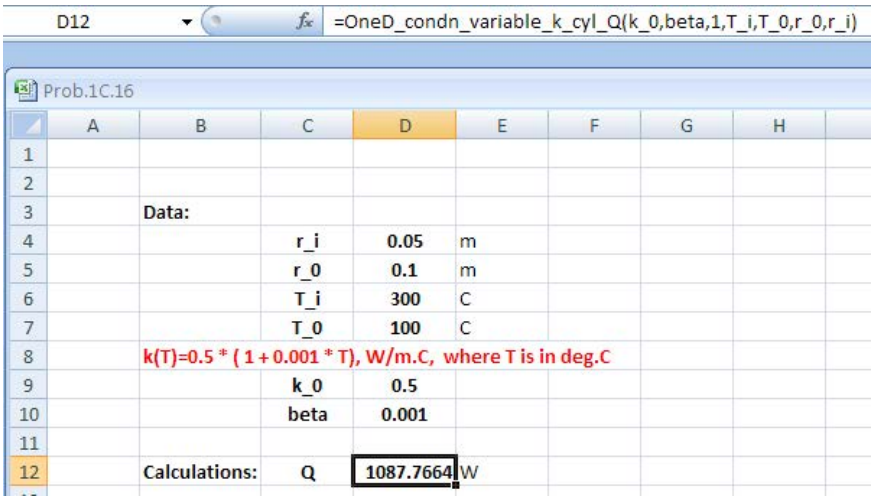
Line 8, 9: calculation of T_m and k_m

Line 10, 11: Function calculation. Note that PI and Ln are functions available in EXCEL only (not in VBA); so, they written as: Application.PI() and Application.Ln().Here, Application refers to EXCEL.

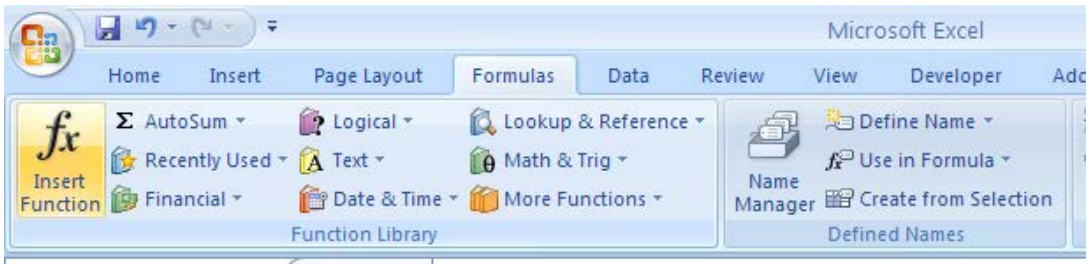
Line 12: End statement of Function.

Similarly, study the code for other two Functions to calculate Tr and R_cyl.

5. Now, go back to EXCEL worksheet (by clicking on EXCEL emblem at the top left of VBA window). Let us calculate the heat transferred Q:



Note the formula entered in cell D12 in the Formula bar. This is the VBA code we wrote for Q. It is available now as a built-in Function in EXCEL under the *'user defined'* category. To use it, first select the cell D12 (which is empty) and click on Formulas – Insert Function:



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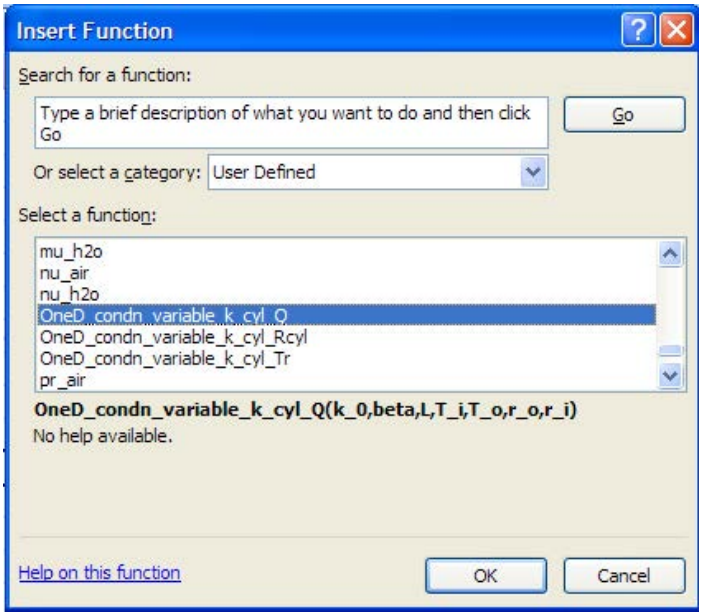
Click on Insert Function. We get:



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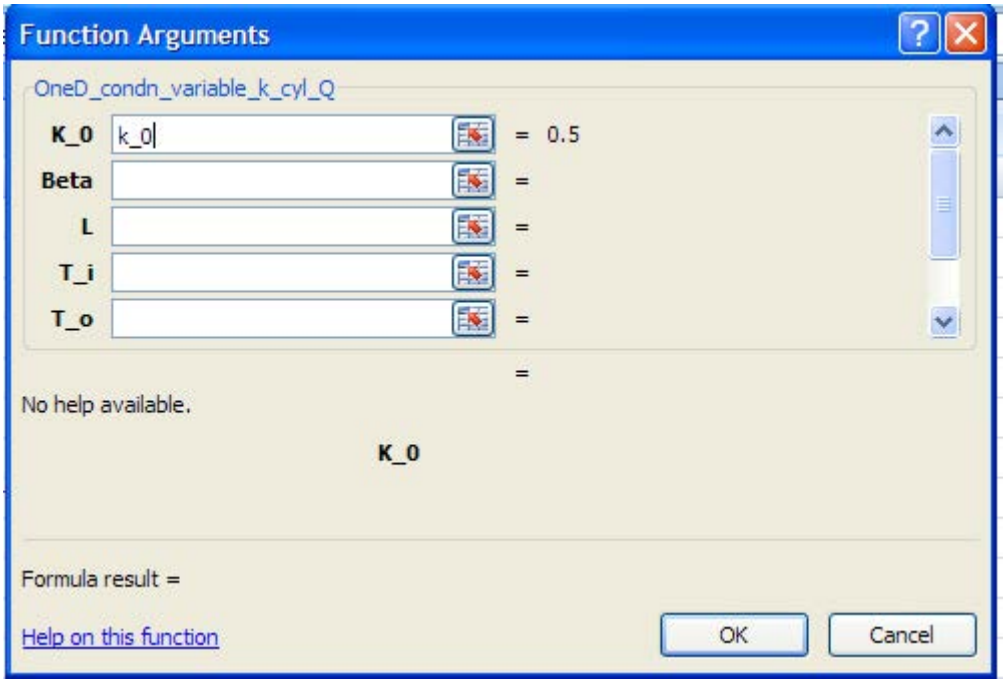
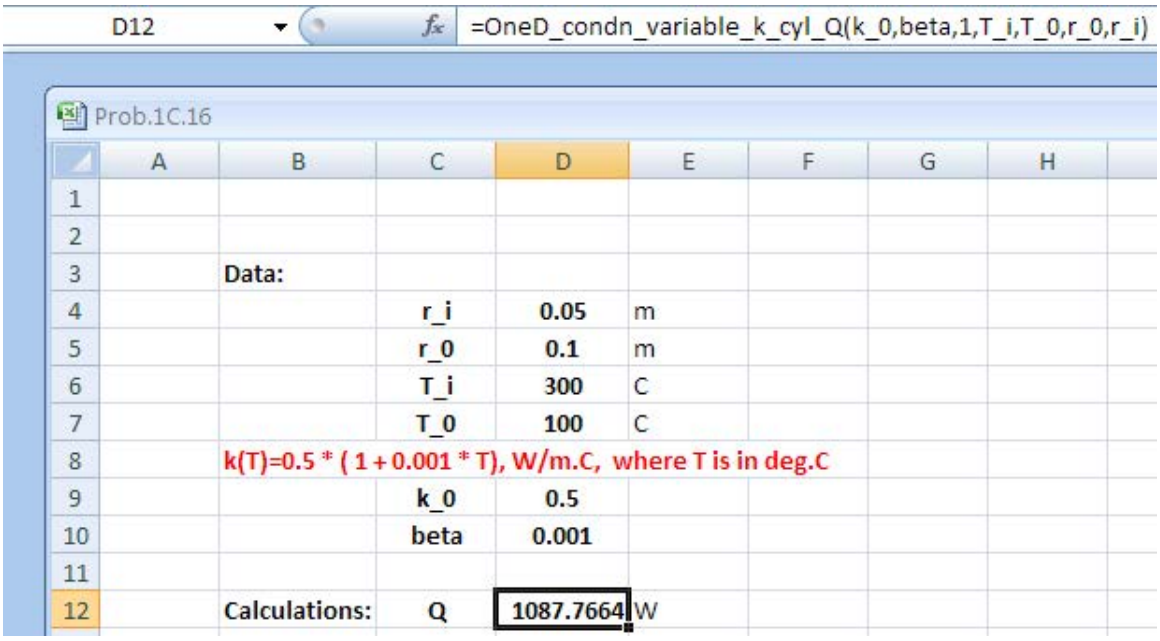
Select the Function for Q as shown above and click OK. We get:



Fill up all the variables (*by pointing and clicking* at the concerned cells D4 to D10) and click OK. We get the final result in cell D12 as shown below:



Thus, Q = 1087.766 W … Ans.

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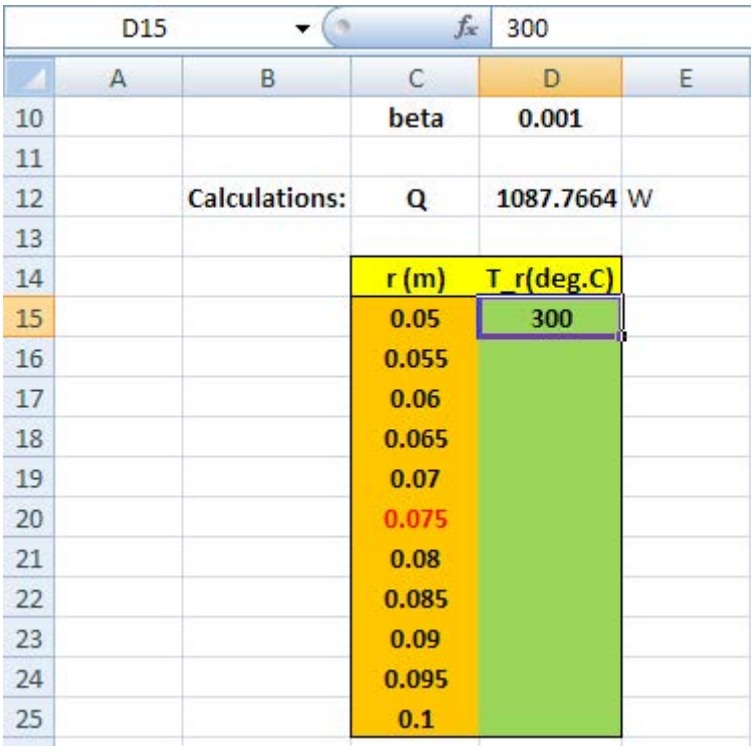
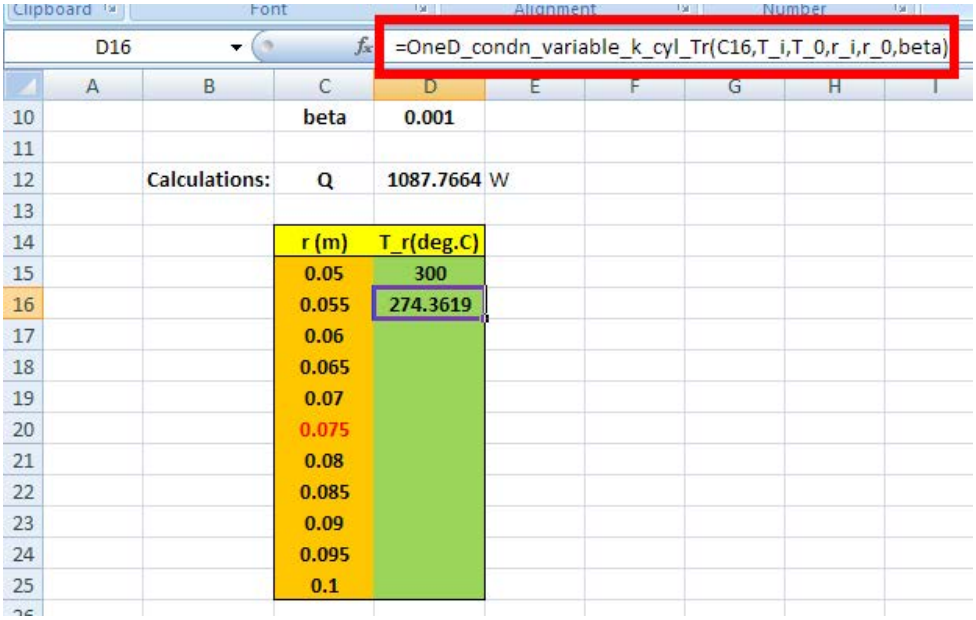
6. Now, we would like to draw the temp profile as radius changes. First prepare a Table of r and Tr as shown. Note that at r – r_i the temp is known. Also, at r = r_0, the temp should be verified.



	A	B	C	D	E
10			beta	0.001	
11					
12		Calculations:	Q	1087.7664	W
13					
14			r (m)	T_r(deg.C)	
15			0.05	300	
16			0.055		
17			0.06		
18			0.065		
19			0.07		
20			0.075		
21			0.08		
22			0.085		
23			0.09		
24			0.095		
25			0.1		

7. Now, enter the Formula for Tr in the D16, against r = 0.055 m:



	A	B	C	D	E	F	G	H	I
10			beta	0.001					
11									
12		Calculations:	Q	1087.7664	W				
13									
14			r (m)	T_r(deg.C)					
15			0.05	300					
16			0.055	274.3619					
17			0.06						
18			0.065						
19			0.07						
20			0.075						
21			0.08						
22			0.085						
23			0.09						
24			0.095						
25			0.1						

