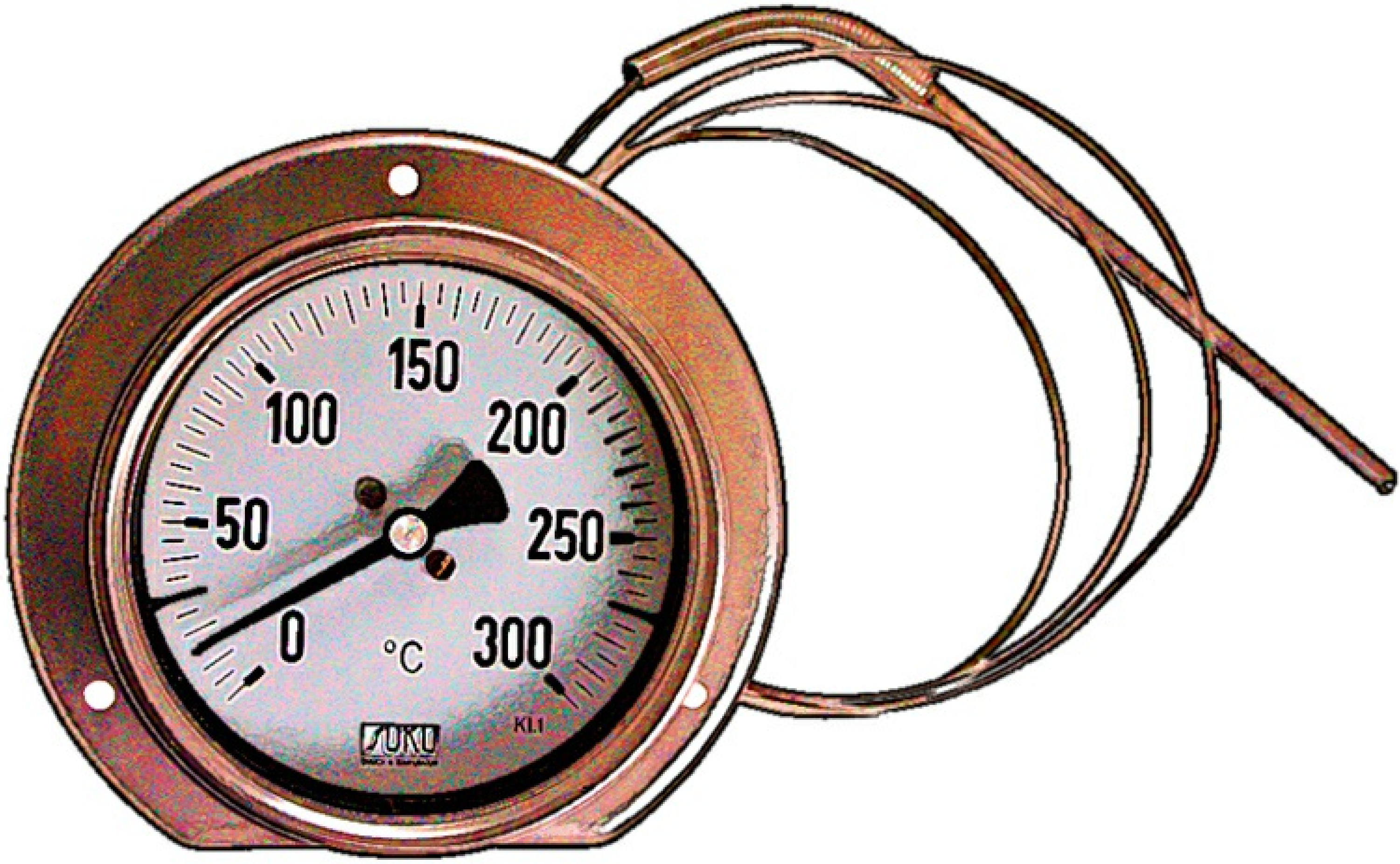
Basic Thermodynamics: Software Solutions – Part I

Dr. M. Thirumaleshwar



bookboon.com
The eBook company

Dr. M. Thirumaleshwar

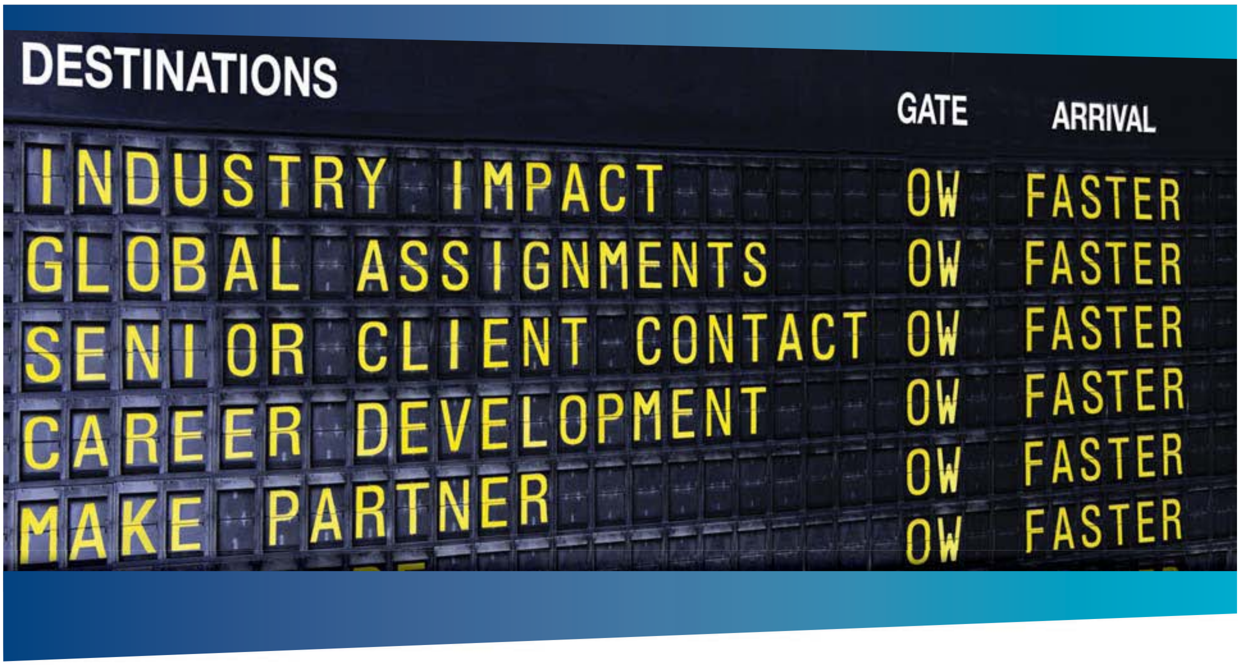
Basic Thermodynamics: Software Solutions – Part I

(Software used, Units, Pressure, Temp, Pure substances)

Basic Thermodynamics: Software Solutions – Part I
1st edition

ISBN 978-87-403-0672-9

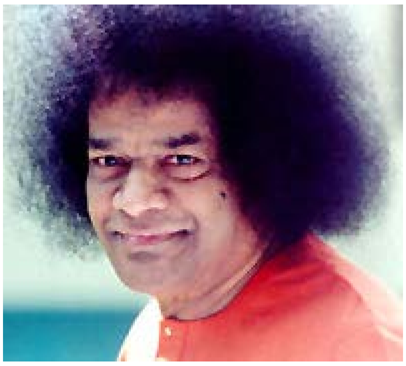
Contents


DESTINATIONS
GATE
ARRIVAL
INDUSTRY IMPACT OW FASTER
GLOBAL ASSIGNMENTS OW FASTER
SENIOR CLIENT CONTACT OW FASTER
CAREER DEVELOPMENT OW FASTER
MAKE PARTNER OW FASTER


Could you think of 101 new things
to do with eggs and oil?

Dedication

This work is lovingly dedicated at the lotus feet of



"There is only one religion, the religion of Love.
There is only one caste, the caste of Humanity.
There is only one language, the language of the Heart.
There is only one God, He is Omnipresent."

"Help Ever, Hurt Never!"

…Bhagavan Sri Sathya Sai Baba

Message by Rev.Fr. Joseph Lobo

Director, St. Joseph Engineering College, Vamanjoor, Mangalore – 575 028
India

I am honoured to write this message to the E-book written by Dr Thirumaleshwar Muliya. My acquaintance with Dr Muliya is of a short time while he was visiting our college as a visiting faculty to the department of Mechanical Engineering. I admire his simplicity, great humane approach and a deep passion for teaching. As a senior Professor of Mechanical Engineering, a Principal and as the Senior Scientific Officer heading Cryogenics Dept. at Bhabha Atomic Research Centre, Trombay, Mumbai and Centre for Advanced Technology, Indore, he comes across as a man with intellectual calibre, rich competence and a wealth of experience. As a teacher, he has keenly seen the challenges and the problems that are faced by hundreds of students studying Engineering.

Dr Muliya is a great teacher who has integrated both knowledge and experience in his teaching. He has authored many books with a noble purpose for helping the students to acquire the right knowledge. His recent book entitled "***Software Solutions to Problems in Basic Thermodynamics***" is here before you. This book is written keeping in mind the syllabus of *Visvesvaraya Technological University* and helping the students to find the right solutions to the problems that are described in each subject.

I congratulate him for his hard work and a very thoughtful initiative taken in accomplishing this wonderful work. This book is made available to all for free as a generous gift publishing as an E-book by bookboon.com. St Joseph Engineering College is very proud of Dr Muliya, of all his outstanding achievements and incalculable contributions that he has made to the society in the field of Science and Technology. May this book be a source of joy to him and a source of learning to every reader across the world.

Fr Joseph J. Lobo
Director – St Joseph Engineering College
Date: 21.03.2014

Preface

“Thermodynamics” is an important subject in engineering studies and has applications in almost all fields of engineering. As such, it is included as a ‘core subject’ in the engineering syllabi of many Universities.

In engineering colleges, generally, the subject of Thermodynamics is taught over two semesters:

a) In the first half, **‘Basic Thermodynamics’** is taught. This covers the topics of Units, Pressure, Temperature, Properties of Pure substances, Zeroth Law, Heat and Work, First Law of Thermodynamics for a closed system and for flow processes, Second Law of Thermodynamics, Heat engines, Refrigerators and Heat Pumps, Entropy, Availability and Irreversibility, Real and Ideal gases and Gas mixtures etc.
b) In the second half, **‘Applied Thermodynamics’** is dealt with. Here, the topics studied are: Thermodynamic relations, Vapour power cycles, Gas power cycles, Refrigeration cycles, Psychrometrics, Reactive Systems and Compressible fluid flow.

Thermodynamics is also considered as an abstract subject by students since many of the concepts introduced are unfamiliar to them. Therefore, the subject is better learnt by solving a large number of problems.

This book contains **solutions to problems in Basic Thermodynamics**, as per the syllabus of B.E. courses in Visweswaraya Technological University (VTU), Karnataka, India (and other Universities as well).

Solutions to Problems in **Applied Thermodynamics** will be presented in a subsequent book.

In this book, problems are solved using three popular software, viz. **“Mathcad”**, **“Engineering Equation Solver (EES)”** and **“The Expert System on Thermodynamics (TEST)”**.

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 software used.

Advantages of using computer software to solve problems are many:

1) It helps in solving the problems fast and accurately
2) Parametric analysis (what – if analysis) and graphical visualization is done very easily. This helps in an in-depth analysis of the problem.
3) Once a particular type of problem is solved, it can be used as a *template* and solving similar problems later becomes extremely easy.
4) In addition, one can plot the data, curve fit, write functions for various properties or calculations and re-use them.
5) 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 expanded version of the teaching notes of the author, who has taught this subject over the past many years to Engineering 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.

This particular book may be used in conjunction with any of the standard Text Books on Engineering Thermodynamics.

The book is presented in ***four Parts*****:**

Part-1 contains the following:

Chapter 1. Introduction to the Software used
Chapter 2. S.I. Units, Unit conversion, Pressure, Temperature etc.
Chapter 3. Properties of Pure substances

Part-2 contains problems on following topics:

Chapter 4. Work, Heat and I Law of Thermodynamics applied to Closed Systems
Chapter 5. I Law of Thermodynamics applied to Flow processes

Part-3 contains problems on following topics:

Chapter 6. II Law of Thermodynamics
Chapter 7. Entropy

Part-4 contains problems on following topics:

Chapter 8. Availability and Irreversibility
Chapter 9. Real and Ideal gases and Gas Mixtures

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.

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 words of encouragement, and for providing a very congenial and academic atmosphere in the college. **He has, very graciously, given a Message to this book to bless my effort.**

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

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

I should mention 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,** who has given continuous support and encouragement, and made many silent sacrifices during the period of writing this book, so that this book becomes a reality.

M. Thirumaleshwar
March 2014

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, 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.

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.

He was 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 recently authored a ***free e-book*** entitled **"Software Solutions to Problems on Heat Transfer"** wherein problems are solved using 4 software viz. Mathcad, EES, FEHT and EXCEL. This book, containing about 2750 pages, is presented in 9 parts and all the 9 parts can be downloaded *for free* from www.bookboon.com.

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

About the Software used

Following three software 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. The Expert System for Thermodynamics (TEST) (Ref: www.thermofluids.net)

Trial versions of the first two software and detailed Instruction Manuals may be down-loaded from the websites indicated.

TEST is a very versatile and popular Java based software for solving Thermodynamics problems and can be accessed freely on the website indicated. Initially, free registration is required.

Chapter 1 gives an introduction to these software as well as some free software available for water/steam properties, humidity calculations and Unit conversions.

To the Student

Dear Student:

Thermodynamics is an important core subject useful in many branches of engineering.

When the subject 'Basic Thermodynamics' is first introduced, students often feel that it is an abstract subject, since the terms such as 'work', 'heat' 'energy' etc seem to appear with new meanings; also, terms such as 'entropy', 'enthalpy', 'exergy' etc are rather unfamiliar! In addition, the teacher talks of the Carnot cycle as an Ideal cycle, but says that 'it is not a practical cycle'! Immediately the student asks himself: 'then, why am I studying this?'. Well, importance of these topics are appreciated by students only when they are exposed to 'Applied Thermodynamics' where topics such as Gas power cycles used in I.C. Engines and Turbines, Vapour power cycles used in Power plants, Refrigeration cycles etc are taught.

Best way to learn such an abstract subject is to work out a large number of problems, particularly of practical applications.

This book contains solutions to problems on **'Basic Thermodynamics'** using three popular software, viz. Mathcad, Engineering Equation Solver (EES), and The Expert System for Thermodynamics (TEST). Trial versions of Mathcad, and EES can be downloaded from the websites indicated. TEST can be accessed directly from the website www.thermofluids.net after an initial, free registration.

Problems in this book are chosen from the University question papers and standard Thermodynamics Text books.

Use of Software in solving problems has many advantages:

1. It helps in logical thinking
2. Problems are solved quickly and accurately
3. Parametric solutions (or 'what-if' solutions) are obtained easily
4. Solutions can be presented in tabular or graphical form, very easily and quickly
5. Once a particular type of problem is solved, solving a similar problem with different data input becomes very easy
6. Ease of getting solutions to problems in tabular or graphical form creates further interest and curiosity on the subject and encourages students to be creative and work further
7. In Thermodynamics, traditionally, one has to interpolate property values from Tables, and this is a very tedious process while solving problems. Use of suitable software allows one to get accurate property values with minimum effort.

How to use this Book?

You need not worry if you don't know about these software. Since each problem is solved systematically step by step, and is well commented, just reading through the solution will make the logic of the solution clear to you. That is the most important thing in solving the problems. ***Then, you must work out the problem yourself, by hand or using the software***. Of course, use of software has the above-mentioned advantages. *Simply reading the book won't do*. Have your favorite Text book nearby, in case you need to refer to it for any formulas or clarifications. There is no other 'easy method'. As they say, ***'Success is 1% inspiration plus 99% perspiration!'***

Lastly, I hope that you too will enjoy as much as I did in solving these problems. Good Luck!

Author

1 Introduction To The Software Used

Learning objectives:

1. In this chapter, a brief overview is given about three very useful commercial, technical software, viz. Mathcad, EES and TEST, particularly useful to solve problems in Thermodynamics.
2. This chapter is not intended as a tutorial on these software. However, *since many examples have been worked out*, it is expected that the reader will get sufficient working knowledge on use of these software.
3. In addition, four 'free' software are described, with worked examples. Out of these, two programs viz. SteamTab of ChemicaLogic and SteamTable of Figener S/A are for finding out properties of Steam/Water and the 'Humidity Calculator' program of Vaisala, Finland is for psychrometric calculations. Also, a very useful program for Units conversion viz. 'UConeer' from Katmar Software is explained. They are handy, little programs, though with some limitations.

1.1 Introduction:

'Thermodynamics' deals with heat, work and their interactions. Traditionally, Thermodynamics course requires considerable amount of problem solving, since the subject is studied better by applying the theory to practical problems. Study of Thermodynamics also involves referring to tables and charts to find out the thermodynamic and other properties of various working substances such as water/steam, air, refrigerants, fuels etc. Interpolation in tables and charts is always a tedious work and is a source of error. With the advent of high speed personal computers, and with the availability of good thermodynamic and technical computing software, calculations and problem solving in Thermodynamics has become easy, fast and straight-forward. However, it must be clearly appreciated that there is no substitute for 'thorough understanding' of the theory on the part of the student; computers are only tools to be used efficiently, and cannot replace the originality, thinking, analysis and intuition associated with human brain.

In this book, problems in Thermodynamics are solved using three popular software, viz. Mathcad, Engineering Equation Solver (EES), and The Expert System for Thermodynamics (TEST). We also introduce four 'free' software, viz. 'SteamTab Companion' (from M/s ChemicaLogic Corporation) and 'SteamTable' (from M/s Figener S/A) to determine the properties of Steam/Water, 'Humidity calculator' from Vysala Oyj (Finland) for psychrometric calculations, and 'Uconeer', a very popular Units conversion program from Katmar Software.

In this Chapter, we shall give an introduction to these software. *It is not intended to give a tutorial on these software*; but, only the salient features immediately required for the purpose of solving problems in the present context, will be explained. These software, have much higher capabilities than explained here, and for a detailed information on any of them, the reader must refer to the respective instruction manual or specialized publications on that particular software.

1.2 About the software:

1.2.1 Mathcad:

What is Mathcad?

Mathcad, supplied by M/s Parametric Technology Corporation, USA, 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 graphics, '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.

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

$B^2 - 4 \cdot A \cdot C = {}^{-}59$ ....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.

'What-if' analysis in Mathcad:

If a phenomenon depends on any variables, estimating the effect of varying one variable on the phenomenon, while rest of the variables are held constant, is known as 'what-if' analysis. Such an analysis is carried out very easily in Mathcad.

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

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

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

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 are interested 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 = 0.785×10^{-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, $A := 0.785 \cdot 10^{-4}$ m2

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

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 K

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.

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 air standard efficiency (η_{otto}) of Otto cycle against the compression ratio (r_k).

$$\eta_{otto}(\gamma, r_k) := 1 - \frac{1}{r_k^{(\gamma - 1)}}$$ ….η_{otto} is defined as a function of γ and r_k

To draw the Table: First, define a range variable r_k, varying from 6 to 15 with an increment of 1. Then typing 'r_k = ' immediately gives the values of r_k one below the other; similarly, type '$\eta_{otto}(\gamma, r_k)$ =', and values of $\eta_{otto}(\gamma, r_k)$ 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:

$\gamma := 1.4$ ..ratio of sp. heats for air

$r_k := 6, 7 .. 15$.... define range value of comp. ratio

$$\eta_{otto}(\gamma, r_k) := 1 - \frac{1}{r_k^{(\gamma - 1)}}$$ ....η_{otto} is defined as a function of γ and rk

r_k	$\eta_{otto}(\gamma, r_k)$
6	0.512
7	0.541
8	0.565
9	0.585
10	0.602
11	0.617
12	0.63
13	0.642
14	0.652
15	0.661

Graphing in Mathcad:

Graphing in Mathcad is very easy. Let us say, we would like to produce a graph of the Air standard effcy. of Otto cycle against the compression ratio.