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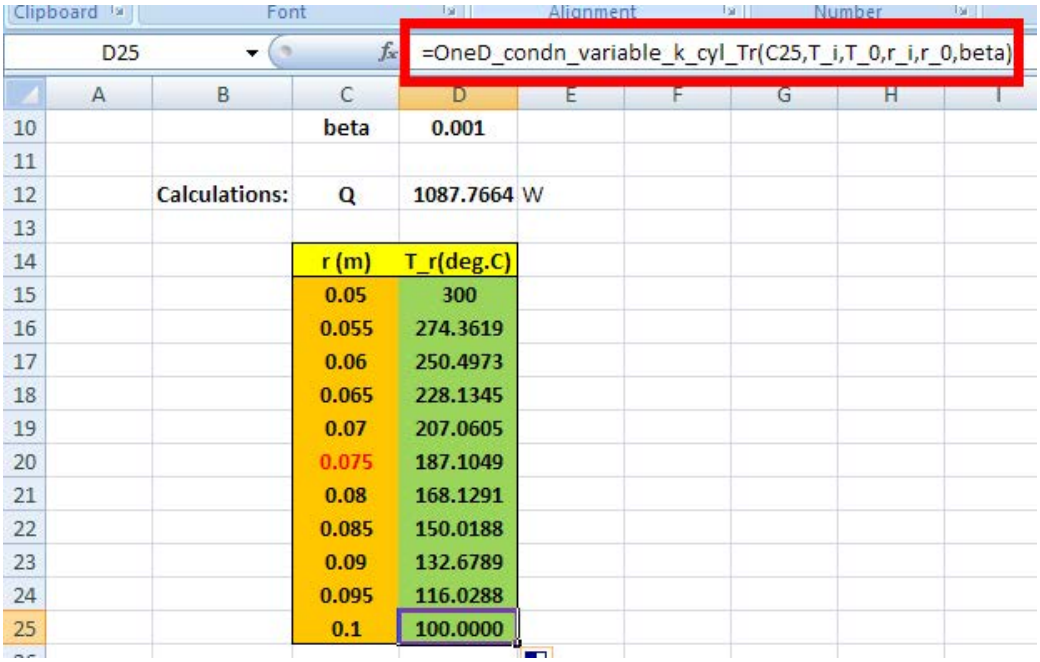
See the Formula bar above to see the eqn entered in cell D16. Note that while entering the eqn, we have written relative reference for 'r', i.e. C16, so that while drg-copying downwards, the other values for 'r' in column C are automatically entered.

8. Now, drag-copy the cell D16 up to cell D25. Immediately, all calculations are completed:



	A	B	C	D	E	F	G	H	I
10			beta	0.001					
11									
12		Calculations:	Q	1087.7664	W				
13									
14			r (m)	T_r(deg.C)					
15			0.05	300					
16			0.055	274.3619					
17			0.06	250.4973					
18			0.065	228.1345					
19			0.07	207.0605					
20			0.075	187.1049					
21			0.08	168.1291					
22			0.085	150.0188					
23			0.09	132.6789					
24			0.095	116.0288					
25			0.1	100.0000					

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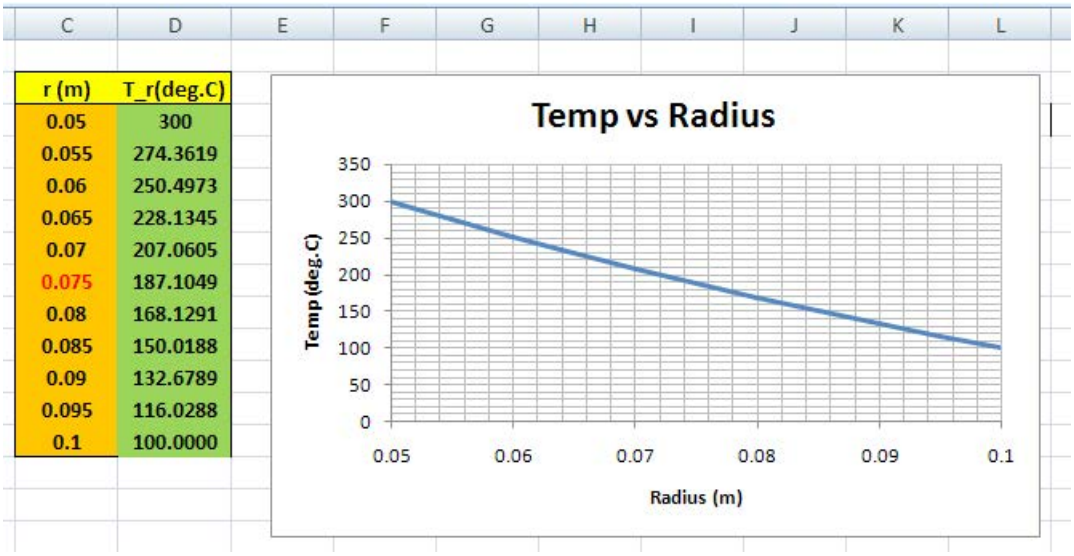
Note that at r = 0.1 m, the temp is 100 deg.C, as it should be. This also indicates that we have written the formula for Tr correctly in the VBA code.

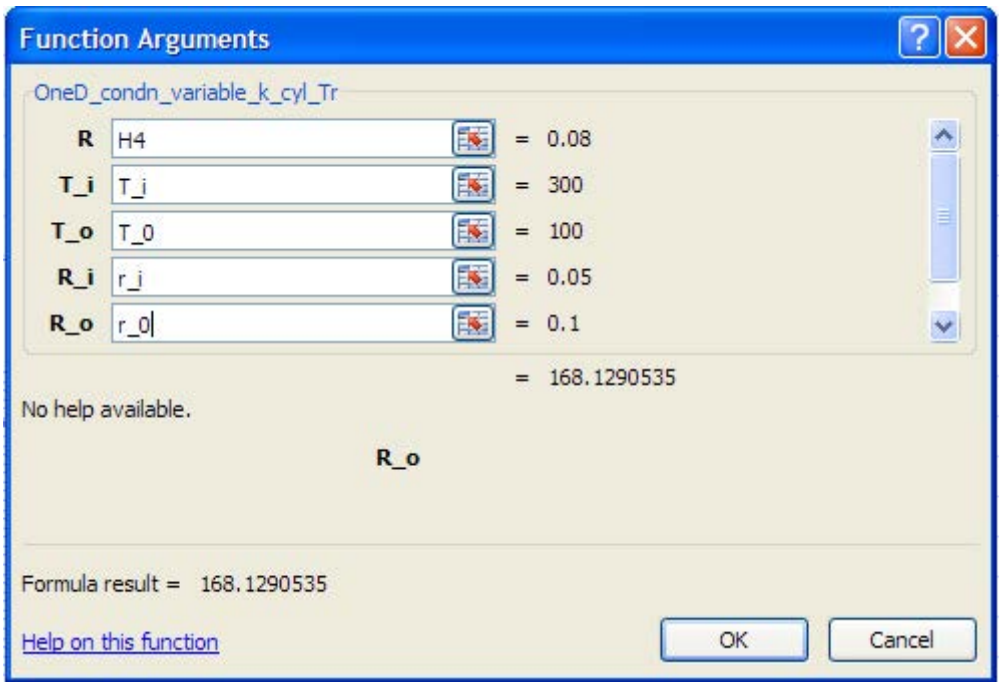
We see that: at r = 0.075 m, i.e. at mid-thickness, the temp is 187.105 deg. C … Ans.