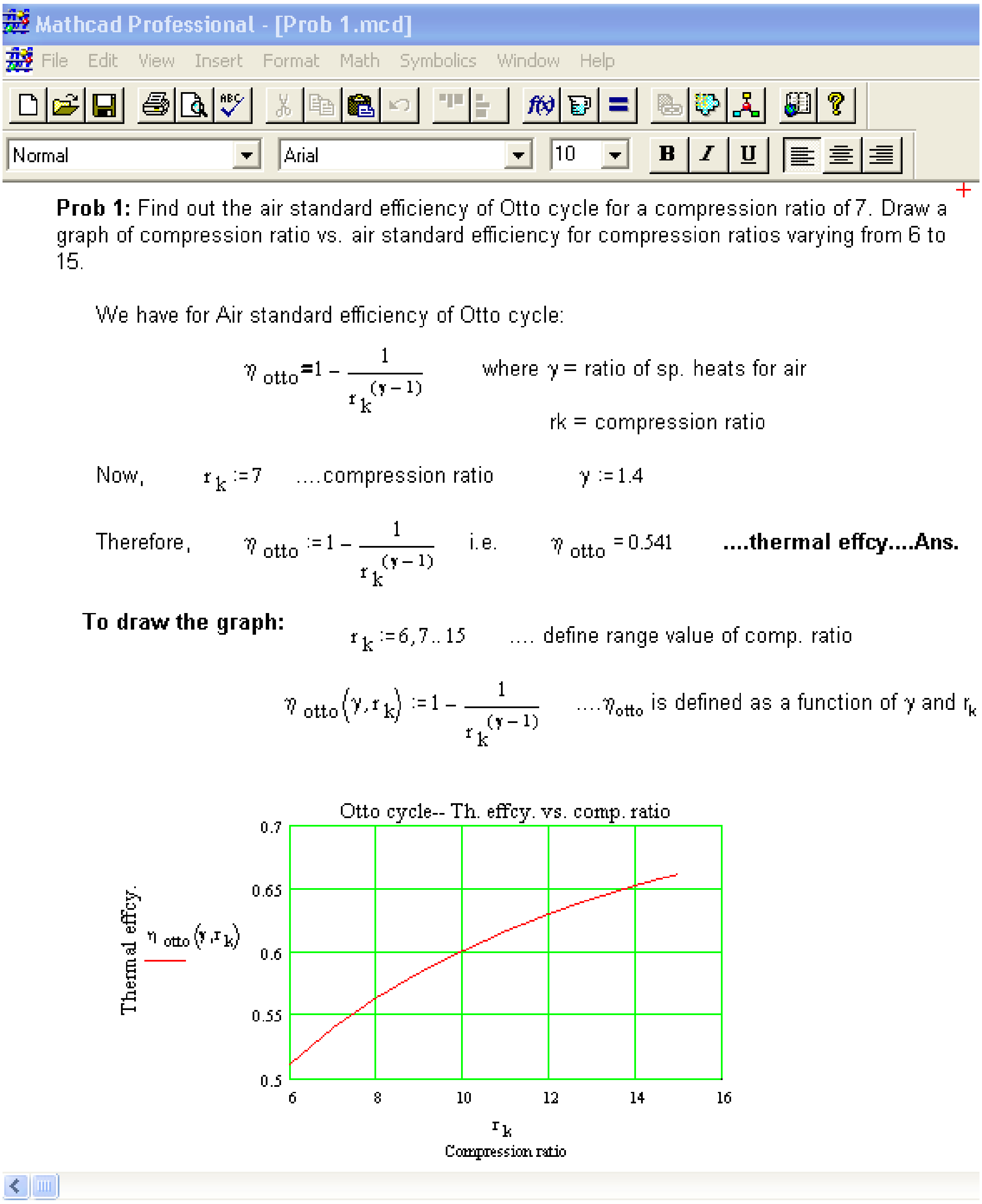
We have:

$\eta_{otto}(\gamma, r_k) := 1 - \frac{1}{r_k^{(\gamma - 1)}}$ ....η_{otto} is defined as a function of γ and r_k

First step is to define a 'range variable' r_k, varying from say, 6 to 15, in increments of 1. In Mathcad, it is written in the form:

$r_k := 6, 7 .. 15$ .... define range value of comp. ratio

Then click on the graphing palette, and select the x-y graph. A graphing area appears with two 'place holders', one on the x-axis and the other on the y-axis. Fill in the x-axis place holder with r_k. On the y-axis place holder, fill in $\eta_{otto}(\gamma, r_k)$. Click any where outside the graph and immediately the graph appears. 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:



Prob 1: Find out the air standard efficiency of Otto cycle for a compression ratio of 7. Draw a graph of compression ratio vs. air standard efficiency for compression ratios varying from 6 to 15.

We have for Air standard efficiency of Otto cycle:

$$\eta_{otto} = 1 - \frac{1}{r_k^{(\gamma-1)}}$$

where γ = ratio of sp. heats for air

rk = compression ratio

Now, $r_k := 7$ ....compression ratio $\gamma := 1.4$

Therefore, $\eta_{otto} := 1 - \frac{1}{r_k^{(\gamma-1)}}$ i.e. $\eta_{otto} = 0.541$ **....thermal effcy....Ans.**

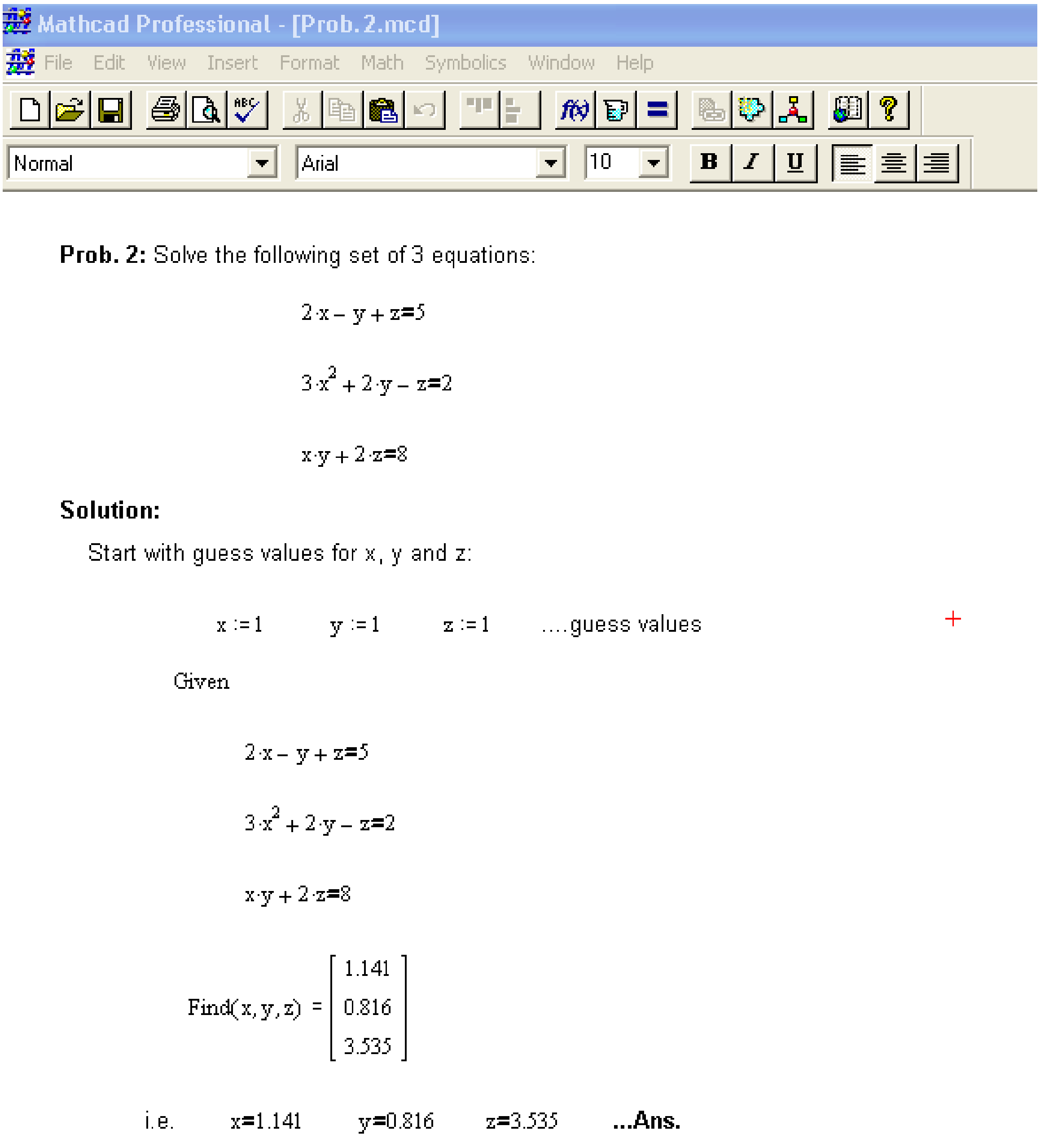
To draw the graph: $r_k := 6, 7 .. 15$ .... define range value of comp. ratio

$\eta_{otto}(\gamma, r_k) := 1 - \frac{1}{r_k^{(\gamma-1)}}$ ....η_{otto} is defined as a function of γ and r_k

Fig. 1.1 Mathcad Worksheet for producing graph of Otto cycle efficiency

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, y, z. 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,y,z) =' , and immediately, the answer appears, in vector form, giving values of x, y and z, in that order. Entire worksheet of solving a set of three equations is shown below:



Prob. 2: Solve the following set of 3 equations:

$$2\cdot x - y + z = 5$$

$$3\cdot x^2 + 2\cdot y - z = 2$$

$$x\cdot y + 2\cdot z = 8$$

Solution:

Start with guess values for x, y and z:

$x := 1$ $y := 1$ $z := 1$ ....guess values

Given

$$2\cdot x - y + z = 5$$

$$3\cdot x^2 + 2\cdot y - z = 2$$

$$x\cdot y + 2\cdot z = 8$$

$$\text{Find}(x, y, z) = \begin{bmatrix} 1.141 \\ 0.816 \\ 3.535 \end{bmatrix}$$

i.e. $x = 1.141$ $y = 0.816$ $z = 3.535$ **...Ans.**

Fig. 1.2 Mathcad Worksheet for solving simultaneous equations

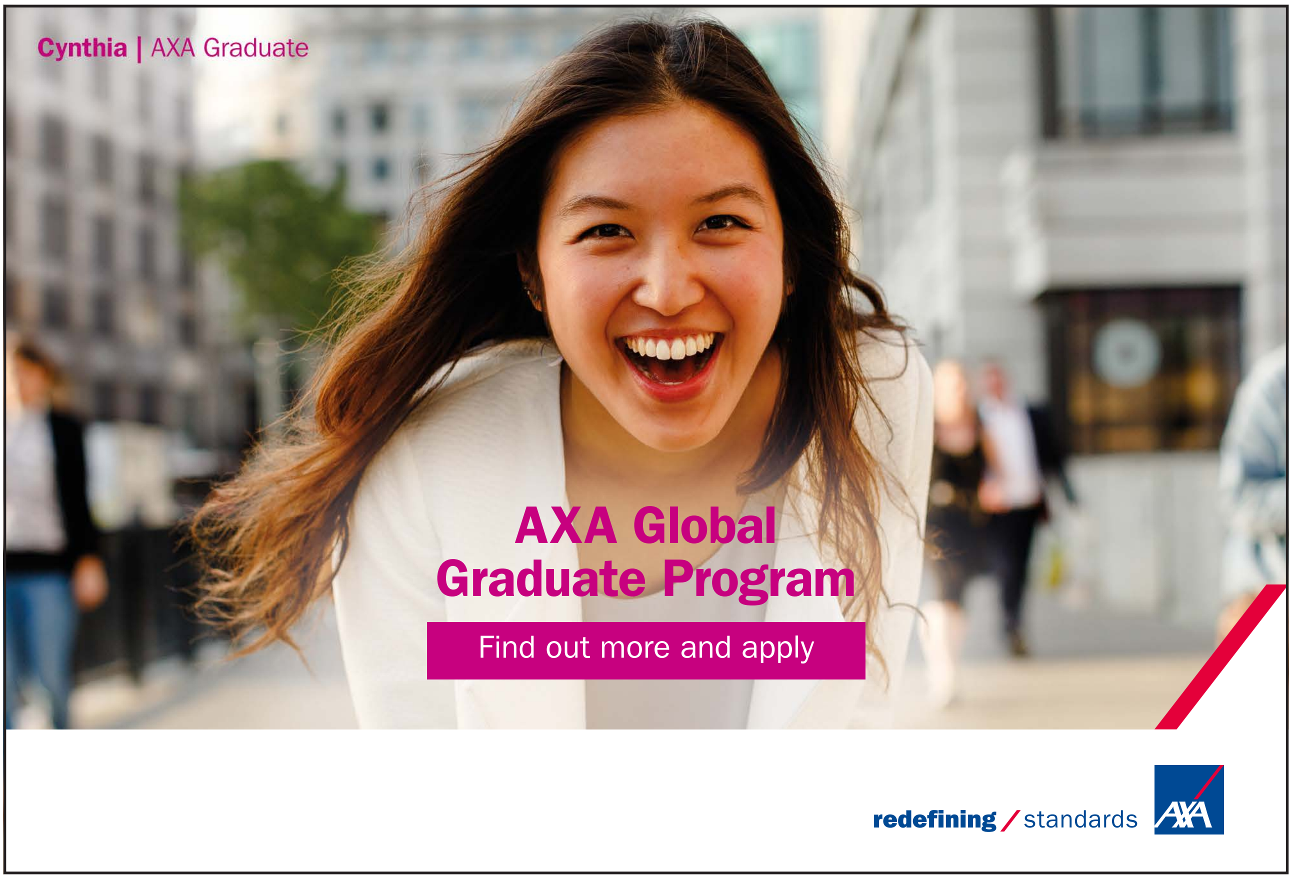
Mathcad has several other capabilities such as: differentiation, integration, matrices, symbolic calculations etc. There is also programming capability in Mathcad with the usual constructs such as if–then–else, do-loops etc. Thus, with its very wide mathematical and graphing functionality, coupled with programming capability and the convenience of Windows platform, Mathcad is a very powerful and versatile tool for engineering and scientific calculations.

Note: It is pertinent to make one note here. Mathcad does not contain built-in functions for thermodynamic properties of working substances such as steam/water, air, refrigerants, fuels etc; one has to buy separately add-in programs supplied by third parties.

1.2.2 Engineering Equation Solver (EES):

What is EES?

EES, supplied by M/s F-Chart Software, USA, 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. 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.



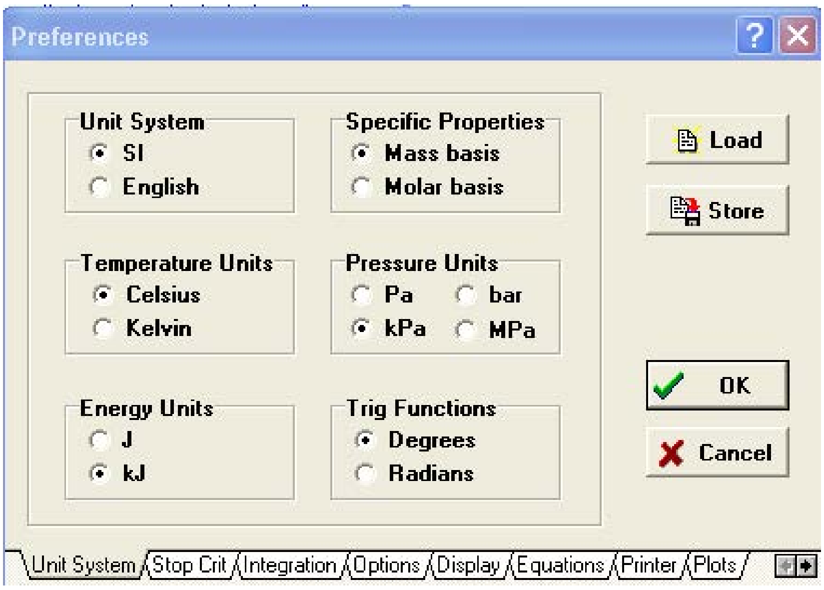
Equations Window of EES:

As you start EES, equations window appears. Here, you enter your equations. Formatting rules are as follows (Ref: F-chart.com):

1. Upper and lower case letters are not distinguished. EES will (optionally) change the ease 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.

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:



Preferences

Unit System: ● SI ○ English
Specific Properties: ● Mass basis ○ Molar basis
Temperature Units: ● Celsius ○ Kelvin
Pressure Units: ○ Pa ○ bar ● kPa ○ MPa
Energy Units: ○ J ● kJ
Trig Functions: ● Degrees ○ Radians

Fig. 1.3 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.

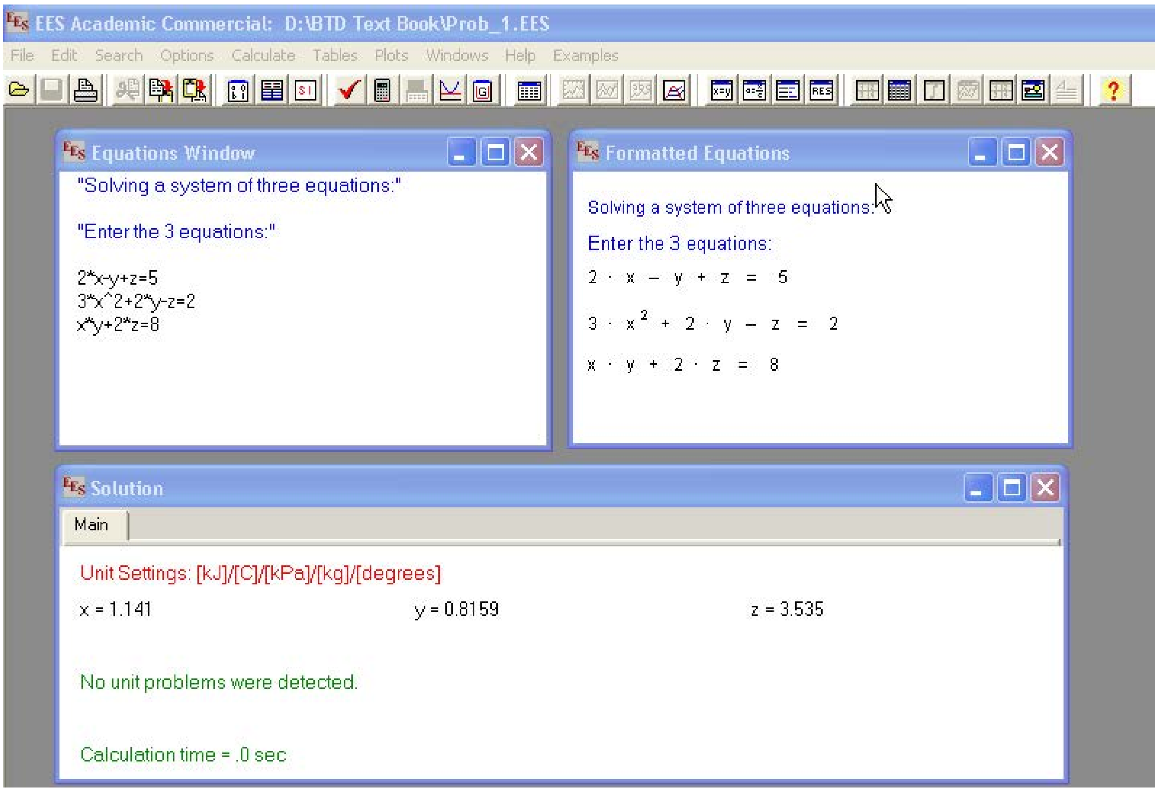
Formatted equations Window:

In this window, 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 properly.

Solutions Window:

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

Example: Let us now solve in EES the same system of three equations, solved in Mathcad earlier. Equations window, Formatted equations window and Solutions window are shown below:



```
"Solving a system of three equations:"

"Enter the 3 equations:"

2*x-y+z=5
3*x^2+2*y-z=2
x*y+2*z=8
```

Solving a system of three equations:

Enter the 3 equations:

$$2 \cdot x - y + z = 5$$

$$3 \cdot x^2 + 2 \cdot y - z = 2$$

$$x \cdot y + 2 \cdot z = 8$$

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

x = 1.141 y = 0.8159 z = 3.535

No unit problems were detected.

Calculation time = .0 sec

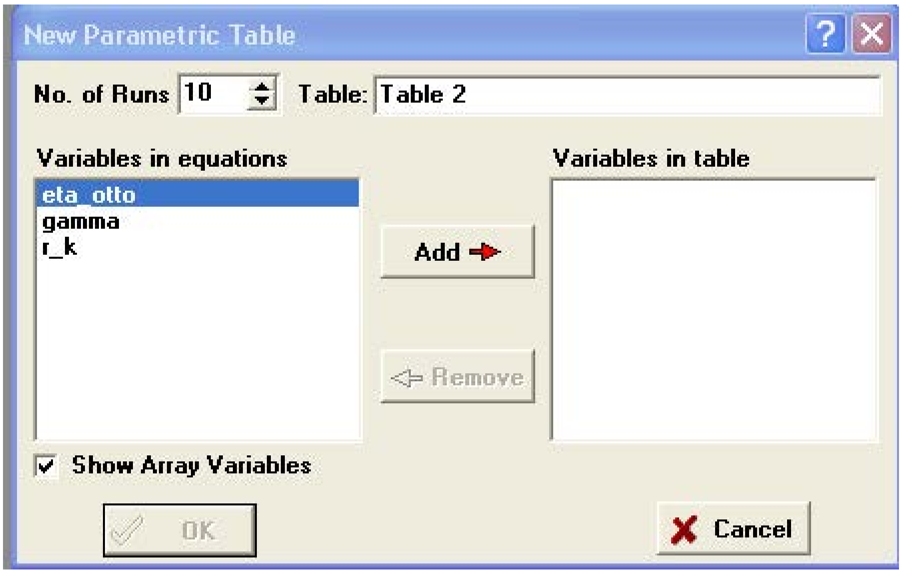
Fig. 1.4 EES Worksheet to solve a system of simultaneous equations

As expected, answers are the same as obtained with Mathcad.

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 Air standard efficiency of Otto cycle for various values of compression ratios. This is the same problem as worked out earlier with Mathcad.

First, enter the equation in the equations window. Next, select the New Table command. A dialog will be displayed listing the variables appearing in the Equations window.

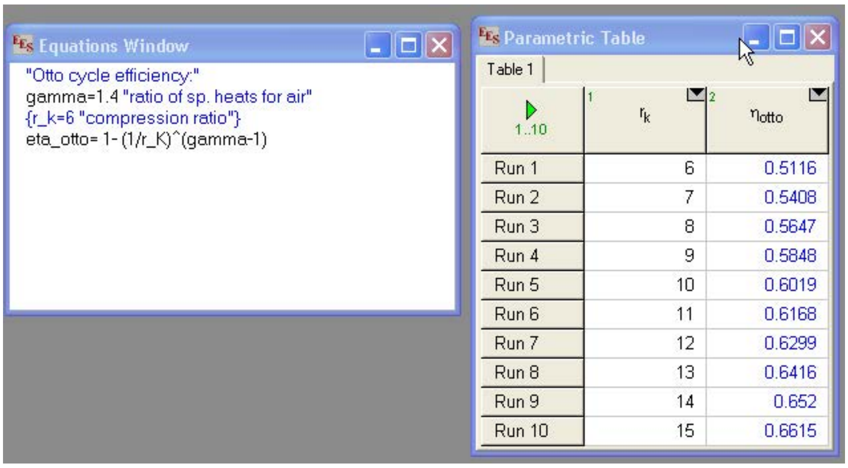


New Parametric Table

No. of Runs 10
Table: Table 2

Fig. 1.5 EES screen shot – setting up the Parametric Table

Choose the variables r_k and eta_otto for the Table and click 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 r_k =6 equation currently in the Equations window or enclose it in comment brackets { }. This equation will not be needed because the value of r_k will be set in the table. Now enter the values of r_k for which eta_otto are be determined. Values of r_k = 6 to 15 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_otto will be entered into the table.



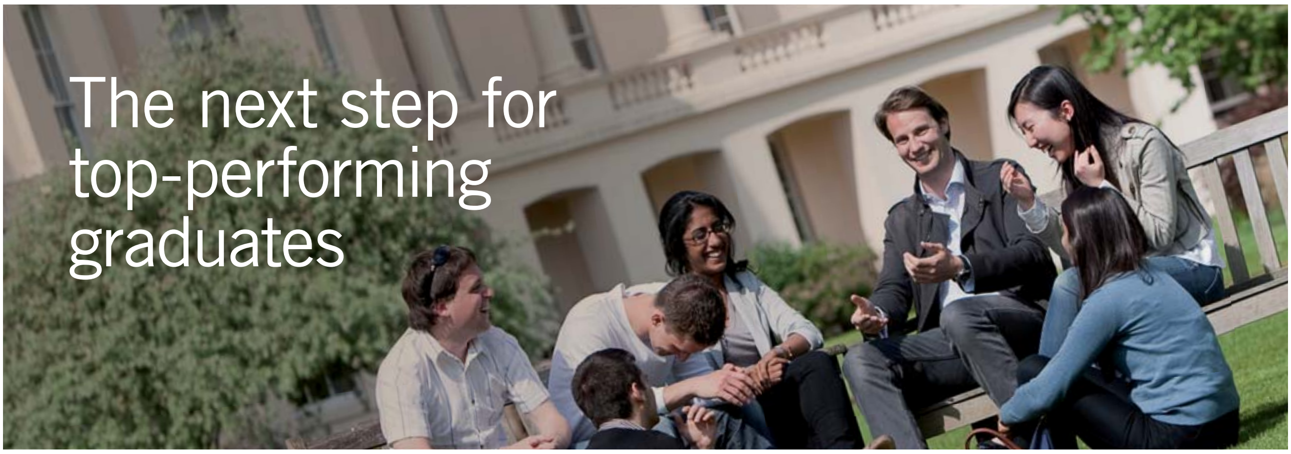
```
"Otto cycle efficiency:"
gamma=1.4 "ratio of sp. heats for air"
{r_k=6 "compression ratio"}
eta_otto= 1-(1/r_K)^(gamma-1)
```

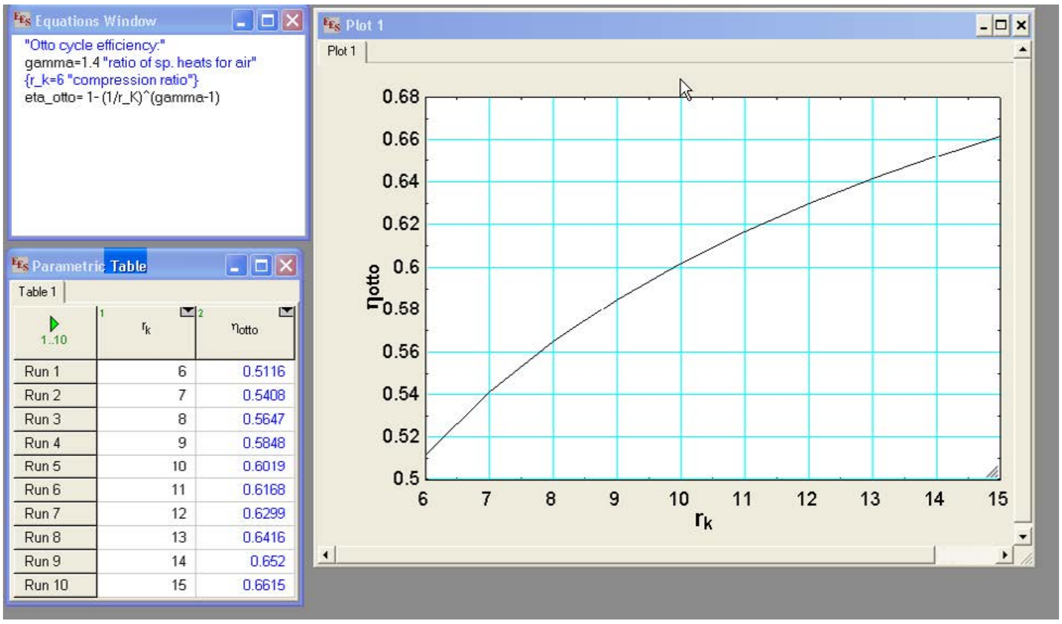
1..10	r_k	η_{otto}
Run 1	6	0.5116
Run 2	7	0.5408
Run 3	8	0.5647
Run 4	9	0.5848
Run 5	10	0.6019
Run 6	11	0.6168
Run 7	12	0.6299
Run 8	13	0.6416
Run 9	14	0.652
Run 10	15	0.6615

Fig. 1.6 EES Worksheet – calculations in Parametric Table

Graphing in EES:

Select New Plot Window from the Plot menu. The New Plot Window dialog window shown below will appear. Choose r_k to be the x-axis by clicking on r_k in the x-axis list. Click on eta_otto in the y-axis list. Select the scale limits for r_k and eta_otto, if required. Grid lines make the plot easier to read. Click on the Grid Lines control for both the x and y axes. When you click the OK button, the plot will be constructed and the plot window will appear. In the screen shot shown below, all the tree windows (i.e. Equation, Parametric Table and the Plot windows) are arranged side by side:





```
"Otto cycle efficiency:"
gamma=1.4 "ratio of sp. heats for air"
{r_k=6 "compression ratio"}
eta_otto= 1- (1/r_K)^(gamma-1)
```

	r_k	η_{otto}
Run 1	6	0.5116
Run 2	7	0.5408
Run 3	8	0.5647
Run 4	9	0.5848
Run 5	10	0.6019
Run 6	11	0.6168
Run 7	12	0.6299
Run 8	13	0.6416
Run 9	14	0.652
Run 10	15	0.6615

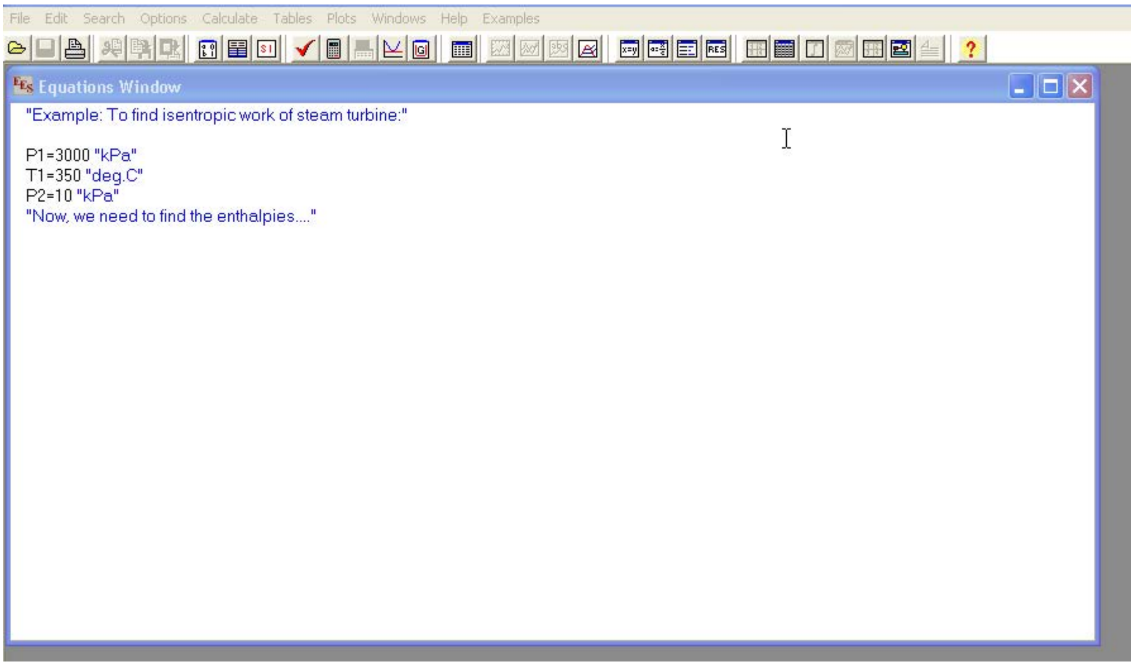
Fig. 1.7 EES graph – screen shot

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.

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:

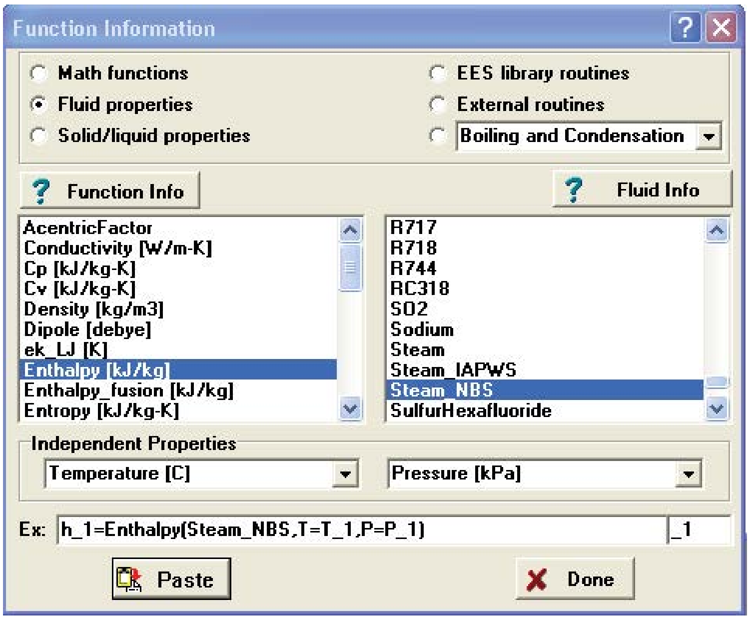


```
"Example: To find isentropic work of steam turbine:"

P1=3000 "kPa"
T1=350 "deg.C"
P2=10 "kPa"
"Now, we need to find the enthalpies...."
```

Fig. 1.8 EES Worksheet to find Isentropic work of Turbine

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 OK, 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, in Ex: (see the screen shot below).



Function Information

○ Math functions
● Fluid properties
○ Solid/liquid properties
○ EES library routines
○ External routines
○ Boiling and Condensation

AcentricFactor
Conductivity [W/m-K]
Cp [kJ/kg-K]
Cv [kJ/kg-K]
Density [kg/m3]
Dipole [debye]
ek_LJ [K]
Enthalpy [kJ/kg]
Enthalpy_fusion [kJ/kg]
Entropy [kJ/kg-K]

R717
R718
R744
RC318
SO2
Sodium
Steam
Steam_IAPWS
Steam_NBS
SulfurHexafluoride

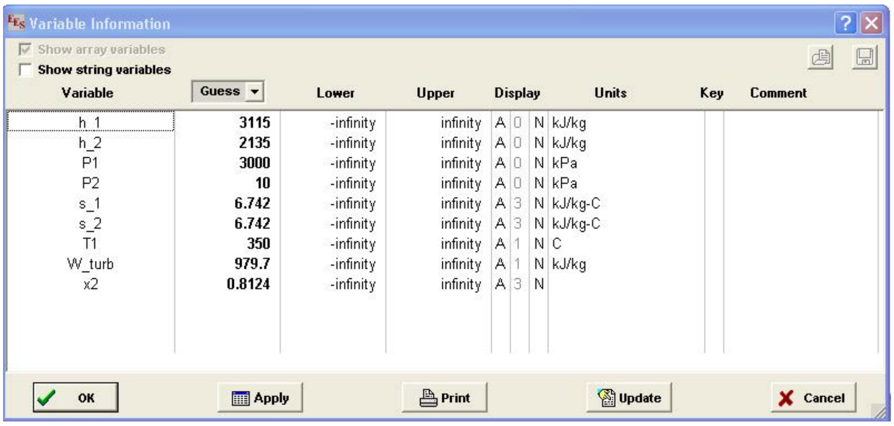
Independent Properties
Temperature [C]
Pressure [kPa]

Ex: h_1=Enthalpy(Steam_NBS,T=T_1,P=P_1)   _1

Fig. 1.9 EES – Function Info window

Now, paste the format on the equations window, taking care to enter the same notations for P and T 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.

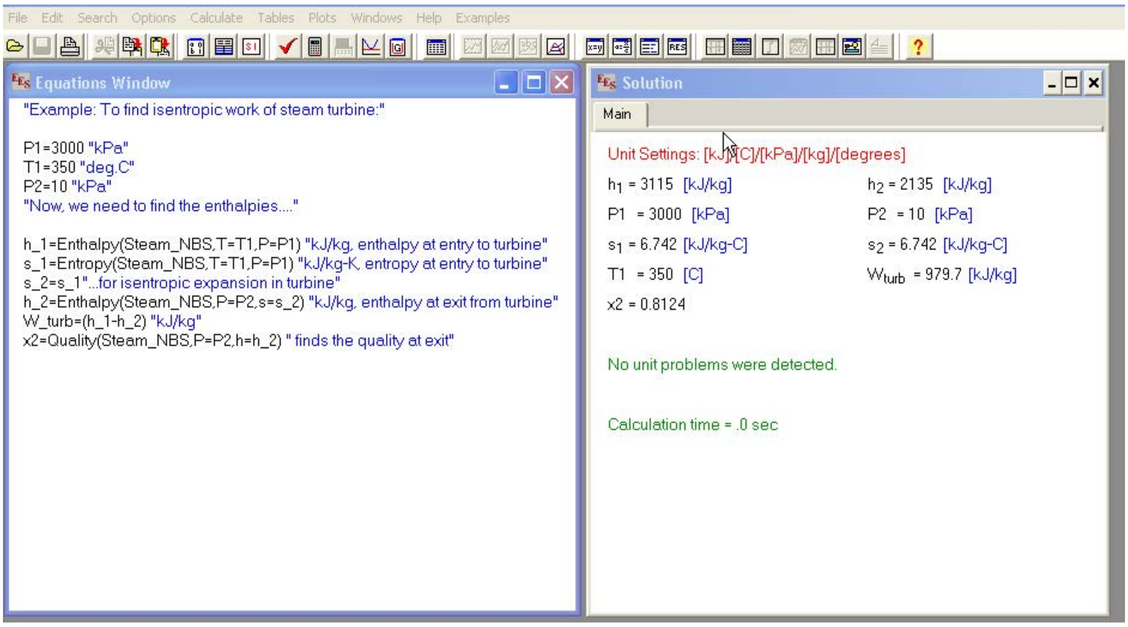
Go to 'Variable Info' under OPTIONS menu and set the units of all variables to make sure that all units are consistent and no unnecessary error messages pop up. Screen shot is shown below:



Variable	Guess	Lower	Upper	Display	Units	Key	Comment
h_1	3115	-infinity	infinity	A 0 N	kJ/kg		
h_2	2135	-infinity	infinity	A 0 N	kJ/kg		
P1	3000	-infinity	infinity	A 0 N	kPa		
P2	10	-infinity	infinity	A 0 N	kPa		
s_1	6.742	-infinity	infinity	A 3 N	kJ/kg-C		
s_2	6.742	-infinity	infinity	A 3 N	kJ/kg-C		
T1	350	-infinity	infinity	A 1 N	C		
W_turb	979.7	-infinity	infinity	A 1 N	kJ/kg		
x2	0.8124	-infinity	infinity	A 3 N			

Fig. 1.10 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:



```
"Example: To find isentropic work of steam turbine:"

P1=3000 "kPa"
T1=350 "deg.C"
P2=10 "kPa"
"Now, we need to find the enthalpies...."

h_1=Enthalpy(Steam_NBS,T=T1,P=P1) "kJ/kg, enthalpy at entry to turbine"
s_1=Entropy(Steam_NBS,T=T1,P=P1) "kJ/kg-K, entropy at entry to turbine"
s_2=s_1"...for isentropic expansion in turbine"
h_2=Enthalpy(Steam_NBS,P=P2,s=s_2) "kJ/kg, enthalpy at exit from turbine"
W_turb=(h_1-h_2) "kJ/kg"
x2=Quality(Steam_NBS,P=P2,h=h_2) " finds the quality at exit"
```

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

h_1 = 3115 [kJ/kg] h_2 = 2135 [kJ/kg]
P1 = 3000 [kPa]   P2 = 10 [kPa]
s_1 = 6.742 [kJ/kg-C] s_2 = 6.742 [kJ/kg-C]
T1 = 350 [C] W_{turb} = 979.7 [kJ/kg]
x2 = 0.8124

No unit problems were detected.

Calculation time = .0 sec

Fig. 1.11 EES Solution Window-- Isentropic work of Turbine

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 because of its built-in functions for a large number of substances. EES is developed by Prof. Klein and his colleagues who teach Thermodynamics and Heat Transfer at Wisconsin University, USA.

1.2.3 The Expert System for Thermodynamics (TEST):

What is TEST?

TEST is a web based learning tool for Thermodynamics. It is not a 'commercial' software, in its strict sense. Educational version of TEST is freely made available to Educators by the author of TEST, Prof. Subrata Bhattacharjee. 'Mirroring' is also encouraged to ensure that every one has access to the same, updated version.

TEST, according to its author, Prof. Subrata Bhattacharjee of San Diego State University, USA, is "…a visual environment to solve thermo problems, pursue what-if scenarios, perform numerical experiments, and engage in a life-long learning experience… It is a visual platform where a user can look up traditional charts and tables, explore hundreds of thermodynamic systems through Flash animations, browse online solutions to problems". Calculations in TEST are done by…Daemons – smart thermodynamic calculators customized for specific classes of problems". A TEST solution is visual in nature, but can be saved and recreated later.

'Daemons' (i.e. TEST calculators) can be used to evaluate thermodynamic properties, define complete states, analyze thermodynamic systems such as: IC engines, gas turbines, steam power plants, refrigeration, air-conditioning, combustion, etc., and perform what-if analysis, produce solution report, plot thermodynamic charts, and create solution macros called TEST-codes, which can be saved for later use. TEST has a rich database of working substances – solids, liquids, gases, gas mixtures, phase-change fluids, moist air etc. One can also create a custom solid, liquid, or gas. There are more than forty refrigerants in the TEST database. TEST also has hundreds of animations of systems and old fashioned thermodynamic tables and charts are also provided. There is an I/O panel, wherein one can perform numerical calculations in an 'Excel-like' environment. Refer to the exhaustive tutorial of TEST (Ref: www.thermofluids.net) for complete instructions on using TEST.

While TEST is great as a visual solution to problems in thermodynamics, another aspect to be remembered is that the equations, formulas and steps involved in calculations are hidden 'behind the scene'. Therefore TEST is very much useful as a visual tool for quick calculations and verification of designs. To produce 'publication quality' graphs, it is recommended that the graph data produced in TEST are transferred to some other software such as Excel (or any other) for further processing.

Systematic approach to solve thermodynamic problems:

Fig. 1.12 shows the TEST – Map i.e. classification of daemons for solving different types of thermodynamic problems. Essentially, there are 3 types of daemons: Basic, State and System daemons. See the sub-classification under each type of daemon. Note that under "Basic' daemons, there is a very good Units conversion program, a desk calculator and conventional thermodynamic property tables. Click on the appropriate daemon to bring it to surface. "…The core of the daemon is its robust state calculator, which bundles the relevant state variables (*p, T, v, u, h, s,* etc.) into a single graphical interface called a state. You can enter the known state variables in any desired units and calculate the state fully or partially by the click of a button. The daemon checks for redundancy in inputs, determines phase composition, and plots simple thermodynamic diagrams (such as the T-s diagram, psychrometric plot etc.)".