9. Now, plot the graph of Tr vs r in EXCEL:



r (m)	T_r(deg.C)
0.05	300
0.055	274.3619
0.06	250.4973
0.065	228.1345
0.07	207.0605
0.075	187.1049
0.08	168.1291
0.085	150.0188
0.09	132.6789
0.095	116.0288
0.1	100.0000

10. Now, let us say, we need to find out at what radius the temp is 125 deg.C. We use 'Goal seek' in EXCEL. Enter a trial value for r in cell H4 and find out Tr *inserting* the Function for Tr in cell H5:



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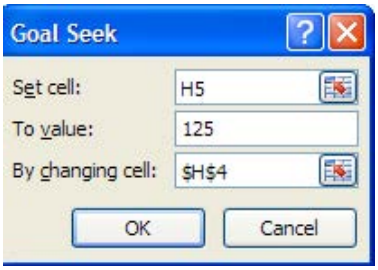
Click OK, and we get:

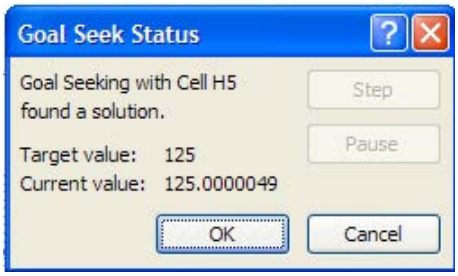
H5 =OneD_condn_variable_k_cyl_Tr(H4,T_i,T_0,r_i,r_0,beta)

	A	B	C	D	E	F	G	H	I
1									
2									
3		Data:							
4			r_i	0.05	m		r =	0.08	m
5			r_0	0.1	m		Tr=	168.1291	C
6			T_i	300	C				
7			T_0	100	C				
8		k(T)=0.5 * (1 + 0.001 * T), W/m.C, where T is in deg.C							
9			k_0	0.5					
10			beta	0.001					

Now, use Goal seek to make cell H5 equal to 125 by changing cell H4: Go to Data-What If Analysis-Goal seek: We get:



Click OK; we get:



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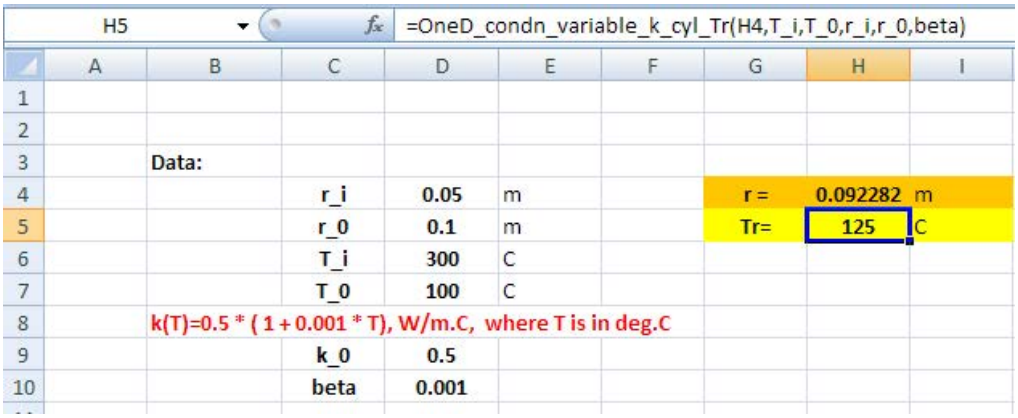
And, the worksheet shows:



H5 | =OneD_condn_variable_k_cyl_Tr(H4,T_i,T_0,r_i,r_0,beta)

	A	B	C	D	E	F	G	H	I
1									
2									
3		Data:							
4			r_i	0.05	m		r =	0.092282	m
5			r_0	0.1	m		Tr=	125	C
6			T_i	300	C				
7			T_0	100	C				
8		k(T)=0.5 * (1 + 0.001 * T), W/m.C, where T is in deg.C							
9			k_0	0.5					
10			beta	0.001					

Thus, radius at which temp is 125 deg. C is: 0.09228 m….Ans.

==========

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1D Critical radius problem:

Learning objectives:

1. Generally, addition of insulation does reduce the heat loss; however, there are some cases where this may not be so, and the addition of insulation, in fact, increases the heat loss!
2. Considering an insulated pipe (or sphere) of radius r_1, as the insulation thickness is increased i.e. as insulation radius r_2 is increased, conductive resistance of insulation increases; however, convective resistance, given by [1/(h. A_o)] goes on decreasing since A_o, the outside surface area goes on increasing with increasing radius. Therefore, the total resistance may increase or decrease, depending on the relative rates of change of these two resistances. And, there are situations where the total resistance does decrease as the insulation thickness increases i.e. the heat transfer rate Q increases as the thickness is increased!
3. **The insulation radius at which the resistance to heat flow is minimum is called 'critical radius', r_c; i.e. the heat flow is a maximum at the critical radius**.
4. In this section we will study such cases and determine the 'critical radius of insulation', variation of different resistances involved and the variation of heat flow with insulation thickness.

"**Prob.1D.1.** A wire of 6.5 mm dia at a temp of 60 C is to be insulated by a material having k = 0.174 W/m.C. Convection heat transfer coeff = 8.722 W/m^2.C. The ambient temp is 20 C. For maximum heat loss, what is the min. thickness of insulation and the heat loss per metre length? Also find percentage increase in heat dissipation as compared to a bare wire. [VTU-6th Sem-B.E.- Dec.09–Jan.-2010]"

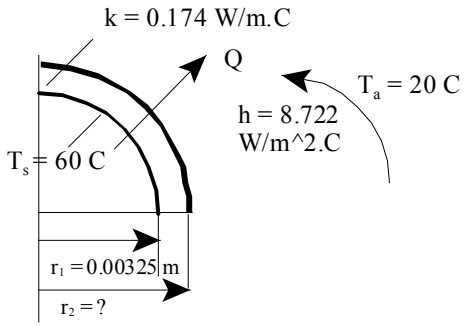

Fig.Prob.1D.1

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EES Solution:

"Data:"

r_1 = 3.25E-03[m]
T_s = 60[C]
k = 0.174 [W/m-C]
h = 8.722 [W/m^2-C]
T_a = 20 [C]
L = 1[m]

"Calculations:"

r_cr = k/h "[m], …crit. radius…. for a cylindrical system"
t_ins = r_cr – r_1 "[m] .. thickness of insulation"

Q_bare = h*(2*pi*r_1*L)*(T_s – T_a) "[W]…. heat loss from bare wire"

"When there a sheath of insulation on the wire:"

"Thermal resistances:"

R_ins = ln(r_cr/r_1)/(2*pi*k*L) "[C/W] … thermal resistance by conduction through cyl layer"
R_conv = 1/(h*2*pi*r_cr*L) "[C/W] … convective thermal resistance at the surface of insulation layer"
R_tot = R_ins + R_conv "[C/W] … total thermal resistance = conduction + convection"

"Heat transfer:"

Q_sheath = (T_s -T_a)/R_tot "[W]…. heat loss from wire with sheath"

Percent_Increase = (Q_sheath -Q_bare)*100/Q_bare "….percentage increase in heat transfer"

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Results:

Unit Settings: SI C kPa kJ mass deg

$h = 8.722$ [W/m^2-C]	$k = 0.174$ [W/m-C]	$L = 1$ [m]
$Percent_{Increase} = 118.1$ [-]	$Q_{bare} = 7.124$ [W]	$Q_{sheath} = 15.54$ [W]
$r_1 = 0.00325$ [m]	$R_{conv} = 0.9147$ [C/W]	$r_{cr} = 0.01995$ [m]
$R_{ins} = 1.66$ [C/W]	$R_{tot} = 2.574$ [C/W]	$T_a = 20$ [C]
$t_{ins} = 0.0167$ [m]	$T_s = 60$ [C]	

Thus:

t_ins = 0.0167 m = 16.7 mm for max. heat transfer … Ans.