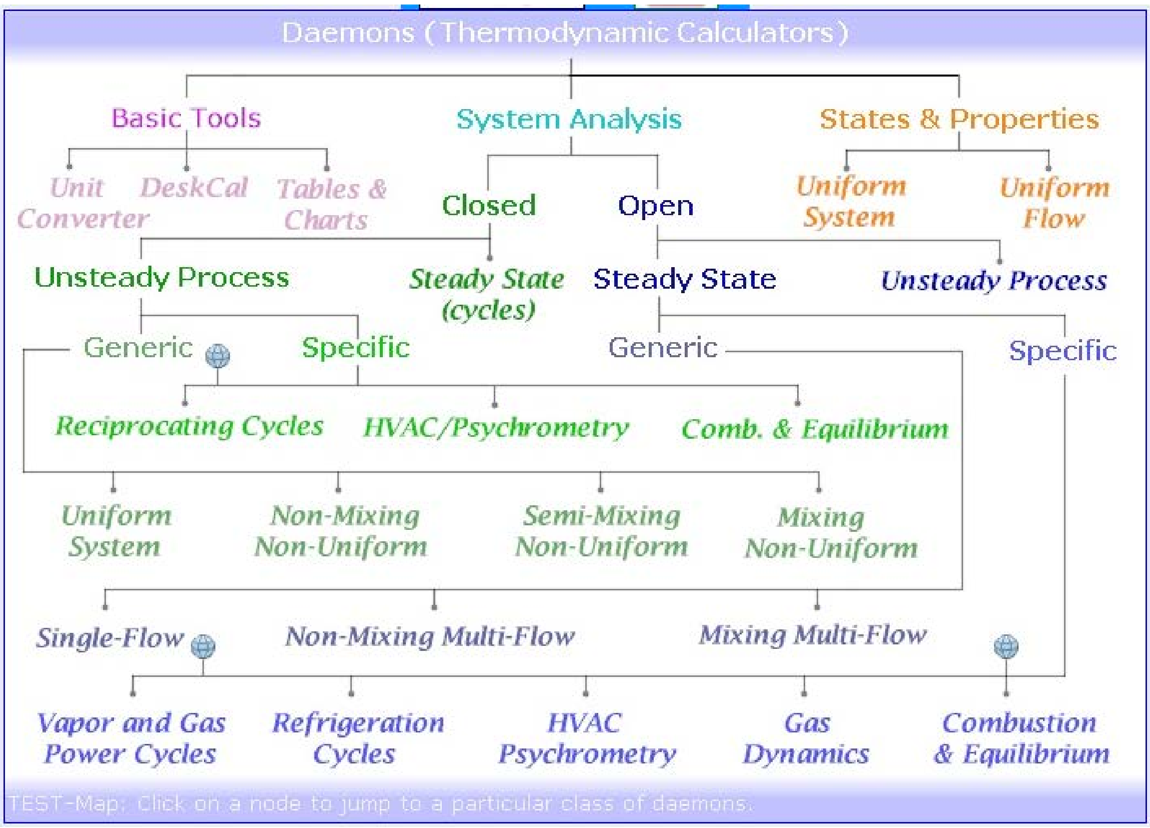
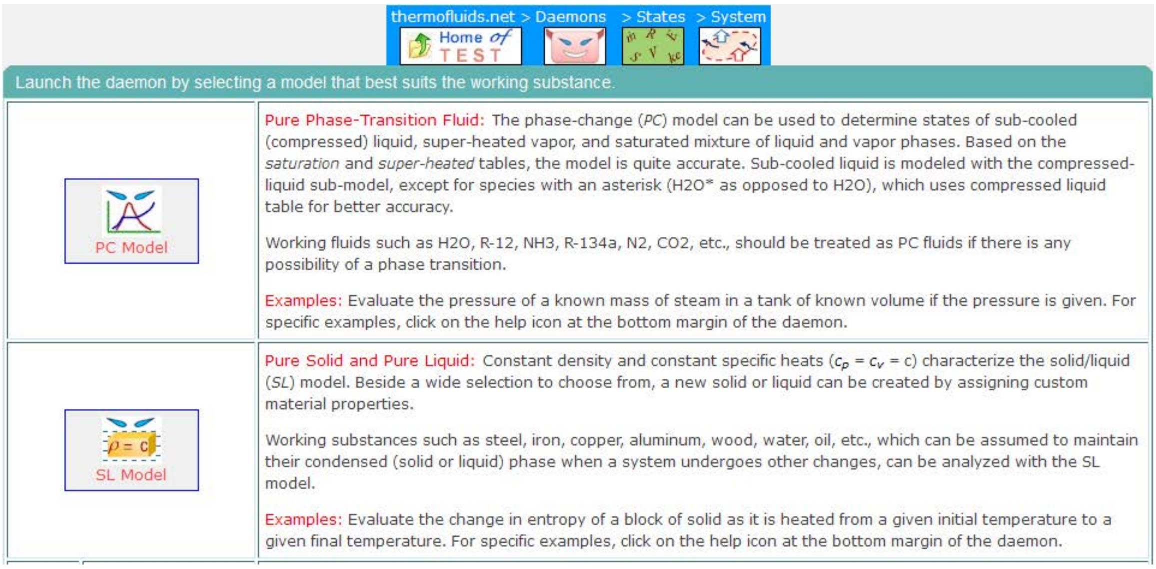


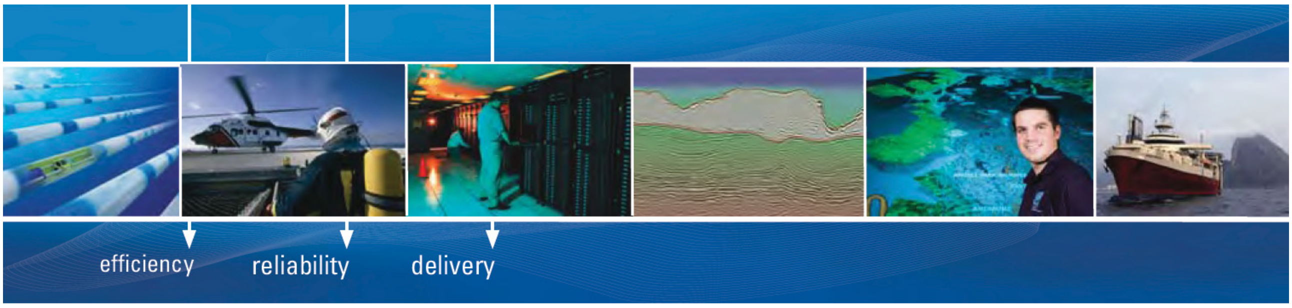
Fig. 1.12 TEST – Map

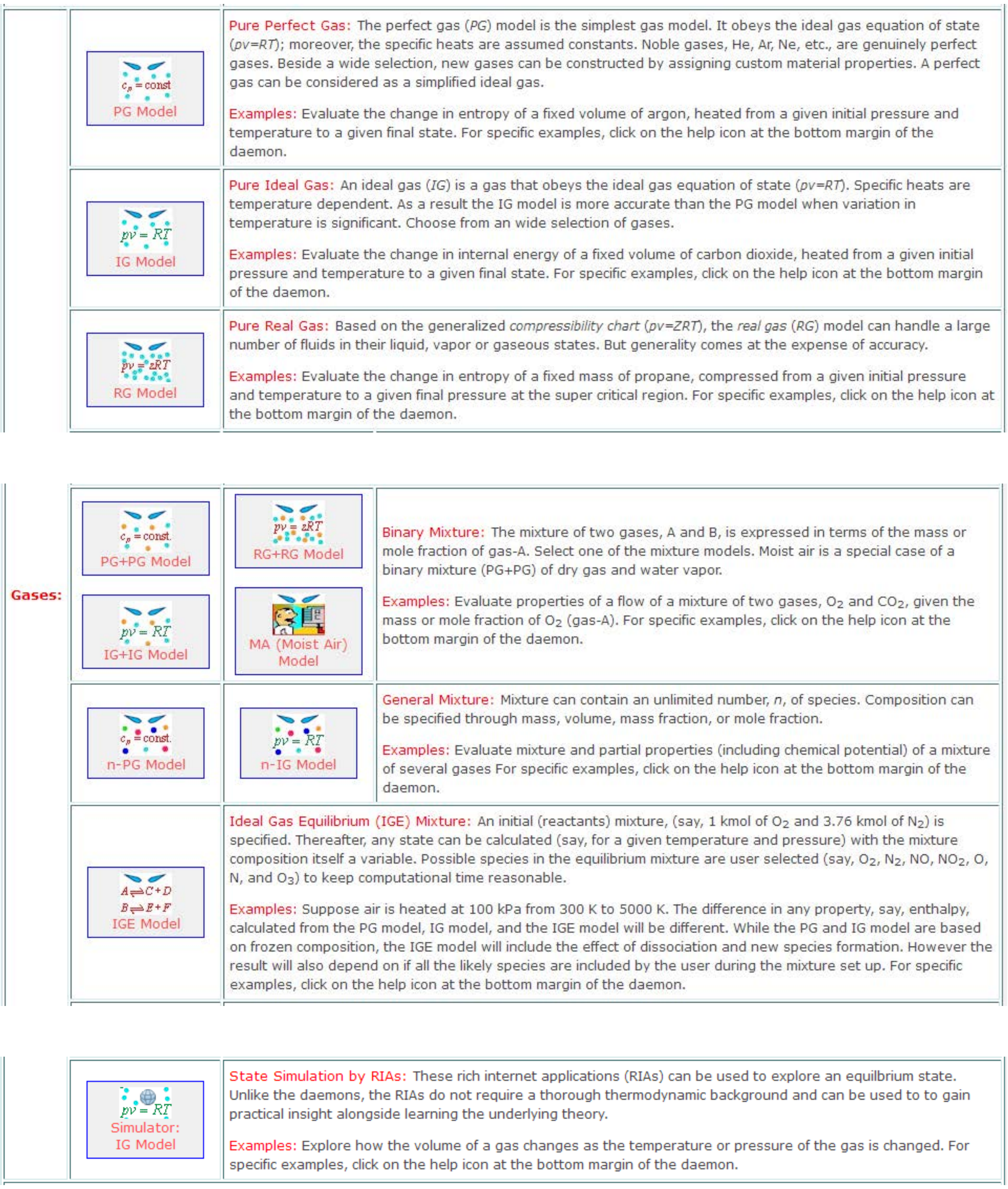
After selecting the system, you have to select the material model before the daemon is launched. There are four models of working substances: Solid/Liquid, Gases, Gas mixtures and Phase change fluids. Gas models are subdivided into Perfect (i.e. constant cp), Ideal and Real gas models. Phase change fluids' refers to Steam/Water, Refrigerants etc. As an example, in TEST-Map shown above, if you click on States-Uniform System, following screen will appear from where you choose the material model.



Launch the daemon by selecting a model that best suits the working substance.

PC Model	Pure Phase-Transition Fluid: The phase-change (*PC*) model can be used to determine states of sub-cooled (compressed) liquid, super-heated vapor, and saturated mixture of liquid and vapor phases. Based on the *saturation* and *super-heated* tables, the model is quite accurate. Sub-cooled liquid is modeled with the compressed-liquid sub-model, except for species with an asterisk (H2O* as opposed to H2O), which uses compressed liquid table for better accuracy. Working fluids such as H2O, R-12, NH3, R-134a, N2, CO2, etc., should be treated as PC fluids if there is any possibility of a phase transition. Examples: Evaluate the pressure of a known mass of steam in a tank of known volume if the pressure is given. For specific examples, click on the help icon at the bottom margin of the daemon.
SL Model	Pure Solid and Pure Liquid: Constant density and constant specific heats ($c_p = c_v = c$) characterize the solid/liquid (*SL*) model. Beside a wide selection to choose from, a new solid or liquid can be created by assigning custom material properties. Working substances such as steel, iron, copper, aluminum, wood, water, oil, etc., which can be assumed to maintain their condensed (solid or liquid) phase when a system undergoes other changes, can be analyzed with the SL model. Examples: Evaluate the change in entropy of a block of solid as it is heated from a given initial temperature to a given final temperature. For specific examples, click on the help icon at the bottom margin of the daemon.





Pure Perfect Gas: The perfect gas (*PG*) model is the simplest gas model. It obeys the ideal gas equation of state (*pv=RT*); moreover, the specific heats are assumed constants. Noble gases, He, Ar, Ne, etc., are genuinely perfect gases. Beside a wide selection, new gases can be constructed by assigning custom material properties. A perfect gas can be considered as a simplified ideal gas.

Examples: Evaluate the change in entropy of a fixed volume of argon, heated from a given initial pressure and temperature to a given final state. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Ideal Gas: An ideal gas (*IG*) is a gas that obeys the ideal gas equation of state (*pv=RT*). Specific heats are temperature dependent. As a result the IG model is more accurate than the PG model when variation in temperature is significant. Choose from an wide selection of gases.

Examples: Evaluate the change in internal energy of a fixed volume of carbon dioxide, heated from a given initial pressure and temperature to a given final state. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Real Gas: Based on the generalized *compressibility chart* (*pv=ZRT*), the *real gas* (*RG*) model can handle a large number of fluids in their liquid, vapor or gaseous states. But generality comes at the expense of accuracy.

Examples: Evaluate the change in entropy of a fixed mass of propane, compressed from a given initial pressure and temperature to a given final pressure at the super critical region. For specific examples, click on the help icon at the bottom margin of the daemon.

Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: Evaluate properties of a flow of a mixture of two gases, O_2 and CO_2, given the mass or mole fraction of O_2 (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.

General Mixture: Mixture can contain an unlimited number, *n*, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.

Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.

Ideal Gas Equilibrium (IGE) Mixture: An initial (reactants) mixture, (say, 1 kmol of O_2 and 3.76 kmol of N_2) is specified. Thereafter, any state can be calculated (say, for a given temperature and pressure) with the mixture composition itself a variable. Possible species in the equilibrium mixture are user selected (say, O_2, N_2, NO, NO_2, O, N, and O_3) to keep computational time reasonable.

Examples: Suppose air is heated at 100 kPa from 300 K to 5000 K. The difference in any property, say, enthalpy, calculated from the PG model, IG model, and the IGE model will be different. While the PG and IG model are based on frozen composition, the IGE model will include the effect of dissociation and new species formation. However the result will also depend on if all the likely species are included by the user during the mixture set up. For specific examples, click on the help icon at the bottom margin of the daemon.

State Simulation by RIAs: These rich internet applications (RIAs) can be used to explore an equlibrium state. Unlike the daemons, the RIAs do not require a thorough thermodynamic background and can be used to to gain practical insight alongside learning the underlying theory.

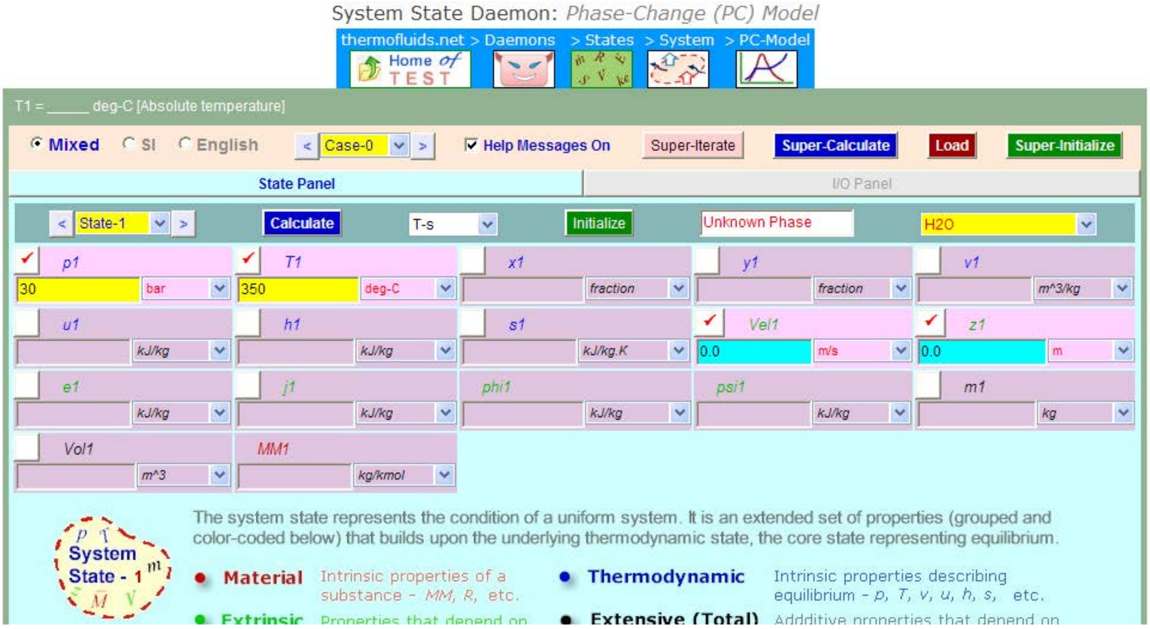
Examples: Explore how the volume of a gas changes as the temperature or pressure of the gas is changed. For specific examples, click on the help icon at the bottom margin of the daemon.

Fig. 1.13 TEST – Material models

Depending upon the problem, choose the material model.

As an ***example,*** let us find out the properties of steam at 30 bar and 350 C.

So, in TEST-Map, choose States-Uniform System (Fig. 1.12), and, then choose the PC (i.e. Phase Change) model in the Fig. 1.13 and the PC model daemon will appear. In that screen, working fluid is already chosen as H2O; change the fluid in case you are working with any other fluid, such as refrigerants etc. Select P and T (since these are given as data in the problem) and enter the respective values. Note that you can the units as you require. This is shown in the following screen shot:



T1 = _____ deg-C [Absolute temperature]

● Mixed ○ SI ○ English
Case-0
☑ Help Messages On
State-1
T-s
Unknown Phase
H2O

☑ p1: 30 bar
☑ T1: 350 deg-C
☐ x1: fraction
☐ y1: fraction
☐ v1: m^3/kg
☐ u1: kJ/kg
☐ h1: kJ/kg
☐ s1: kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: kJ/kg
☐ j1: kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: kg
☐ Vol1: m^3
MM1: kg/kmol

The system state represents the condition of a uniform system. It is an extended set of properties (grouped and color-coded below) that builds upon the underlying thermodynamic state, the core state representing equilibrium.

System State - 1

- Material: Intrinsic properties of a substance - MM, R, etc.
- Thermodynamic: Intrinsic properties describing equilibrium - p, T, v, u, h, s, etc.
- Extrinsic: Properties that depend on
- Extensive (Total): Addditive properties that depend on

Fig. 1.14 TEST – to find properties of Steam

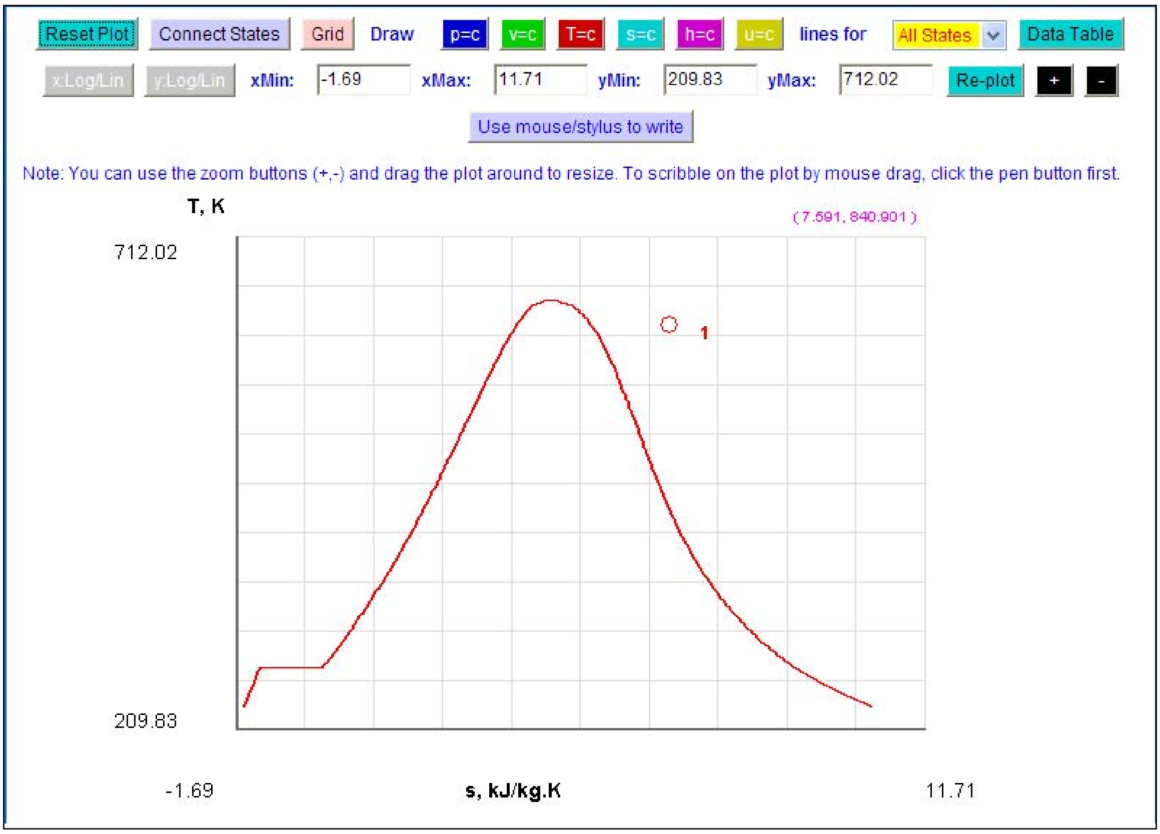
Now, click on 'Calculate' or hit Enter, and immediately, all other property values will appear on the screen. Along with it, a T-s plot will also be presented if we choose T-s plot from the plot widget. See fig. below:

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English
Case-0
☑ Help Messages On
©State-1
No-Plots
Superheated Vapor
H2O

☑ p1: 30.0 bar
☑ T1: 350.0 deg-C
☐ x1: fraction
☐ y1: fraction
☐ v1: 0.09053 m^3/kg
☐ u1: 2843.641 kJ/kg
☐ h1: 3115.2256 kJ/kg
☐ s1: 6.74266 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 2843.641 kJ/kg
☐ j1: 3115.2256 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: kg
☐ Vol1: m^3
MM1: 18.0 kg/kmol

Fig. 1.15 (a) TEST – properties of Steam at 30 bar, 350 C



Note: You can use the zoom buttons (+,-) and drag the plot around to resize. To scribble on the plot by mouse drag, click the pen button first.