Q_sheath = 15.54 W …. Heat loss per metre length … Ans.

Percentage increase in heat transfer due to sheath = 118.1 % … Ans.

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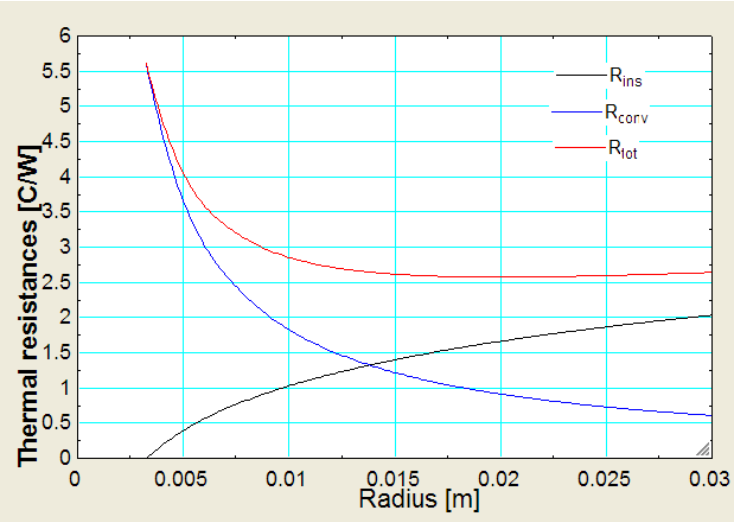
Additionally:

Draw the variation of thermal resistances as thickness of insulation increases:

First construct the parametric table and then plot the graph:



Note from the graph above that:

1) Starting with the bare wire (r_1 = 0.00325 m), as we go on increasing the insulation thickness, conduction resistance of the insulation goes on increasing,
2) But, the convection resistance at the outer surface of insulation goes on decreasing.
3) As a result, the total resistance, which is the sum of conduction and convection resistances, goes through a minimum.
4) Radius at which the total resistance is minimum is known **as 'critical radius'**. Obviously, at this radius the heat transferred is **maximum.**

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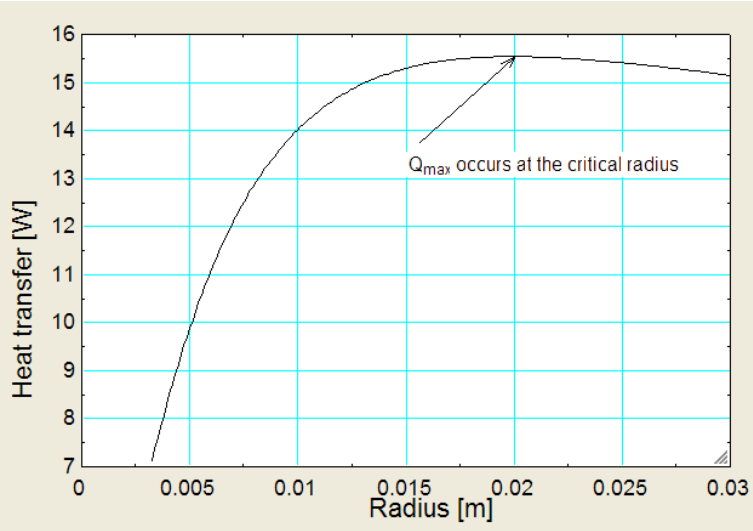
Also:

Draw the variation heat transfer Q as thickness of insulation increases:

Construct the parametric table and then plot the graph:



Note: It may be observed from the plot that Q increases from r_1 up to the critical radius r_cr and then decreases as the radius increases.

==========

"**Prob.1D.2.** An electric cable of 10 mm dia is to be laid in atmosphere at 20 C. Estimated surface temp of the cable due to heat generation is 65 C. Find the max percentage increase in heat dissipation when the wire is insulated with rubber of k = 0.155 W/m.C. Take h = 8.5 W/m^2.C. [VTU-6th Sem-B.E.-May–June – 2006]"

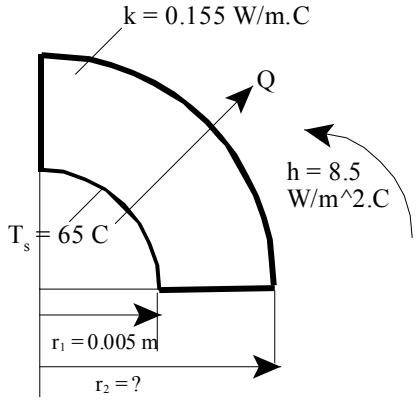


Fig.Prob.1D.2

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EES Solution:

"Data:"

r_1 = 5E-03 [m]
T_s = 65 [C]
k = 0.155 [W/m-C]
h = 8.5 [W/m^2-C]
T_a = 20 [C]
L = 1[m]

"Calculations:"

"Heat transfer is max at the critical radius:"

r_cr = k/h "[m], …crit. radius"

Q_bare = h*(2*pi*r_1*L)*(T_s – T_a) "[W]…. heat loss from bare wire"

"When there rubber insulation on the cable:"

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R_tot = ln(r_cr/r_1)/(2*pi*k*L) + 1/(h*2*pi*r_cr*L) "[C/W] … total thermal resistance = conduction + convection"

Q_sheath = (T_s -T_a)/R_tot "[W]…. heat loss from cable with sheath"

Percent_Increase = (Q_sheath -Q_bare)*100/Q_bare "….percentage increase in heat transfer"

Results:

Unit Settings: SI C kPa kJ mass deg

$h = 8.5$ [W/m^2-C]	$k = 0.155$ [W/m-C]	$L = 1$ [m]
$Percent_{Increase} = 58.99$	$Q_{bare} = 12.02$ [W]	$Q_{sheath} = 19.1$ [W]
$r_1 = 0.005$ [m]	$r_{cr} = 0.01824$ [m]	$R_{tot} = 2.355$ [C/W]
$T_a = 20$ [C]	$T_s = 65$ [C]	

Thus:

Percentage increase in heat dissipation (because of insulation) = 58.99 % …. Ans.

==========

"**Prob.1D.3.** A refrigerant suction line 25 mm OD is to be insulated using a material of k = 0.25 W/m.K. The surface heat transfer coeff is 10 W/m^2.K. Verify if the insulation is effective or not. What should be the max value of thermal conductivity of the insulation to reduce the heat transfer?.Take T_a = 40 C. [M.U. – Dec. 2000]"

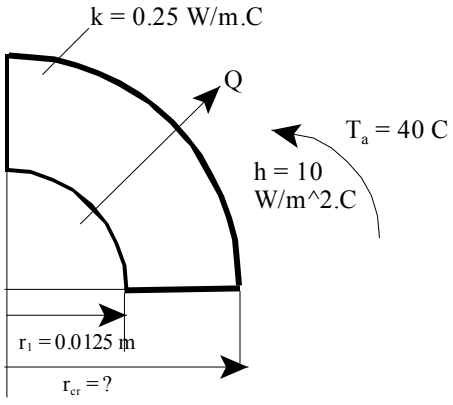

Fig. Prob.1D.3

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EES Solution:

"Data:"

r_1 = 12.5E-03 [m]
k_ins = 0.25 [W/m-C]
h = 10 [W/m^2-C]
T_a = 40 [C]
L = 1"[m]….assumed"

"Calculations:"

"**To find if the insulation is effective or not:**

By applying the insulation the heat transfer should be reduced. If it does not happen, then the insulation is not effective.