Fig. 1.15 (b) TEST – T-s plot for Steam at 30 bar, 350 C

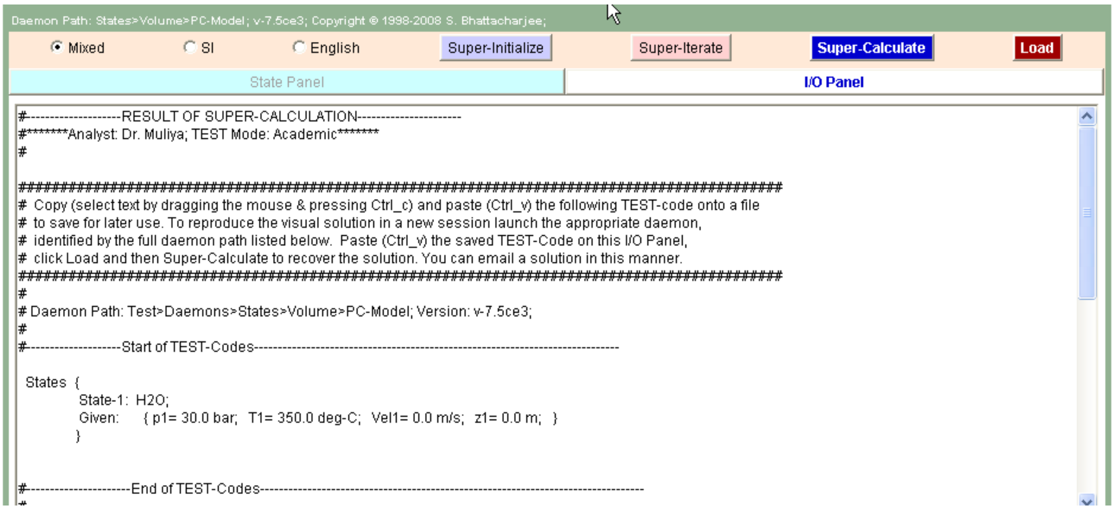
If required, state point can be shown on a variety of plots by selecting the type of plot from the widget in the State panel. In the fig. below, p-v plot and the State point 1 is drawn:

xMin: 5.0E-4 xMax: 195.3 yMin: 1.06457 yMax: 60064.1

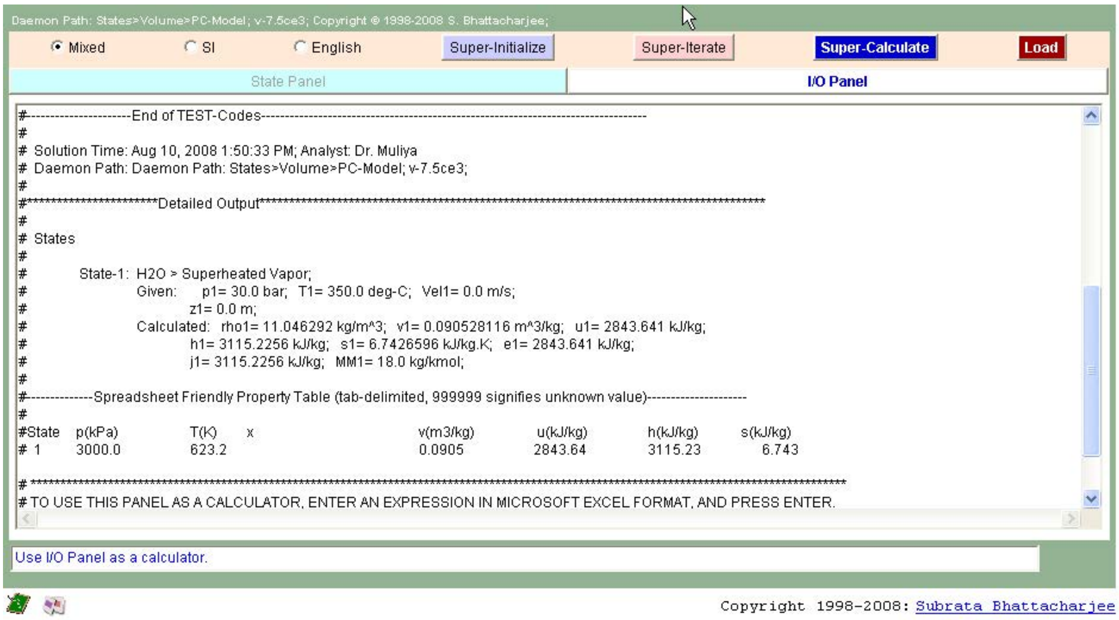
Note: You can use the zoom buttons (+,-) and drag the plot around to resize. To scribble on the plot by mouse drag, click the pen button first.

Fig. 1.16 TEST – Steam at 30 bar, 350 C- state point on p-v plot

TEST Codes: The results of this calculation can be stored as a TEST code, which can be used to recreate this TEST solution, later. To do so, simply click on 'Super-Calculate' button, and then go to the I/O panel. There, TEST code and the detailed results are available. You can copy the TEST code on a word processor (say, MS Word) and save it as a separate file. This window is shown in two halves below:



```
#-------------------RESULT OF SUPER-CALCULATION---------------------
#*******Analyst: Dr. Muliya; TEST Mode: Academic*******
#

##########################################################################################
#  Copy (select text by dragging the mouse & pressing Ctrl_c) and paste (Ctrl_v) the following TEST-code onto a file
#  to save for later use. To reproduce the visual solution in a new session launch the appropriate daemon,
#  identified by the full daemon path listed below.  Paste (Ctrl_v) the saved TEST-Code on this I/O Panel,
#  click Load and then Super-Calculate to recover the solution. You can email a solution in this manner.
##########################################################################################
#
# Daemon Path: Test>Daemons>States>Volume>PC-Model; Version: v-7.5ce3;
#
#-------------------Start of TEST-Codes--------------------------------------------------------------------------

 States  {
          State-1:  H2O;
          Given:     { p1= 30.0 bar;   T1= 350.0 deg-C;   Vel1= 0.0 m/s;   z1= 0.0 m;   }
         }


#--------------------End of TEST-Codes----------------------------------------------------------------------------
#
```



```
#--------------------End of TEST-Codes------------------------------------------------------------------------
#
# Solution Time: Aug 10, 2008 1:50:33 PM; Analyst: Dr. Muliya
# Daemon Path: Daemon Path: States>Volume>PC-Model; v-7.5ce3;
#
#*********************Detailed Output*****************************************************************************
#
# States
#
#         State-1: H2O > Superheated Vapor;
#                  Given:      p1= 30.0 bar;   T1= 350.0 deg-C;   Vel1= 0.0 m/s;
#                              z1= 0.0 m;
#                  Calculated:  rho1= 11.046292 kg/m^3;  v1= 0.090528116 m^3/kg;  u1= 2843.641 kJ/kg;
#                              h1= 3115.2256 kJ/kg;  s1= 6.7426596 kJ/kg.K;  e1= 2843.641 kJ/kg;
#                              j1= 3115.2256 kJ/kg;  MM1= 18.0 kg/kmol;
#
#------------Spreadsheet Friendly Property Table (tab-delimited, 999999 signifies unknown value)-------------------
#
#State   p(kPa)        T(K)    x                       v(m3/kg)      u(kJ/kg)       h(kJ/kg)      s(kJ/kg)
# 1      3000.0        623.2                           0.0905        2843.64        3115.23          6.743

# ******************************************************************************************************************
# TO USE THIS PANEL AS A CALCULATOR, ENTER AN EXPRESSION IN MICROSOFT EXCEL FORMAT, AND PRESS ENTER.
```

Use I/O Panel as a calculator.

Copyright 1998-2008: Subrata Bhattacharjee

Fig. 1.17 TEST – codes for properties of Steam at 30 bar, 350 C

To recreate the solution, go to the relevant daemon page and just copy the TEST code from the saved file on to the I/O panel and click on 'Super-Calculate' button. Then, the code will be 'loaded', and a message will appear on successful completion.

As shown in TEST – Map (Fig. 1.12), TEST can be used not only just to calculate properties at state points, but also to solve many system problems such as Steam power cycles, Gas power cycles, Refrigeration cycles, Psychrometry.. etc. We shall show more examples of using TEST when we deal with those chapters.

1.2.4 Comparison of Mathcad, EES and TEST:

Features of these three software are presented below in a tabular form for comparison:

Sl. No.	Feature	Mathcad	EES	TEST
1	Type of Interface	Free form – i.e. eqns., text and graphics can all be put on the same screen	Eqns. and text on eqn. window and graphics on plot window	Visual interface
2	Entering eqns	Appears as if you write math on a letter pad	Eqns. Appear in a straight line as in 'Fortran' or 'C' languages	No need to write eqns. generally

Sl. No.	Feature	Mathcad	EES	TEST
3	Checking eqns	Very easy and immediate since they appear as you generally write on paper	You have to switch to 'Formatted eqns' window to check	--
4	Computer screen	'Live' as in a Spread sheet, i.e. results appear immediately as you enter '=' (i.e. equals sign)	Press F2 to calculate and results appear in a separate 'Solutions window'	Click on 'Calculate' button; immediately, results are filled in the blank widgets on the same window
5	Programming capability	Yes	Yes	N/A
6	Quality of plots	Publication quality	Publication quality	Indicative plots and Plot data is produced; this data has to be copied to a plotting software, such as Excel, to get Publication quality plots
7	Ease of learning	'Learning curve' is steep; however, easy and powerful after you get proficient with it	Very easy – intuitive interface	Very easy
8	Learning tools & Help	Very good manual and help file	Very good manual and help file	Extremely good – with many tutorials, examples and animations
9	Extra Info	Has 'built-in electronic reference' to get instant access to standard formulae and equations	Wealth of worked out examples – to gain familiarity with EES	Very good collection of examples/ problems to learn/ teach TEST
10	Thermodynamic and other properties of substances	'Add-in' programs are required to be incorporated extra	'Built-in' with EES – a great advantage!	Built into the program – a great advantage!
11	Speciality	Powerful; eqns, text, graphics – all on same screen, great graphing, produce and share publication quality reports	Basically an equation solver; easy to learn and use; built in functions for thermodynamic and other properties of large no. of substances	Great 'visual solutions'; tutorials, examples, animations; built in properties for large no. of substances; can be accessed 'on line' or can be installed on your PC

Sl. No.	Feature	Mathcad	EES	TEST
12	Suitability	Quite powerful technical software; but, needs add – in programs to solve some types of thermodynamics problems	Especially suitable to solve thermodynamics problems since property functions are built in	Specially developed to solve thermodynamics problems
13	Speed (…depends on computer confign. of course)	Fast	Fast	Java applets may take a little time to load on Internet; Fast if TEST is installed on your PC
14	Website	ptc.com	Fchart.com	Thermofluids.net

Table 1.1 Comparison of Mathcad, EES and TEST5

1.3 'Free' Software:

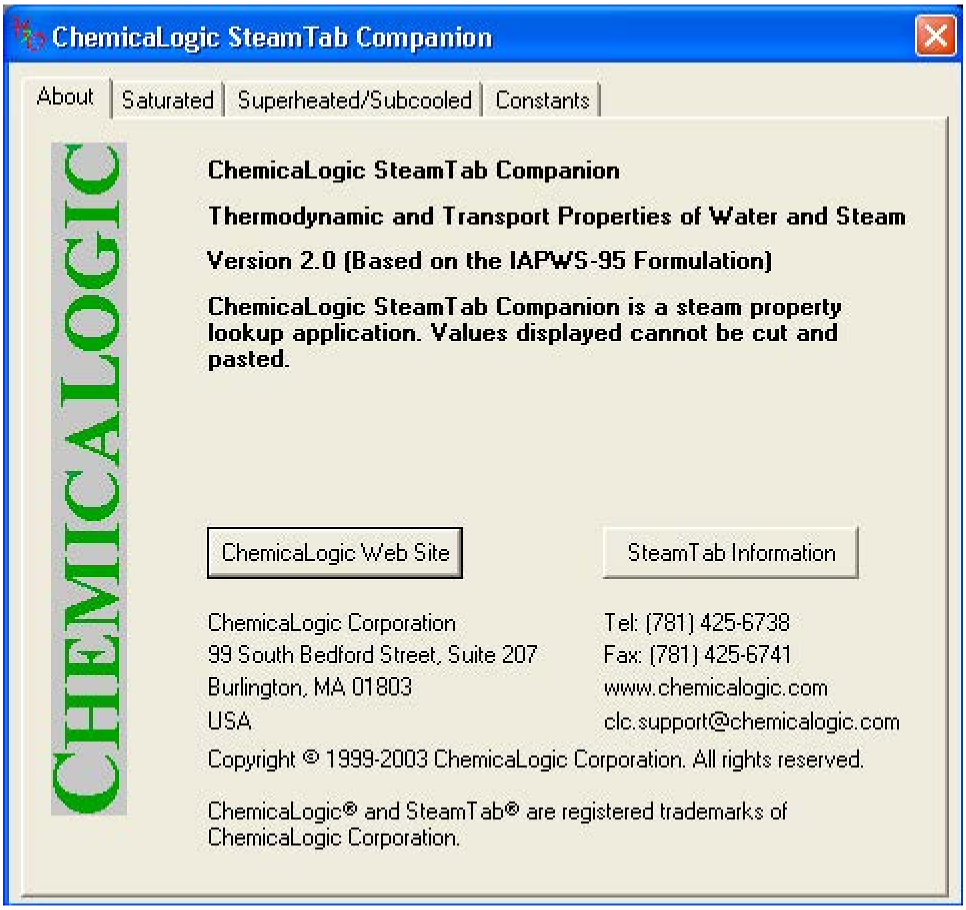
There are many 'free' software available in the Internet, made available by well known companies or some well meaning individuals. Generally, such software are not very versatile and are meant to do some specific job; but, they may do that job very well indeed, some times, even better than commercially available software!

Here, we shall mention about three software: two for finding out properties of Steam/Water, and the other one for doing psychrometric calculations.

1.3.1 ChemicaLogic SteamTab Companion:

This is a small, but handy program to find out the properties of Steam/ Water.

As you start the program, following screen appears:



ChemicaLogic SteamTab Companion

Thermodynamic and Transport Properties of Water and Steam

Version 2.0 (Based on the IAPWS-95 Formulation)

ChemicaLogic SteamTab Companion is a steam property lookup application. Values displayed cannot be cut and pasted.

ChemicaLogic Corporation
99 South Bedford Street, Suite 207
Burlington, MA 01803
USA

Tel: (781) 425-6738
Fax: (781) 425-6741
www.chemicalogic.com
clc.support@chemicalogic.com

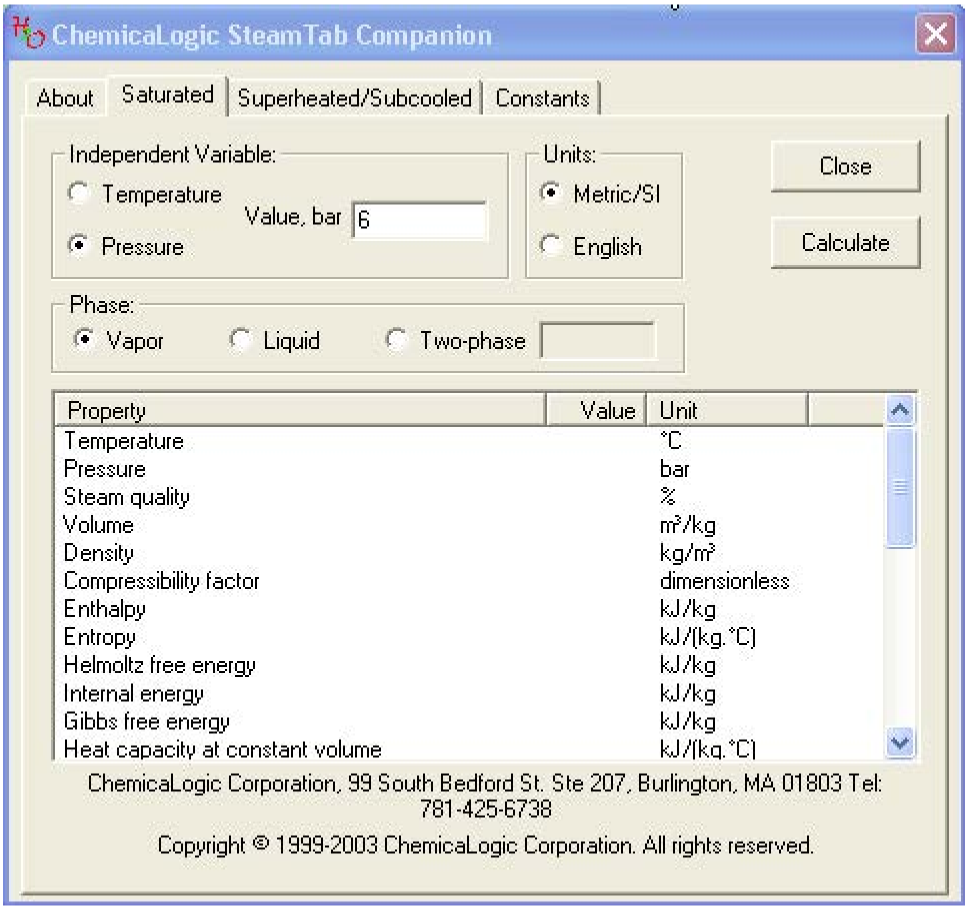
Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

ChemicaLogic® and SteamTab® are registered trademarks of ChemicaLogic Corporation.

Fig. 1.18 About SteamTab Companion

As can be seen in the above fig., there are 4 tabs: About, Saturated, Superheated/Subcooled and Constants. Clicking 'About' brings up the above screen, which gives details about the company etc. 'Saturated' tab gives properties of saturated steam; either P or T has to be input, since in saturated state only one intrinsic property determines the state.

As an example, let us find out the saturated properties at, say, P = 6 bar. Click on the 'Saturated tab and enter the value of P when the screen appears. See the following screen shot:



Independent Variable:
○ Temperature
● Pressure
Value, bar: 6

Units:
● Metric/SI
○ English

Phase:
● Vapor
○ Liquid
○ Two-phase

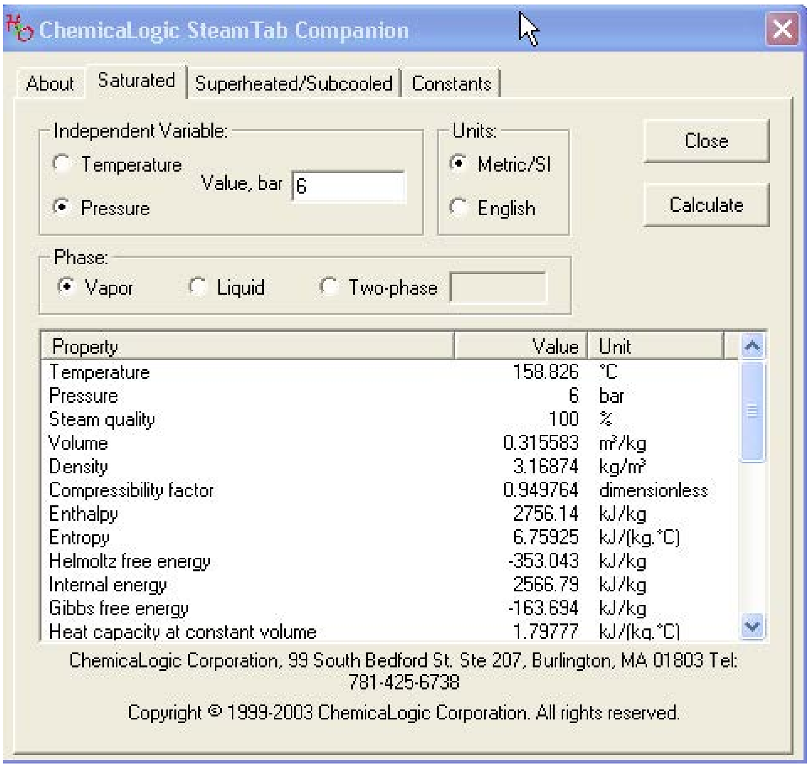
Property	Value	Unit
Temperature		°C
Pressure		bar
Steam quality		%
Volume		m³/kg
Density		kg/m³
Compressibility factor		dimensionless
Enthalpy		kJ/kg
Entropy		kJ/(kg.°C)
Helmoltz free energy		kJ/kg
Internal energy		kJ/kg
Gibbs free energy		kJ/kg
Heat capacity at constant volume		kJ/(kg.°C)

ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

Fig. 1.19 Sat. properties of Steam

Note that P is selected as independent variable. You can also choose either Metric/SI. or English units. We have chosen Metric/SI. We can read either Sat. Vapor properties or Sat. Liquid properties. Here, we have chosen Vapor properties. Now, click 'Calculate' and immediately, the properties are shown on the screen. Following fig. shows both the Sat. Vapor and Sat. Liquid properties:



Independent Variable: ○ Temperature ● Pressure

Value, bar: 6

Units: ● Metric/SI ○ English

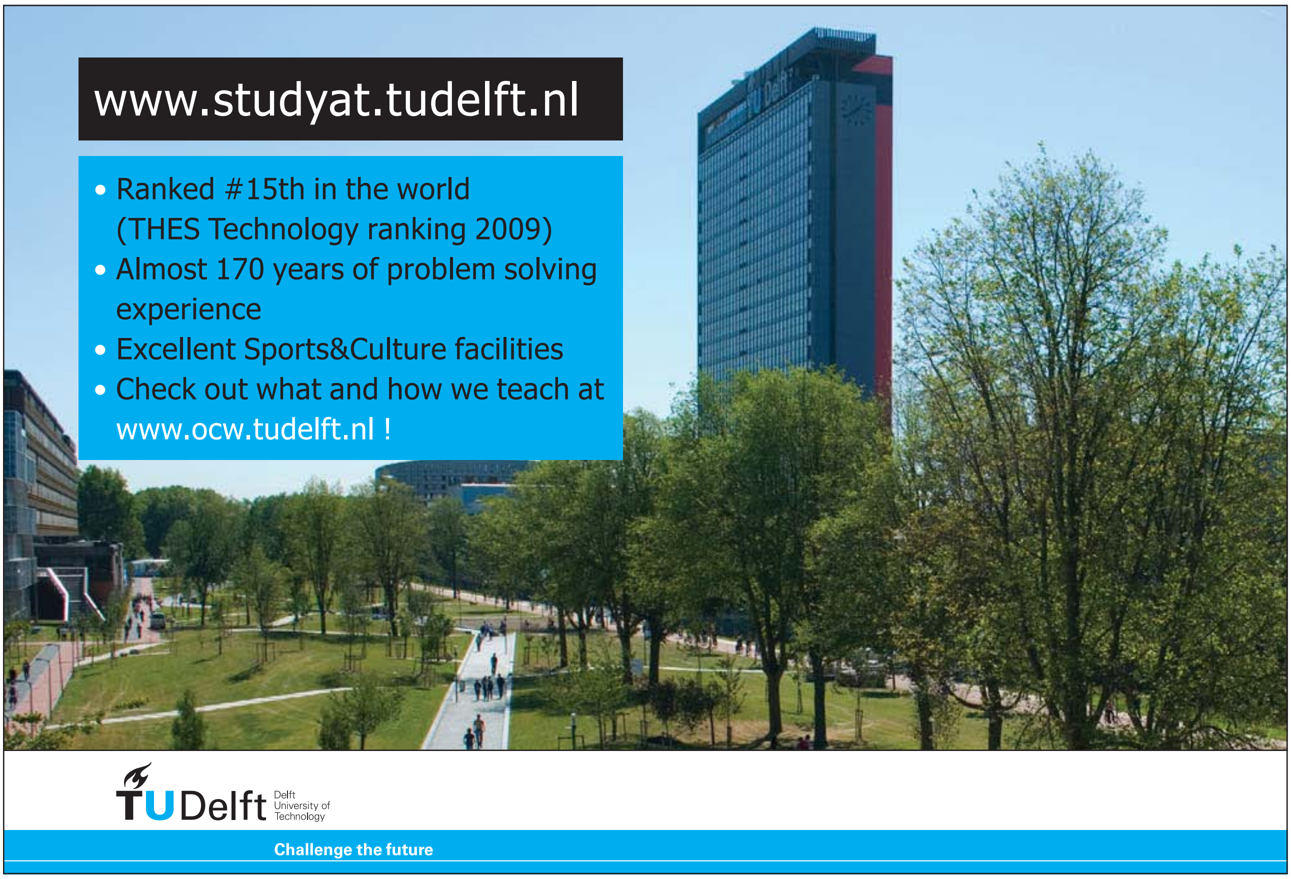
Phase: ● Vapor ○ Liquid ○ Two-phase

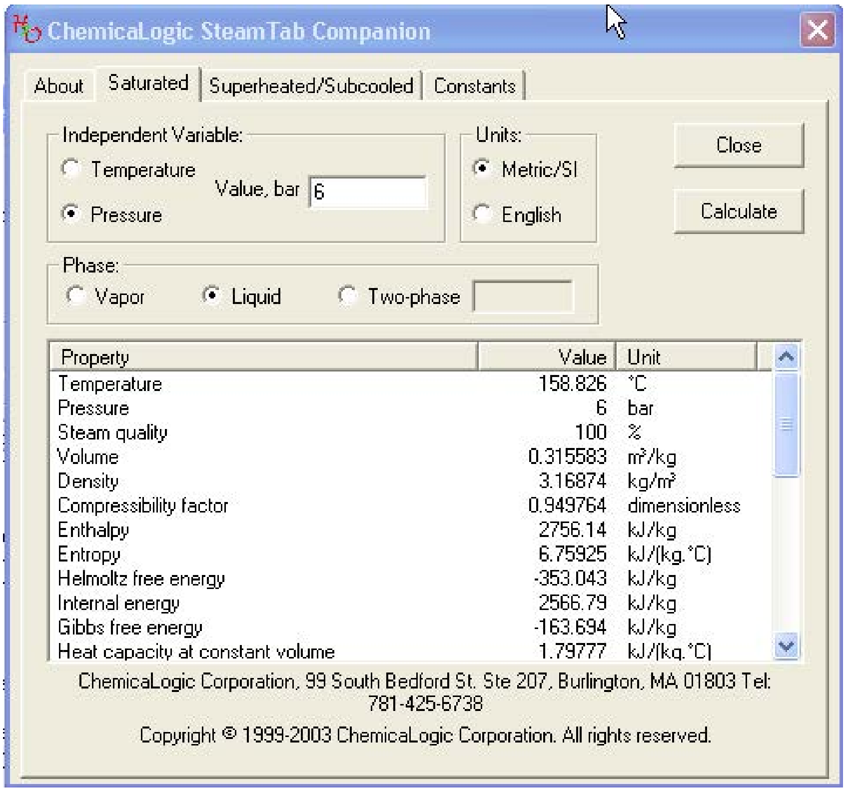
Property	Value	Unit
Temperature	158.826	°C
Pressure	6	bar
Steam quality	100	%
Volume	0.315583	m³/kg
Density	3.16874	kg/m³
Compressibility factor	0.949764	dimensionless
Enthalpy	2756.14	kJ/kg
Entropy	6.75925	kJ/(kg.°C)
Helmoltz free energy	-353.043	kJ/kg
Internal energy	2566.79	kJ/kg
Gibbs free energy	-163.694	kJ/kg
Heat capacity at constant volume	1.79777	kJ/(kg.°C)

ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

Fig. 1.20 (a) Sat. Vap. properties of Steam at P = 6 bar





Independent Variable:
○ Temperature
● Pressure
Value, bar 6

Units:
● Metric/SI
○ English

Phase:
○ Vapor
● Liquid
○ Two-phase

Property	Value	Unit
Temperature	158.826	°C
Pressure	6	bar
Steam quality	100	%
Volume	0.315583	m³/kg
Density	3.16874	kg/m³
Compressibility factor	0.949764	dimensionless
Enthalpy	2756.14	kJ/kg
Entropy	6.75925	kJ/(kg.°C)
Helmoltz free energy	-353.043	kJ/kg
Internal energy	2566.79	kJ/kg
Gibbs free energy	-163.694	kJ/kg
Heat capacity at constant volume	1.79777	kJ/(kg.°C)

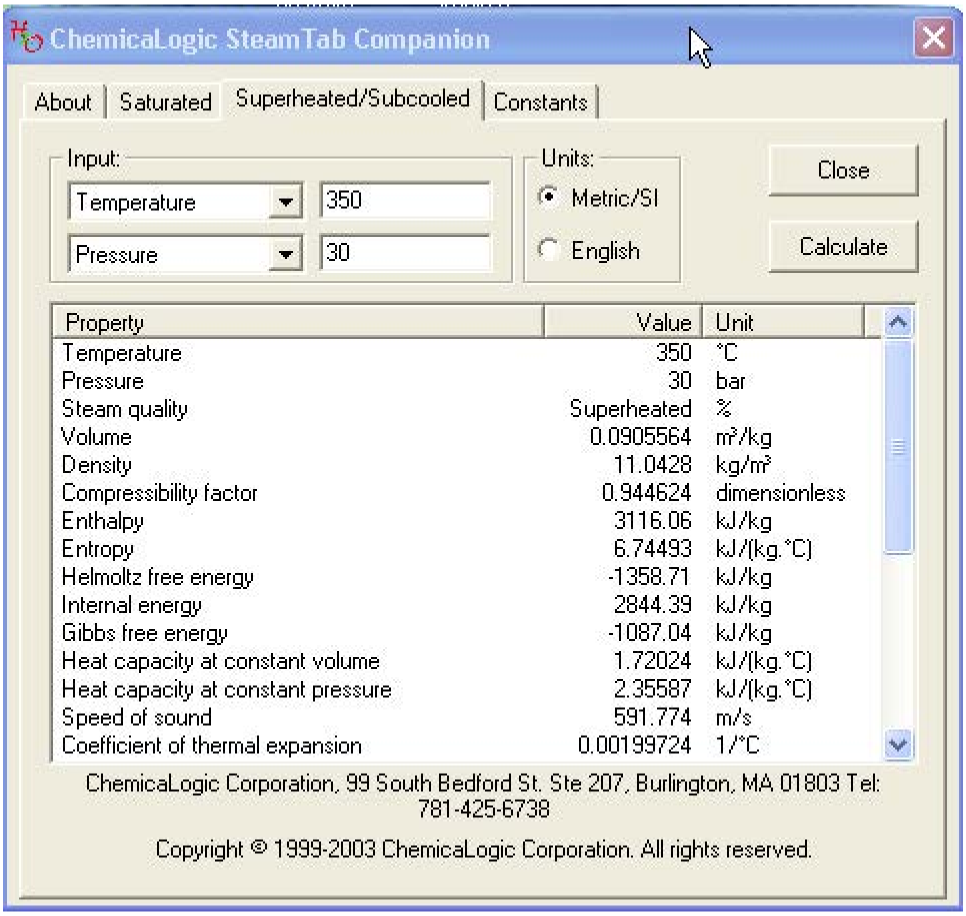
ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

Fig. 1.20 (b) Sat. Liq. properties of Steam at P = 6 bar

Note that there are several other properties which can be read by scrolling down the scroll bar.

Another example to find the Superheated/Subcooled properties of Steam: Consider the earlier example of Steam at 30 bar and 350 C: Click on the 'Superheated/Subcooled' tab; now, two intrinsic properties must be input – so, we enter values of P and T and click on 'Calculate'. Following screen appears giving the results:



Input:
Temperature 350
Pressure 30

Units:
● Metric/SI
○ English

Property	Value	Unit
Temperature	350	°C
Pressure	30	bar
Steam quality	Superheated	%
Volume	0.0905564	m³/kg
Density	11.0428	kg/m³
Compressibility factor	0.944624	dimensionless
Enthalpy	3116.06	kJ/kg
Entropy	6.74493	kJ/(kg.°C)
Helmoltz free energy	-1358.71	kJ/kg
Internal energy	2844.39	kJ/kg
Gibbs free energy	-1087.04	kJ/kg
Heat capacity at constant volume	1.72024	kJ/(kg.°C)
Heat capacity at constant pressure	2.35587	kJ/(kg.°C)
Speed of sound	591.774	m/s
Coefficient of thermal expansion	0.00199724	1/°C

ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

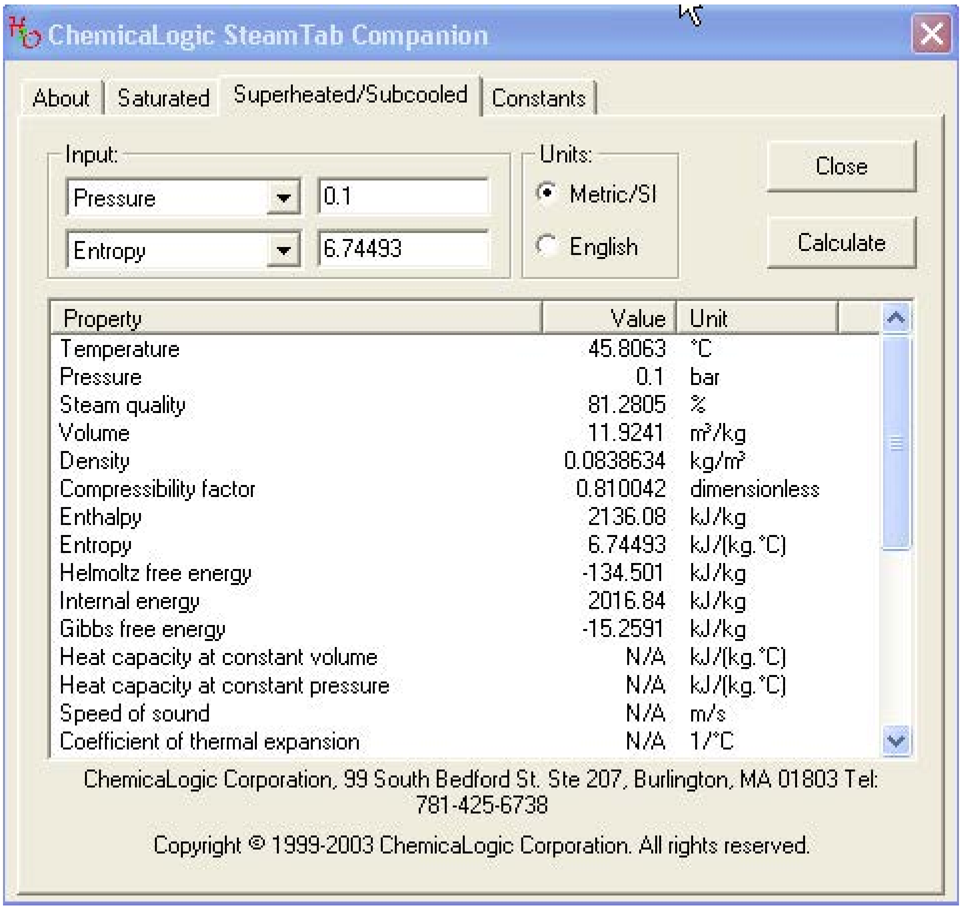
Fig. 1.21 Superheated/Subcooled. properties of Steam at P = 6 bar

Note that at 30 bar, 350 C, enthalpy (h1) = 3116.06 kJ/kg, and entropy (s1) = 6.74493 kJ/kg-C.

Again, more properties are available in this screen if you roll down the scroll bar.

A great advantage is that in 'Superheated/Subcooled' mode, combination of any two of the following properties can be used: Pressure, Volume, Temperature, Enthalpy, Entropy, Internal energy.

Now, if isentropic expansion occurs in a turbine to a pressure of 10 kPa, what is the exit enthalpy and the isentropic work of the turbine? To solve this, input P = 0.1 bar and s2 = s1 = 6.74493 kJ/kg-C. Results are in the following screen shot:



Input:
Pressure: 0.1
Entropy: 6.74493

Units:
● Metric/SI
○ English

Property	Value	Unit
Temperature	45.8063	°C
Pressure	0.1	bar
Steam quality	81.2805	%
Volume	11.9241	m³/kg
Density	0.0838634	kg/m³
Compressibility factor	0.810042	dimensionless
Enthalpy	2136.08	kJ/kg
Entropy	6.74493	kJ/(kg.°C)
Helmoltz free energy	-134.501	kJ/kg
Internal energy	2016.84	kJ/kg
Gibbs free energy	-15.2591	kJ/kg
Heat capacity at constant volume	N/A	kJ/(kg.°C)
Heat capacity at constant pressure	N/A	kJ/(kg.°C)
Speed of sound	N/A	m/s
Coefficient of thermal expansion	N/A	1/°C

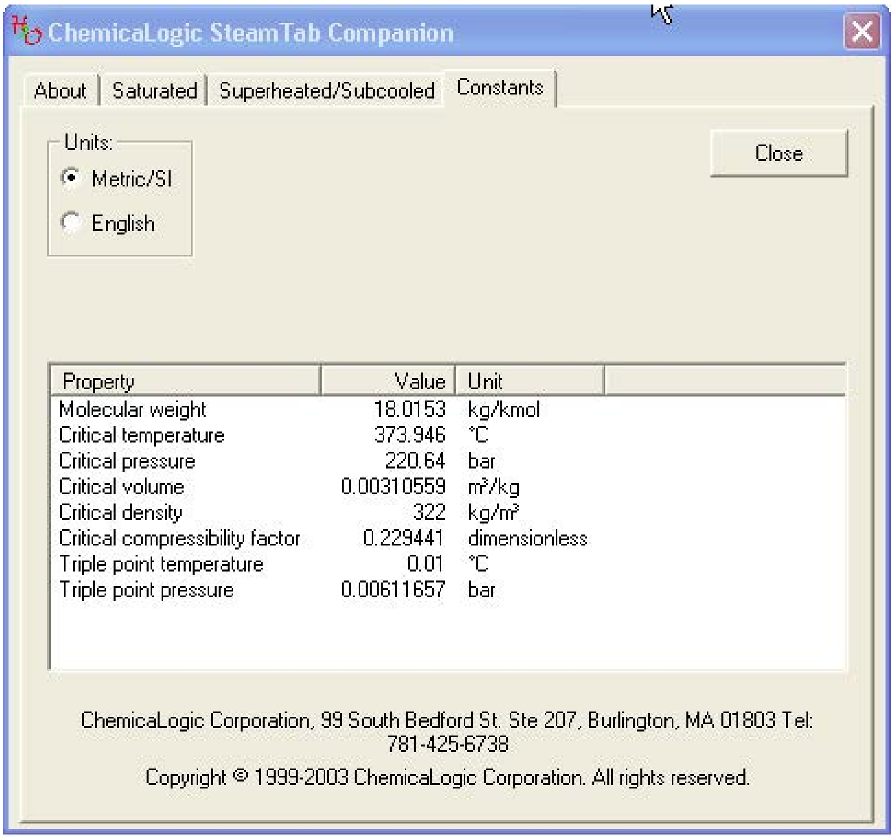
ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

Fig. 1.22 Superheated/Subcooled properties of Steam at P = 0.1 bar, s = 6.74493 kJ/kg-C

Read from the above fig: h2 = 2136.08 kJ/kg. Therefore, Isentropic work of turbine = (h1 – h2) = 979.98 kJ/kg. (Compare this with the value of W = 979.7 kJ/kg, obtained with EES). And, quality at exit of turbine, x2 = 81.2805%, whereas with EES, we got x2 = 81.24%.