So, first find out the value of critical radius, r_cr. I r_cr > r_1, then applying the insulation on r_1 will result in increase of heat transfer till the radius of insulation reaches the value of r_cr."

r_cr = k_ins/h "[m]….crit. radius for a cylindrical system"

"It is observed that r_cr = 0.025 m. i.e. r_cr > r_1, i.e. by applying insulation heat transfer rate Q increases (see the graph below).

i.e. The insulation is NOT EFFECTIVE…..Ans."

"**To find the max value of k_ins to reduce heat transfer:**

This is the value of k_ins corresponding to the value of r_1 = r_cr, since beyond the value of r_cr, heat transfer goes on reducing:"

k_ins_max = r_1 * h "[w/m-C] …. max value of k_ins"

"**In addition:**

Plot variation of heat transfer Q with the insulation radius r:

Let the refrign. suction line surface temp be -10 C. Then:"

T_s = -10 [C]

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"Let r = 15e-03 m:"

{r = 15e-03[m]} "…commented out to get the parametric table and plot the graph"

Q = (T_a – T_s) / (ln(r/r_1)/(2*pi*k_ins*L) + 1/(h*2*pi*r*L)) "[W] … heat transfer from ambient = heat transfer by conduction through insulation and by convection from ambient"

Results:

Unit Settings: SI C kPa kJ mass deg

$h = 10$ [W/m^2-C]	$k_{ins} = 0.25$ [W/m-C]	$k_{ins,max} = 0.125$ [W/m-C]
$L = 1$ [m]	$Q = 42.48$ [W]	$r = 0.015$ [m]
$r_1 = 0.0125$ [m]	$r_{cr} = 0.025$ [m]	$T_a = 40$ [C]
$T_s = -10$ [C]		

Thus:

k_ins_max = 0.125 W/m.C ….. max value of k_ins to reduce heat transfer …. Ans.

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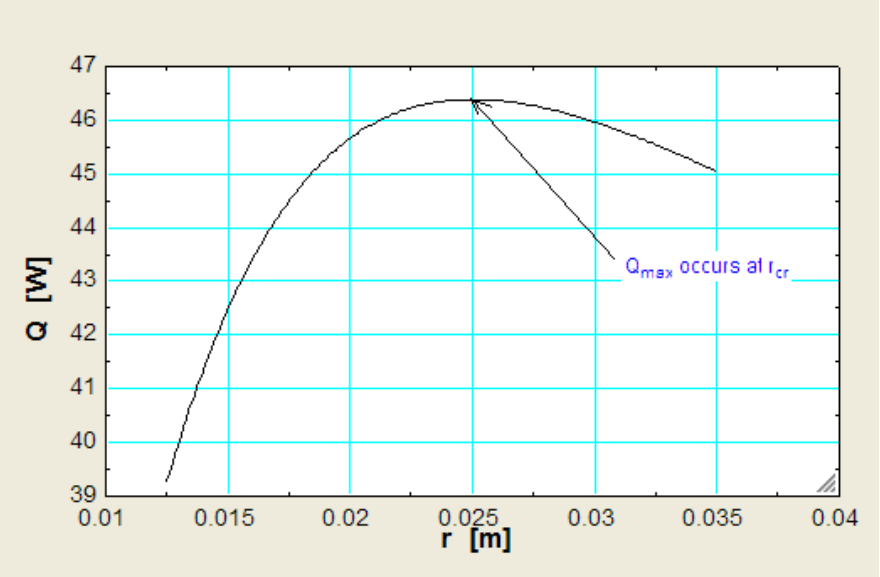

Note from the graph above that as the insulation is increased on the bare pipe (r_1 = 0.0125 m), Q goes on increasing till the value of r_cr = 0.025 m is reached; further increase in insulation thickness results in decrease of heat transfer.

==========

Prob. 1D.4. A 5 mm dia spherical ball at 50 C is covered by a 1 mm thick plastic insulation of k = 0.13 W/m.C. The ball is kept in a medium at 15 C, with a convection heat transfer coeff. of 20 W/m^2.C. What happens to the heat transfer rate?

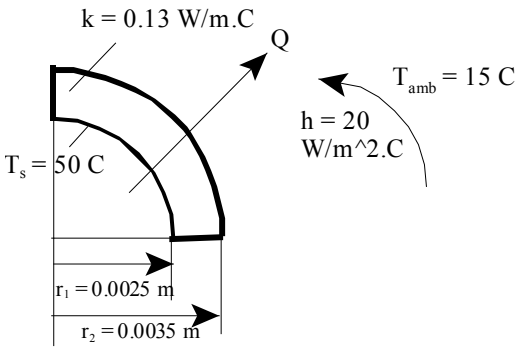

Fig.Prob.1D.4

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Mathcad Solution:

Solution:

Data:

$r_1 := 2.5 \cdot 10^{-3}$ m $\quad r_2 := r_1 + 0.001$ i.e. $r_2 = 3.5 \cdot 10^{-3}$ m

$T_s := 50$ C $\quad T_{amb} := 15$ C $\quad h := 20$ W/m^2.C $\quad k_{ins} := 0.13$ W/m.C

Calculations:

$r_{cr} := \frac{2 \cdot k_{ins}}{h}$ m..... critical radius for a spherical system

i.e. $r_{cr} = 0.013$ m....this value is more than that of r2 ...

... **therefore heat transfer will increase....Ans.**

Thermal resistaces R_ins and R_conv:

$R_{ins}(r_2) := \left(\frac{r_2 - r_1}{4 \cdot \pi \cdot k_{ins} \cdot r_1 \cdot r_2} \right)$ C/W... thermal resistance of the insulation layer as a funcion of r2 for the spherical layer

$R_{conv}(r_2) := \frac{1}{h \cdot 4 \cdot \pi \cdot r_2^2}$ C/W... convection resistance on the outer surface of insulation layer as a funcion of r2

$R_{tot}(r_2) := R_{ins}(r_2) + R_{conv}(r_2)$ C/W... total thermal resistance

To draw the graph of R_ins and R_conv vs r2:

$r_2 := 0.0025, 0.0026 .. 0.02$ ....define a range variable r2, from 0.0025 m to 0.02 m

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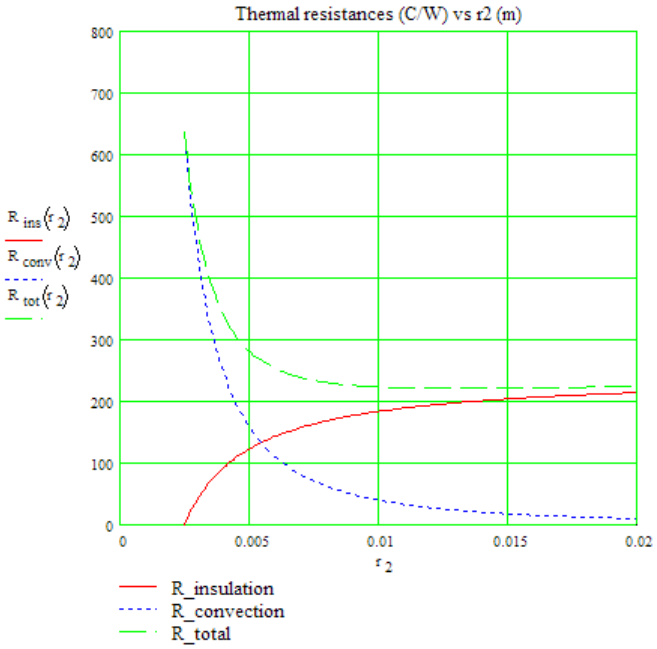

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Note from the graph above that:

1) Starting with the bare spherical ball (r_1 = 0.025 m), as we go on increasing the insulation thickness, conduction resistance of the insulation goes on increasing,
2) But, the convection resistance at the outer surface of insulation goes on decreasing.
3) As a result, the total resistance, which is the sum of conduction and convection resistances, goes through a minimum.
4) Radius at which the total resistance is minimum is known as 'critical radius'. Obviously, at this radius the heat transferred is maximum.