Clicking on 'Constants' tab brings up the screen giving values of some constants pertaining to Steam/Water:



Units:
● Metric/SI
○ English

Property	Value	Unit
Molecular weight	18.0153	kg/kmol
Critical temperature	373.946	°C
Critical pressure	220.64	bar
Critical volume	0.00310559	m³/kg
Critical density	322	kg/m³
Critical compressibility factor	0.229441	dimensionless
Triple point temperature	0.01	°C
Triple point pressure	0.00611657	bar

ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

Fig. 1.23 Constants for Steam/Water

Two disadvantages of this software are:

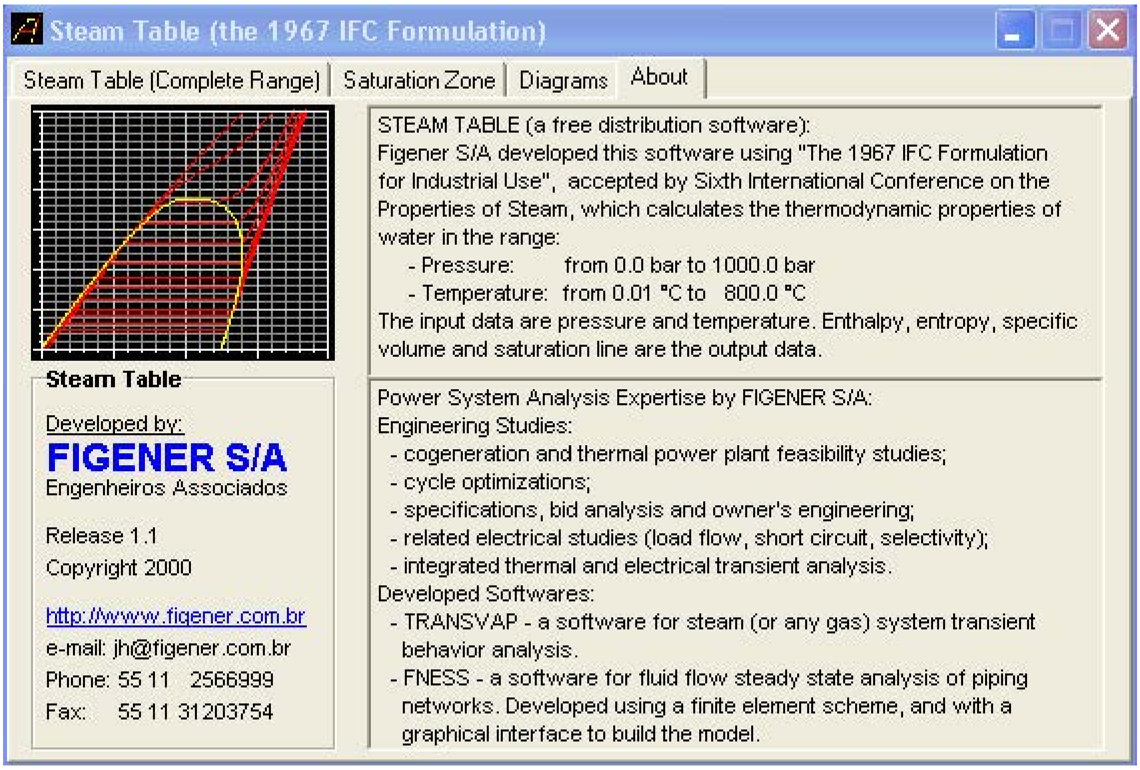
1) there is no 'copy and paste' facility, i.e. you can not copy and paste these values into another file, and
2) there is no 'log' facility, i.e. each time you make a new calculation, results of earlier calculations are lost since they are not stored in a log file.

Still, this software is quite useful since it permits input of any two properties to get a large number of remaining properties.

1.3.2 SteamTable from M/s Figener S/A:

This is also a very handy, little program to find out properties of Steam/Water. In addition, it gives (T-s), (T-h) and (h-s) or Mollier charts for steam, and the state point calculated is also plotted in those charts. Further, a log facility is also provided, so that you can see the record of calculations done by you in one sitting.

As you open the program, following screen appears:



Developed by:

FIGENER S/A

Engenheiros Associados

Release 1.1

Copyright 2000

http://www.figener.com.br

e-mail: jh@figener.com.br

Phone: 55 11 2566999

Fax: 55 11 31203754

STEAM TABLE (a free distribution software):
Figener S/A developed this software using "The 1967 IFC Formulation for Industrial Use", accepted by Sixth International Conference on the Properties of Steam, which calculates the thermodynamic properties of water in the range:

- Pressure: from 0.0 bar to 1000.0 bar
- Temperature: from 0.01 °C to 800.0 °C

The input data are pressure and temperature. Enthalpy, entropy, specific volume and saturation line are the output data.

Power System Analysis Expertise by FIGENER S/A:
Engineering Studies:

- cogeneration and thermal power plant feasibility studies;
- cycle optimizations;
- specifications, bid analysis and owner's engineering;
- related electrical studies (load flow, short circuit, selectivity);
- integrated thermal and electrical transient analysis.

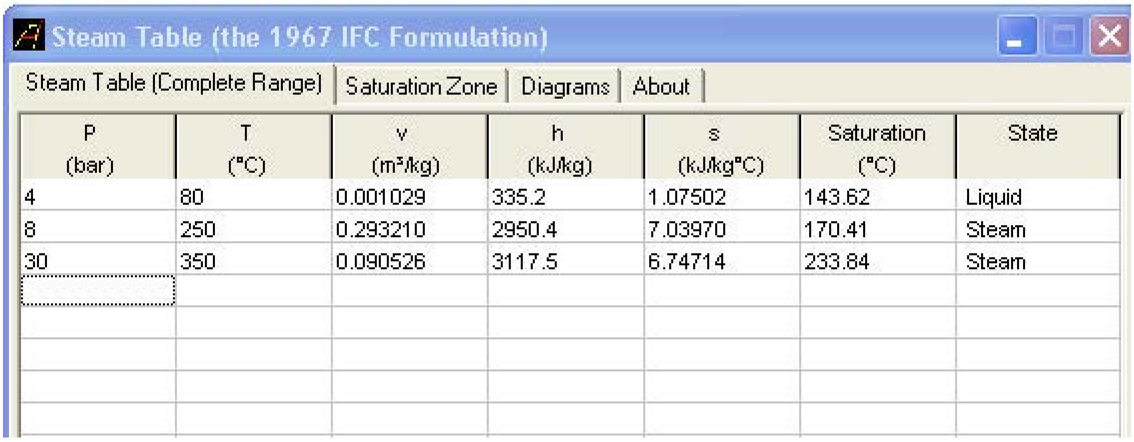
Developed Softwares:

- TRANSVAP - a software for steam (or any gas) system transient behavior analysis.
- FNESS - a software for fluid flow steady state analysis of piping networks. Developed using a finite element scheme, and with a graphical interface to build the model.

Fig. 1.24 SteamTable – opening screen

As can be seen, four tabs: 'About' (i.e. above screen), 'Steam table (complete range)', 'Saturation zone' and 'Diagrams'.

When you click on 'Steam table (complete range)', a table appears, wherein you have to enter both P and T values. Note that there is no other choice of properties available; this is a *draw back* of this software. However, a log facility is available i.e. in the same table, in the next lines, you can get results for other states. See the example in the following screen shot:



P (bar)	T (°C)	v (m³/kg)	h (kJ/kg)	s (kJ/kg°C)	Saturation (°C)	State
4	80	0.001029	335.2	1.07502	143.62	Liquid
8	250	0.293210	2950.4	7.03970	170.41	Steam
30	350	0.090526	3117.5	6.74714	233.84	Steam

Fig. 1.25 SteamTable – Properties at different P and T

If you immediately click the 'Diagrams' tab, and select any of the three diagrams (i.e. T-s, T-h or h-s diagrams), these state points will be shown plotted in that diagram. For example, the T-s diagram is shown below and note that all these 3 points are marked there:

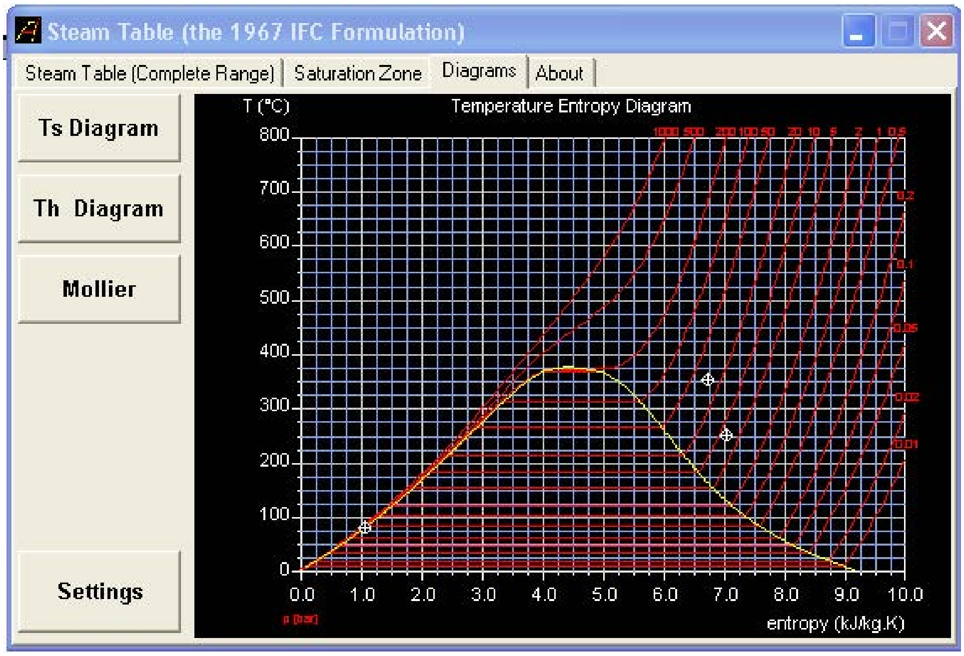
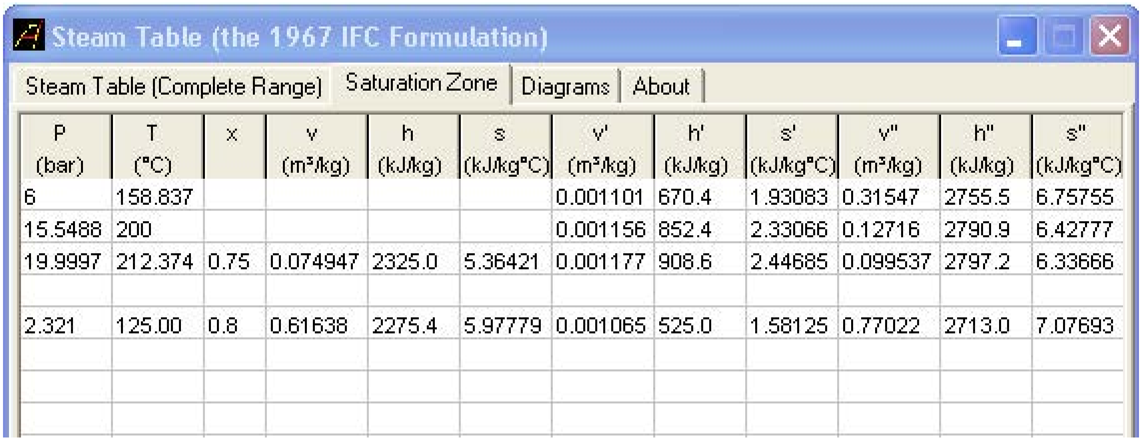


Fig. 1.26 SteamTable – state points on T-s diagram

Scale in the diagrams can be changed by clicking on the 'Settings' button and making necessary changes.

When you click on 'Saturation zone' tab, saturation properties can be calculated. Of course, you have to input either P or T. Also, if you need the properties at some point within the two phase region (i.e. Sat. zone), you can input quality x first, and, then enter either P or T. Following screen shows some results: First, for P = 6 bar, next, for T = 200 C, next for x = 0.75, P= 20 bar, and, then for x = 0.8 and T = 125 C.



P (bar)	T (°C)	x	v (m³/kg)	h (kJ/kg)	s (kJ/kg°C)	v' (m³/kg)	h' (kJ/kg)	s' (kJ/kg°C)	v" (m³/kg)	h" (kJ/kg)	s" (kJ/kg°C)
6	158.837					0.001101	670.4	1.93083	0.31547	2755.5	6.75755
15.5488	200					0.001156	852.4	2.33066	0.12716	2790.9	6.42777
19.9997	212.374	0.75	0.074947	2325.0	5.36421	0.001177	908.6	2.44685	0.099537	2797.2	6.33666
2.321	125.00	0.8	0.61638	2275.4	5.97779	0.001065	525.0	1.58125	0.77022	2713.0	7.07693

Fig. 1.27 SteamTable – properties in Sat. zone

Now, click on 'Diagrams' tab and choose Mollier diagram. The state points are shown in the Mollier diagram below:

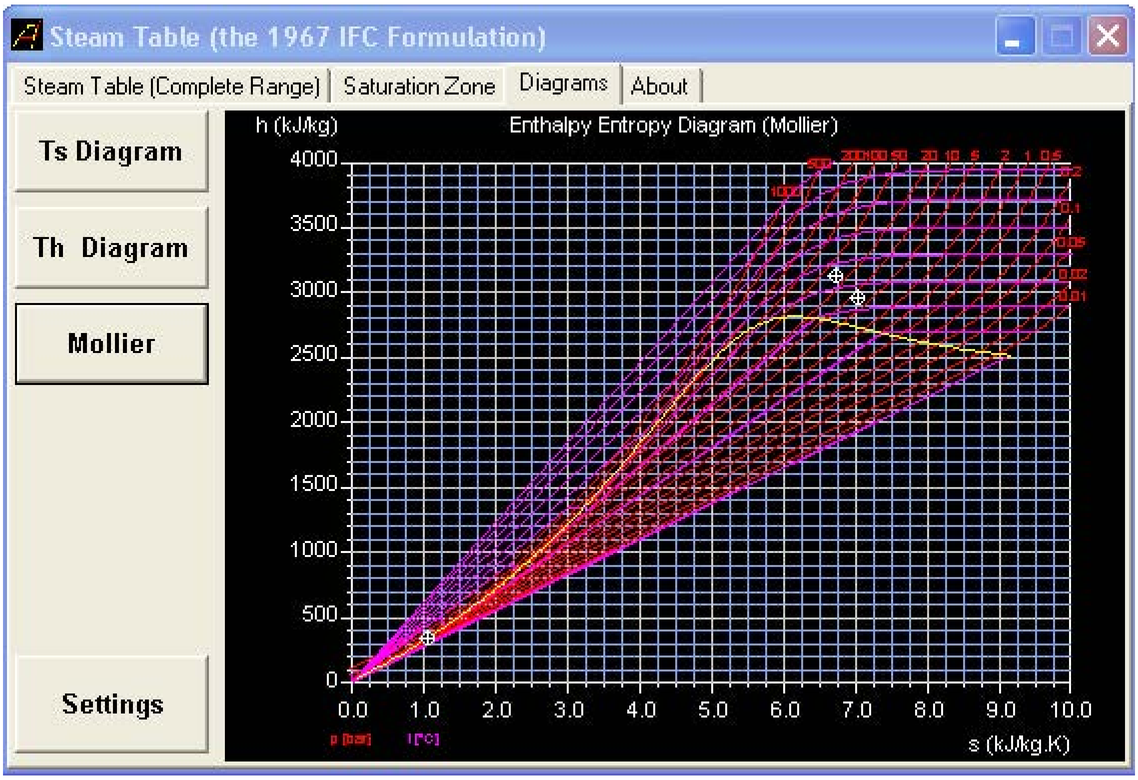


Fig. 1.28 SteamTable – State points in Mollier diagram

Thus, SteamTable is also a useful program. Choice of the three diagrams and log facility are its added advantages.

1.3.3 Humidity Calculator from M/s Vaisala, Finland:

This is a very versatile and extremely useful software for psychrometric calculations. It is very easy to use. A great *advantage* is that the results obtained can be printed to a printer or stored in a file for future reference. There is also a very good 'Help' file which gives relevant technical information on psychrometrics.

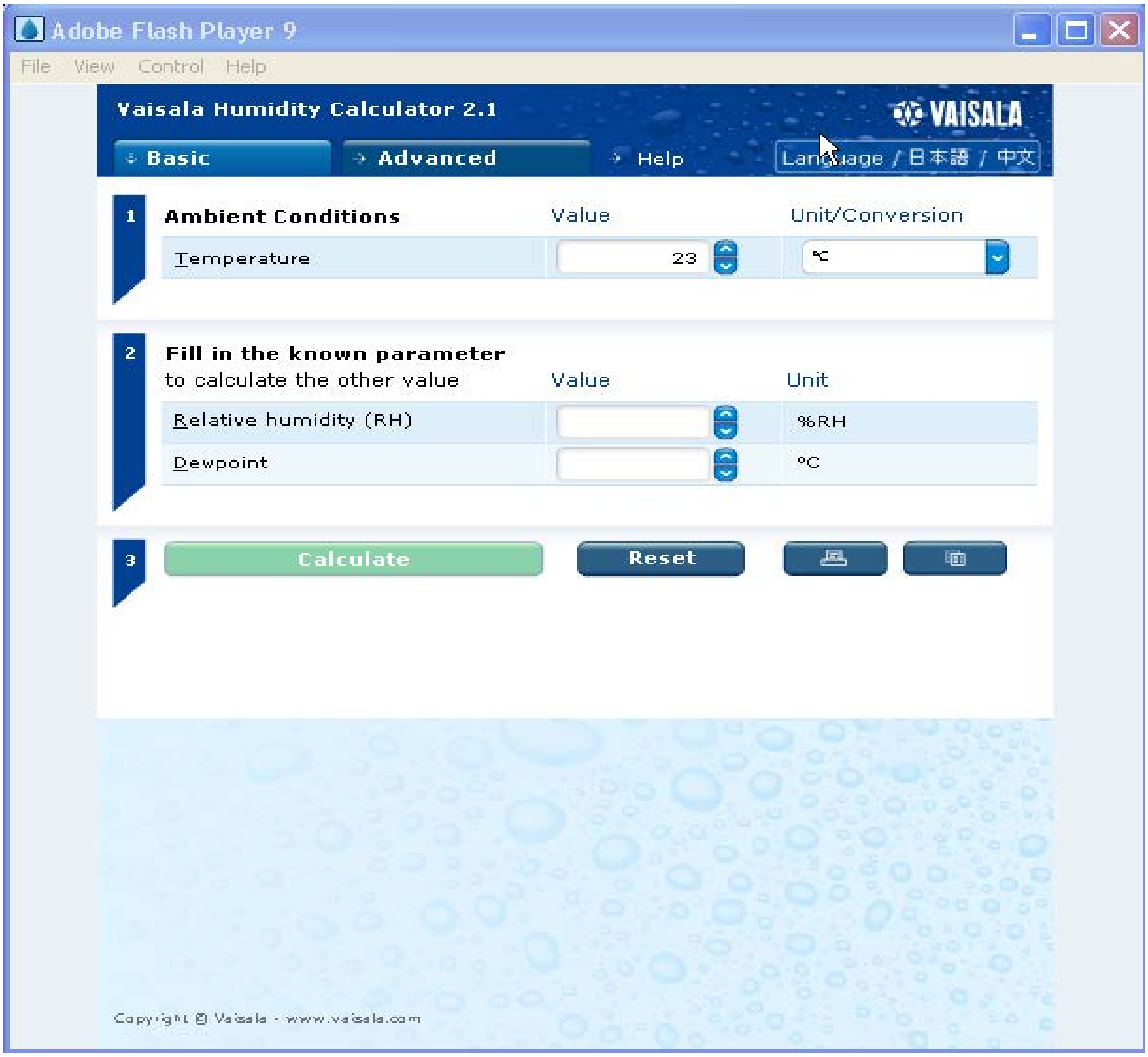
Following is the extract from the details supplied in the 'help' file:

"Vaisala Humidity calculator is a software tool that provides an easy way for solving humidity conversions from one humidity parameter to another. It can also be used to calculate the effect of changing ambient conditions. Vaisala Humidity Calculator includes both a basic version and an advanced version which are shown on the user interface as separate sheets. **The basic version** provides calculations between relative humidity and dew point when one of these parameters and temperature are known. Note that below the freezing point of water (0°C/32°F), *frost point* values are provided by convention, although the word *dew point* is commonly used to express both dew point and frost point. **The advanced version** of Vaisala Humidity Calculator includes calculation of:

- relative humidity
- dewpoint / frostpoint
- parts per million.
- absolute humidity
- mixing ratio
- water content
- vapor pressure
- wet bulb temperature

In the advanced version the user can also choose to output dew point (equilibrium over super-cooled water instead of ice) for values below the freezing point of water (0°C/32°F). For gas dependent humidity parameters (e.g., ppm by weight and mixing ratio) a wide selection of carrier gases is available in addition to air (natural gas, CO_2, SF_6, Ar, O_2, N_2, H_2). The user can specify additional carrier gases but must provide the molecular weight of the gas. Wet bulb calculation can be performed based on standard or WMO coefficients, as well as custom values given by the user".