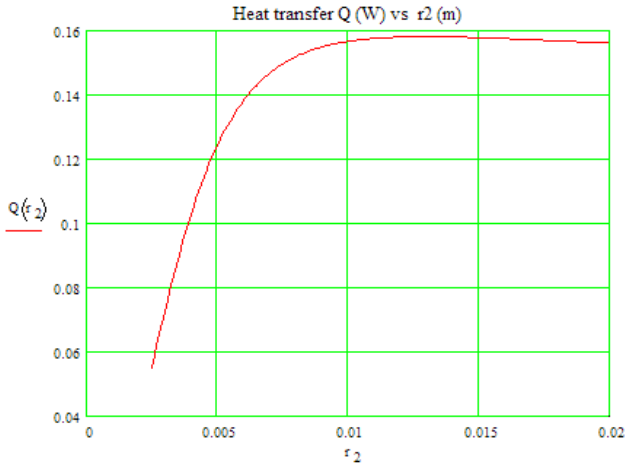
To draw the graph of Q vs r2:

$$Q(r_2) := \frac{T_s - T_{amb}}{\left(\frac{r_2 - r_1}{4\cdot\pi\cdot k_{ins}\cdot r_1\cdot r_2}\right) + \frac{1}{h\cdot 4\cdot\pi\cdot r_2^{\,2}}}$$

W.... heat transferred through insulation by conduction + by convection from the surface to ambient

i.e. Q(0.0035) = 0.089W ... heat transfer when r2 = 0.0035 m

$r_2 := 0.0025, 0.0026 .. 0.02$ ....define a range variable r2, from 0.0025 m to 0.02 m



Note from the graph that Q is maximum at the critical radius of 0.013 m.

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Prob. 1D.5. Consider a refrigerant line 10 mm in dia insulated with cellular glass of k = 0.055 W/m.C. Refrigerant line carries a refrigerant at -20 deg.C and the ambient temp is 25 deg.C. Convective heat transfer coeff. between the pipe and the ambient is 5 W/m^2.C. Determine the critical radius of insulation. Also plot the variation of various thermal resistances and heat transfer rate per unit length of pipe, with the insulation radius up to a radius of 40 mm.

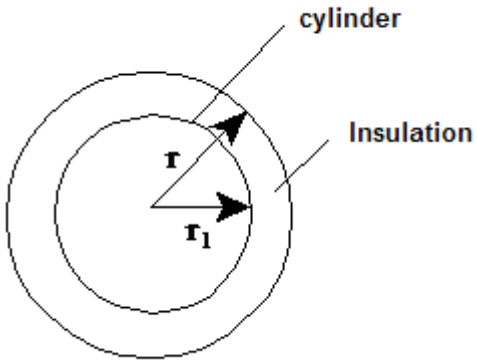

Fig.Prob.1D.5

EXCEL Solution:

Following are the steps in EXCEL Solution:

1) Set up the EXCEL worksheet, enter data, and name the cells:

C7 | fx | k_ins

	A	B	C	D	E
1					
2		Data:			
3			r_1	0.005	m
4			T_s	-20	C
5			T_amb	25	C
6			h	5	W/m^2.C
7			k_ins	0.055	W/m.C
8			L	1	m

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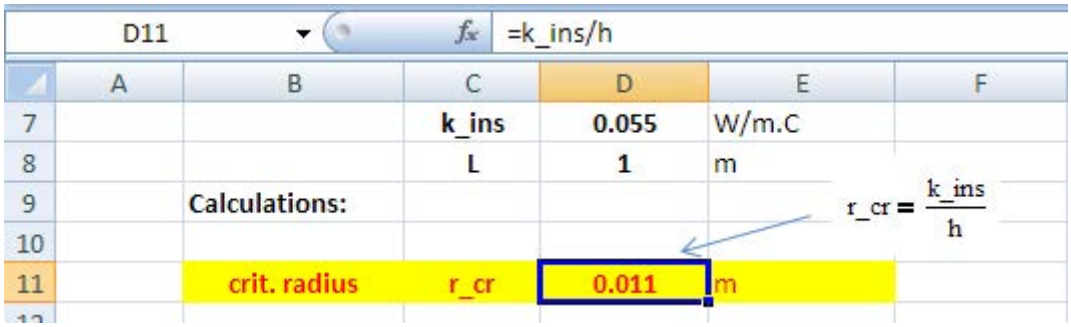
2) Calculate the critical radius:



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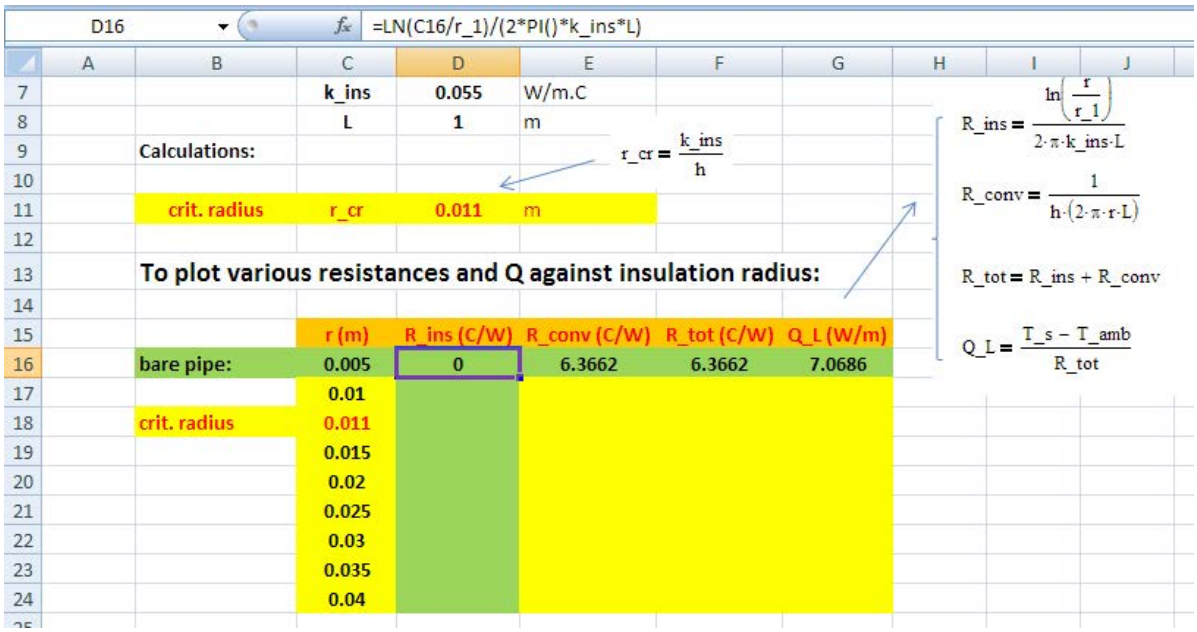
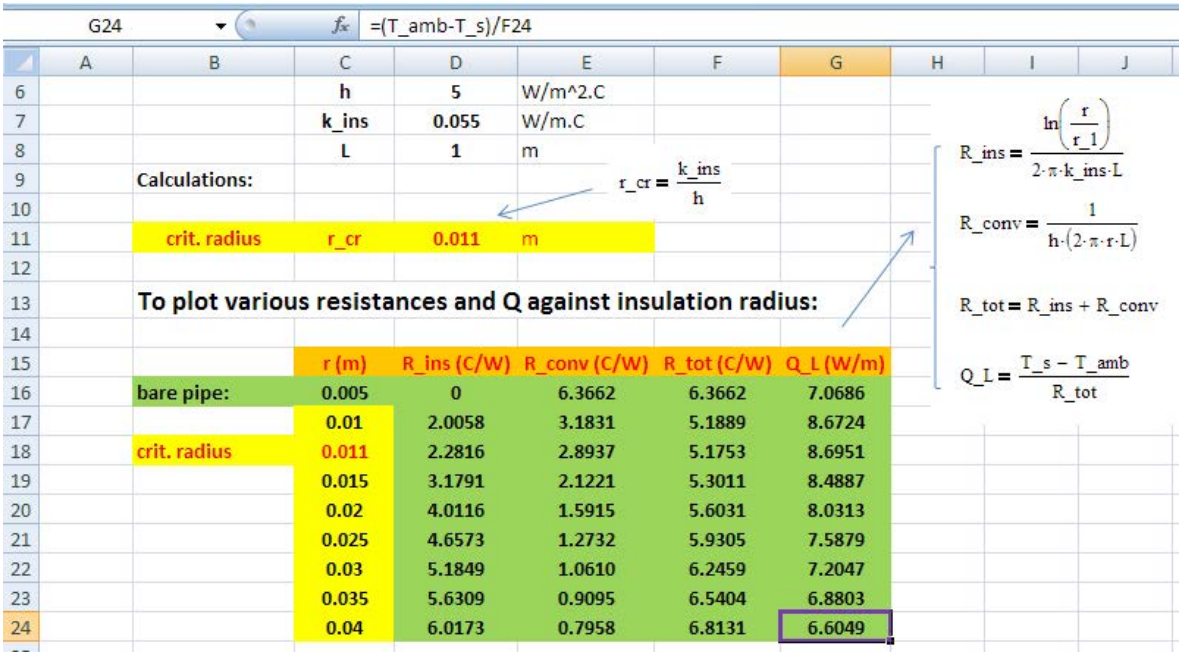
3) Set up the worksheet to plot the various resistances and heat transfer rate Q_L against radius, as shown below. Parameters for bare pipe are shown in this screen shot. The formulas used in calculation are also shown for ready reference.



4) Now, simply select D16 to G16 and drag-copy up to cell G24, to fill the whole Table:



Note that at the critical radius, R_tot is minimum and Q/L is maximum.

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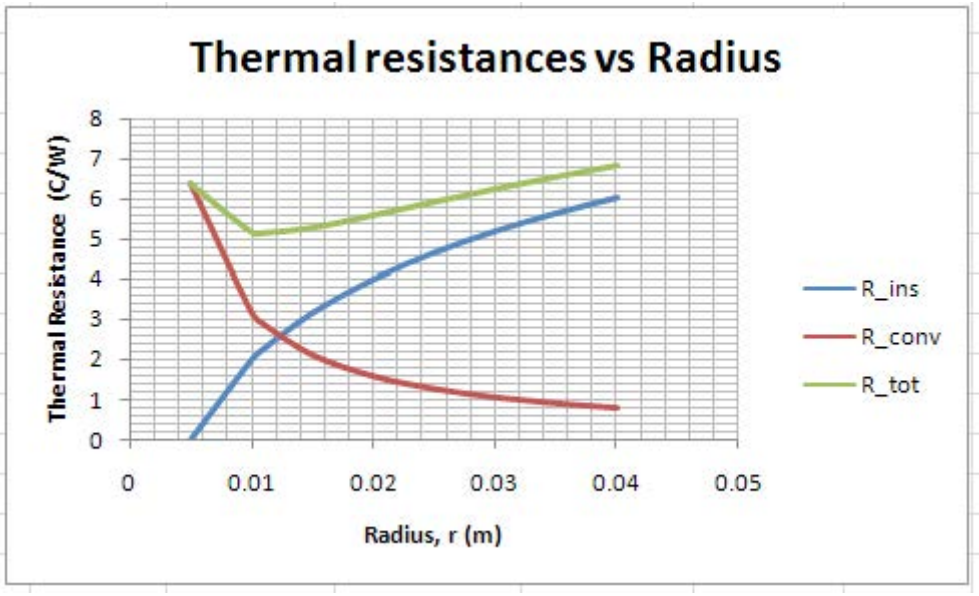
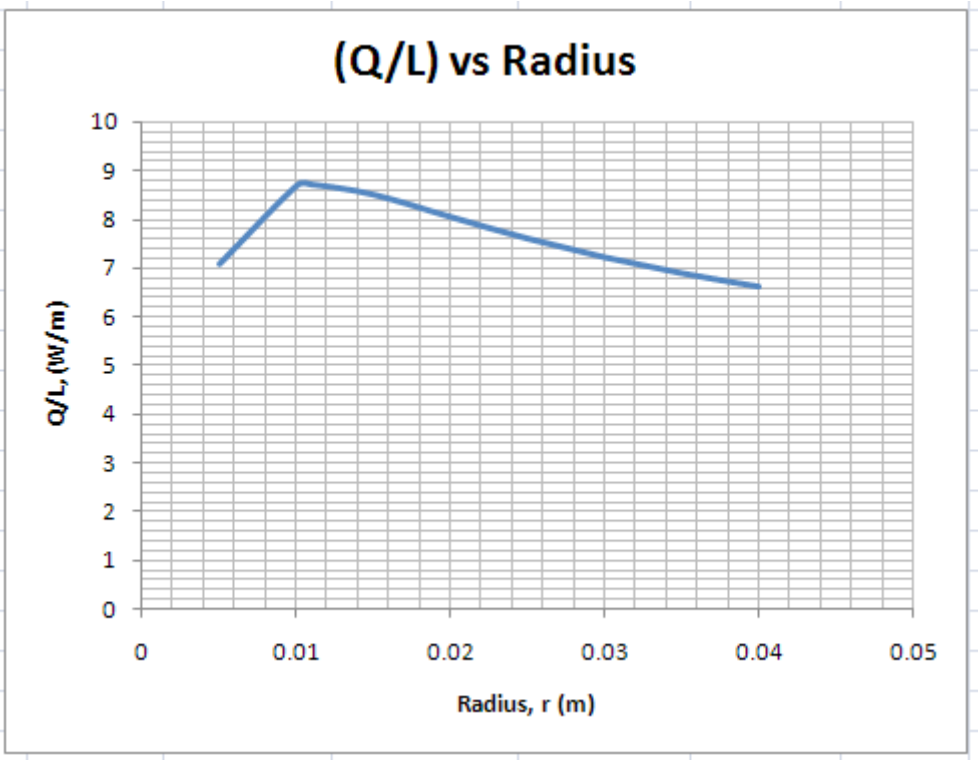
5) Now, plot the various resistances against radius:



And, plot Q/L against Radius:



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