When you start the Humidity Calculator, following screen appears:

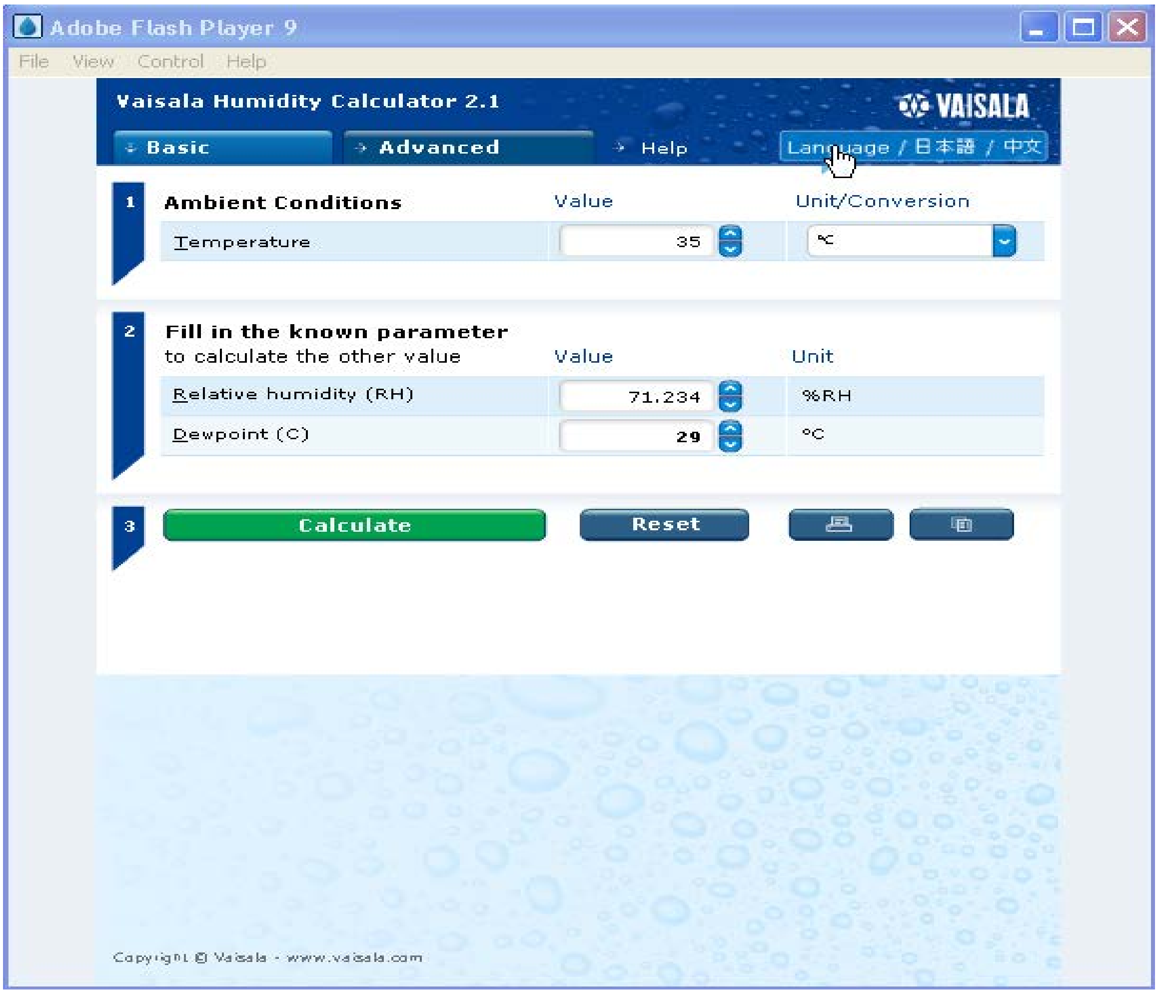


Temperature: 23 °C

Fig. 1.29 Vaisala Humidity Calculator – opening screen (Basic version)

This is the basic version. You can input temperatures in deg. C, deg. F or K.

As an example, let us find out the Relative Humidity (RH) at a dry bulb temperature of 35 C and dew point temperature of 29 C. Fill up these values and click on 'Calculate' button. Read RH = 71.234% as shown below:



1 Ambient Conditions

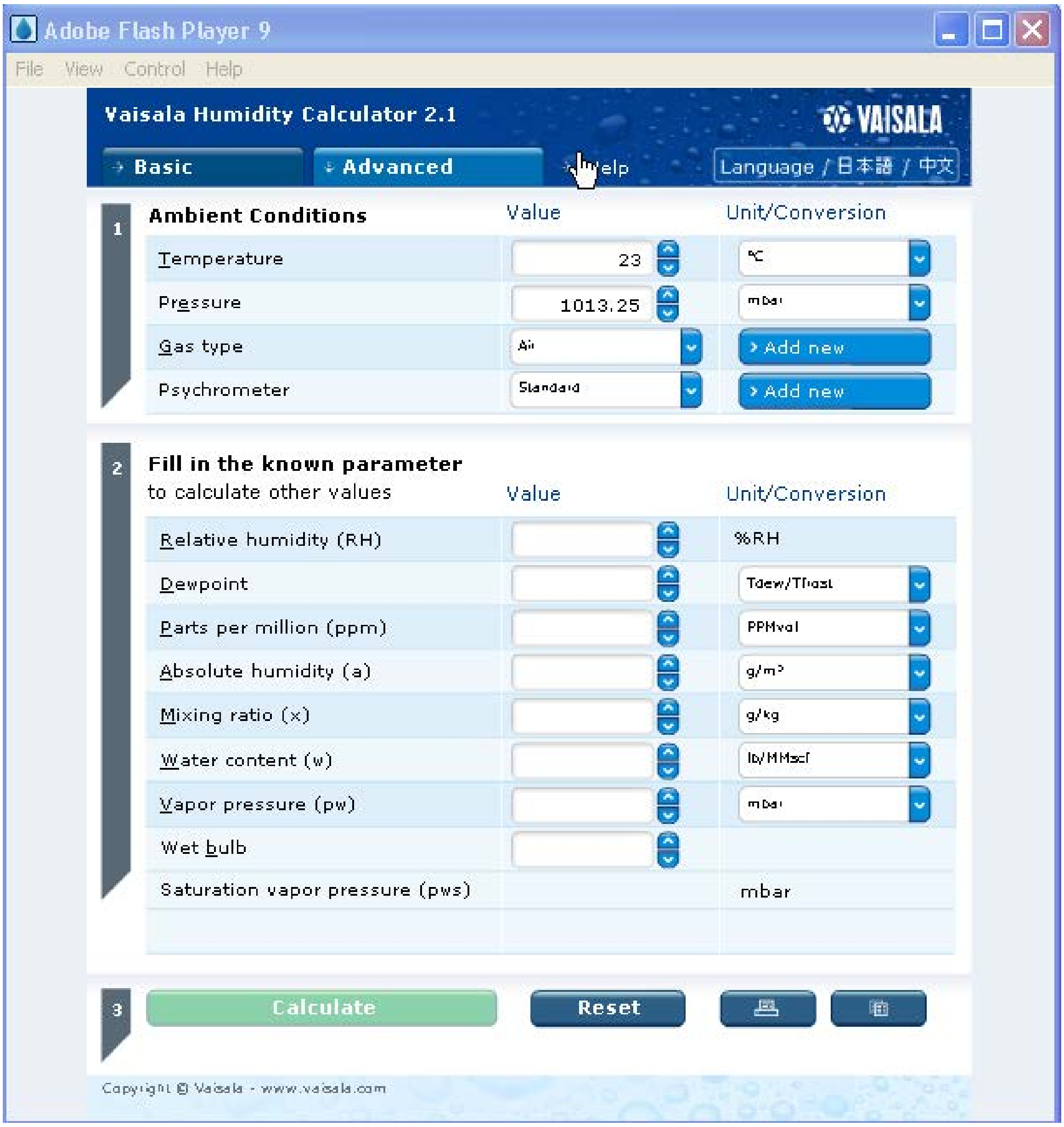
	Value	Unit/Conversion
Temperature	35	°C

2 Fill in the known parameter to calculate the other value

	Value	Unit
Relative humidity (RH)	71.234	%RH
Dewpoint (C)	29	°C

Fig. 1.30 Vaisala Humidity Calculator – typical calculation in Basic Version

To use 'Advanced' version, click on that tab, and following screen appears:

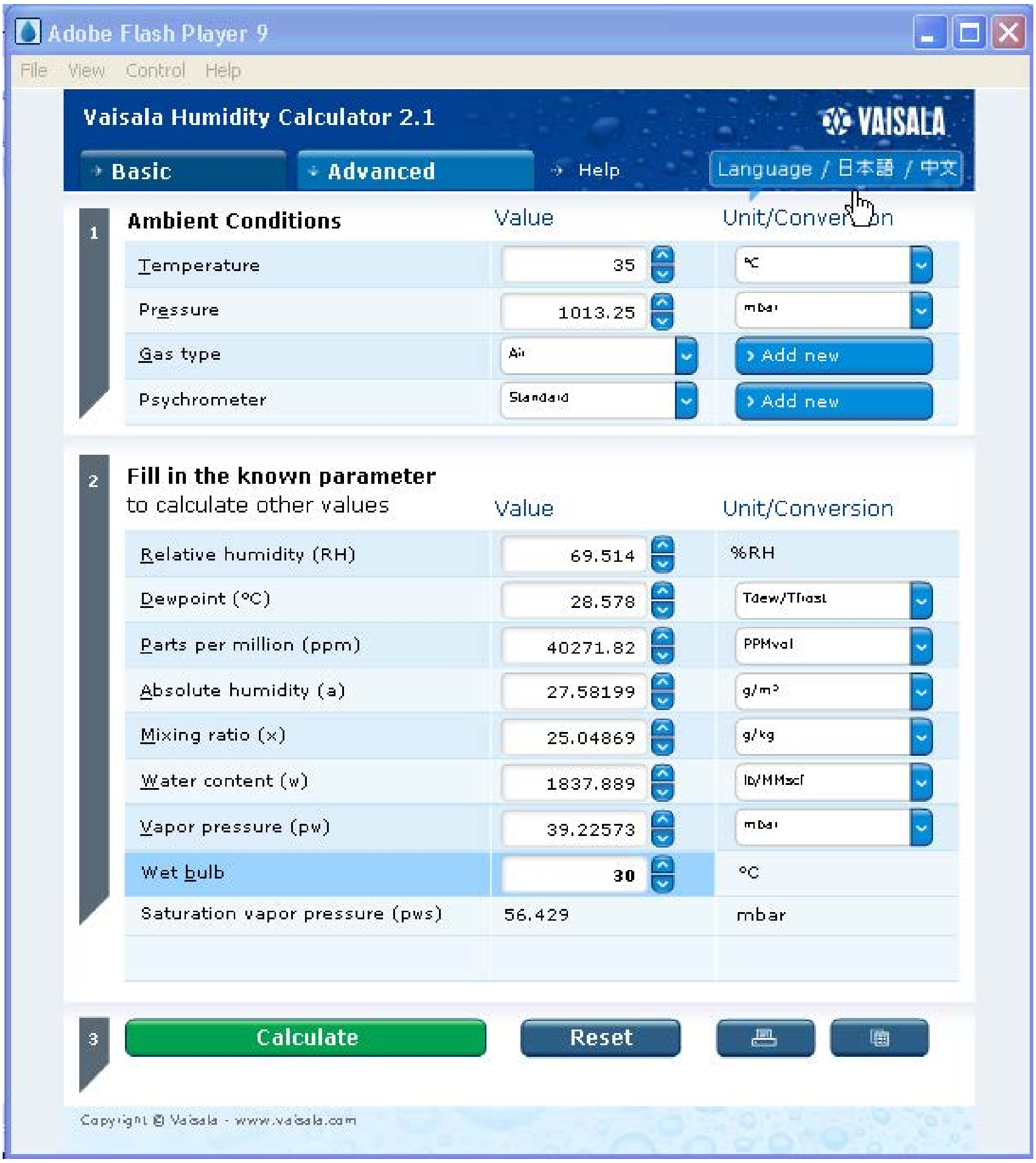


Ambient Conditions	Value	Unit/Conversion
Temperature	23	°C
Pressure	1013.25	mbar
Gas type	Air	Add new
Psychrometer	Standard	Add new

Fill in the known parameter to calculate other values	Value	Unit/Conversion
Relative humidity (RH)		%RH
Dewpoint		Tdew/Tfrost
Parts per million (ppm)		PPMvol
Absolute humidity (a)		g/m³
Mixing ratio (x)		g/kg
Water content (w)		lb/MMscf
Vapor pressure (pw)		mbar
Wet bulb		
Saturation vapor pressure (pws)		mbar

Fig. 1.31 Vaisala Humidity Calculator – Advanced version

Let us again calculate the properties for DBT = 35 C and Wet Bulb Temp (WBT) = 30 C. Enter these values and click on 'Calculate' tab. Following are the results:



Ambient Conditions

	Value	Unit/Conversion
Temperature	35	°C
Pressure	1013.25	mbar
Gas type	Air	
Psychrometer	Standard	

Fill in the known parameter
to calculate other values

	Value	Unit/Conversion
Relative humidity (RH)	69.514	%RH
Dewpoint (°C)	28.578	Tdew/Tfrost
Parts per million (ppm)	40271.82	PPMvol
Absolute humidity (a)	27.58199	g/m³
Mixing ratio (x)	25.04869	g/kg
Water content (w)	1837.889	lb/MMscf
Vapor pressure (pw)	39.22573	mbar
Wet bulb	30	°C
Saturation vapor pressure (pws)	56.429	mbar

Fig. 1.32 Vaisala Humidity Calculator – typical calculation in Advanced version

Note that you can make calculations for different Pressures. All the entered and calculated properties can be expressed in different units; choose the desired units by clicking the 'down arrows' in the widgets under 'Unit/Conversion'.

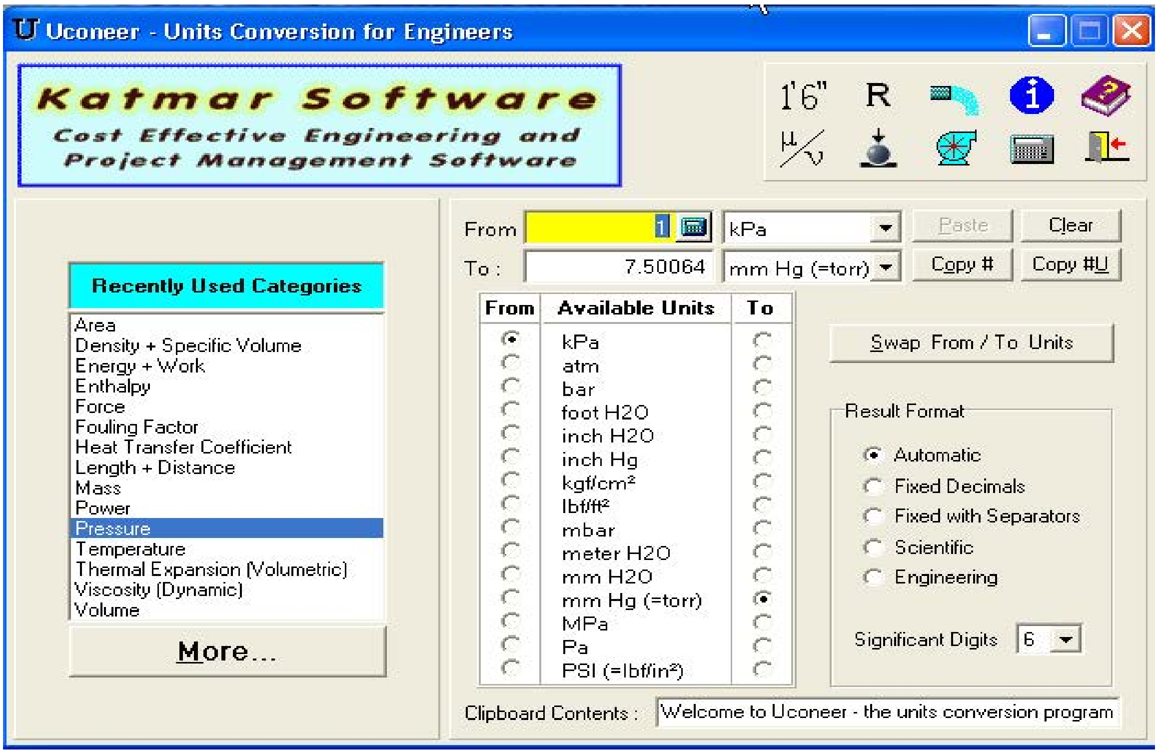
'Reset' button will reset the values, so that you are ready for next calculation. Next to 'Reset' button is the Print button using which you can print the results; and next to Print button is the Copy button. Click on Copy button and then paste the results to MS Word and save as shown below:

Ambient Conditions	Value	Unit/Conversion
Temperature	35	°C
Pressure	1013.25	mbar
Gas type	Air	
Psychrometer	Standard	
Relative humidity (RH)	69.514	%RH
Dewpoint (°C)	28.578	Tdew/Tfrost
Parts per million (ppm)	40271.82	PPMvol
Absolute humidity (a)	27.58199	g/m^3
Mixing ratio (x)	25.04869	g/kg
Water content (w)	1837.889	lb/MMscf
Vapor pressure (pw)	39.22573	mbar
Wet bulb	30	°C
Saturation vapor pressure (pws)	56.429	mbar

1.3.4 Free Unit conversion program – 'Uconeer' from Katmar Software:

This is a very popular unit conversion program – created specifically for engineers. Uconeer has over 397 units arranged in 46 categories. Uconeer is claimed to be 'the easiest to use conversion program available', while still retaining all the units engineers actually use.

When you start the program, you get the following screen:



From 1 kPa

To : 7.50064 mm Hg (=torr)

Recently Used Categories: Pressure

From ● kPa; To ● mm Hg (=torr)

Result Format: ● Automatic

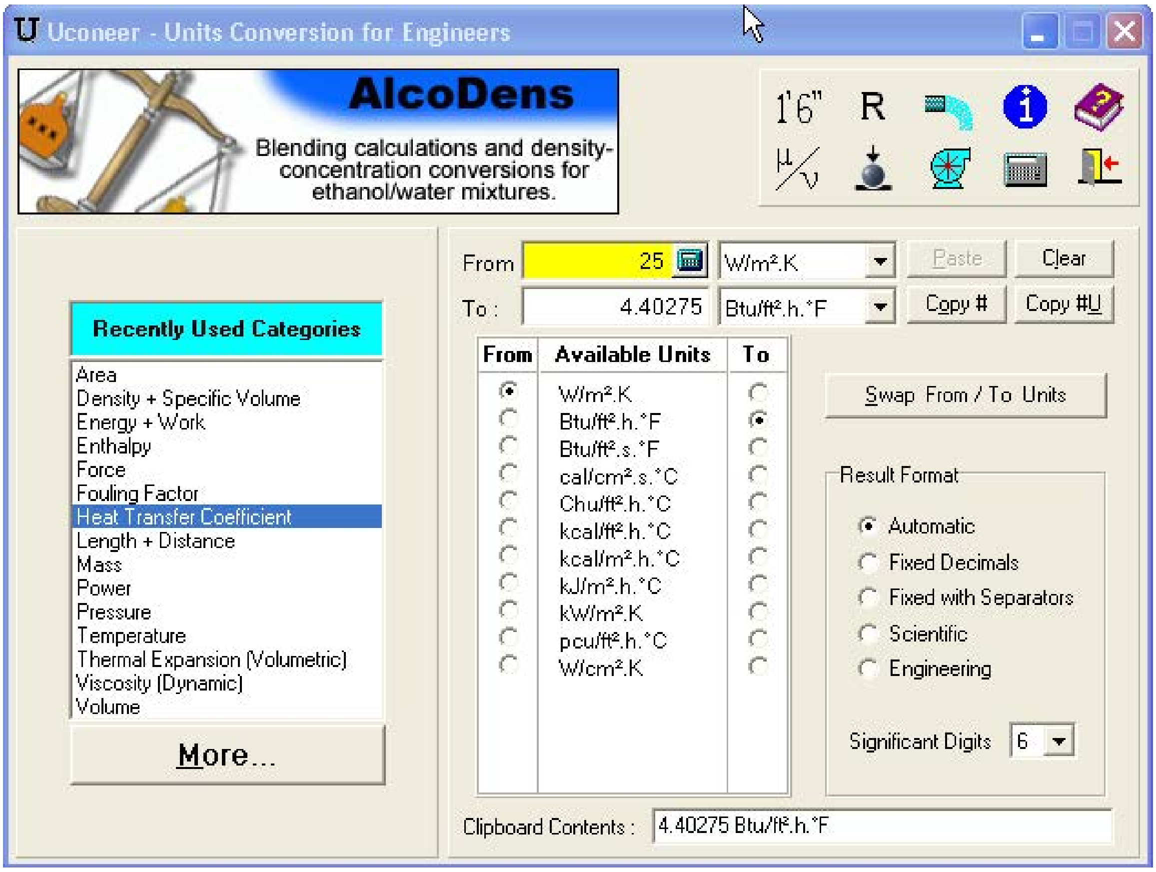
Significant Digits 6

Clipboard Contents : Welcome to Uconeer - the units conversion program

Fig. 1.33 Uconeer – Units conversion program

Select the category and the 'From' and 'To' radio buttons; enter the numerical value of units to be converted, and the result appears immediately.

As an example, consider converting heat transfer coefficient: say, from 25 W/m2-K to BTU/ft2-h-F. Select the category 'heat transfer coeff.' and select 'From' and 'To' buttons as required. Enter 25 in front of 'From' and immediately the answer appears against 'To' as 4.40275 Btu/ft^2.h.°F. The screen shot is shown below:



Uconeer - Units Conversion for Engineers

AlcoDens
Blending calculations and density-concentration conversions for ethanol/water mixtures.

From: 25 W/m^2.K
To: 4.40275 Btu/ft^2.h.°F

Recently Used Categories
- Area
- Density + Specific Volume
- Energy + Work
- Enthalpy
- Force
- Fouling Factor
- Heat Transfer Coefficient
- Length + Distance
- Mass
- Power
- Pressure
- Temperature
- Thermal Expansion (Volumetric)
- Viscosity (Dynamic)
- Volume

From	Available Units	To
●	W/m^2.K	○
○	Btu/ft^2.h.°F	●
○	Btu/ft^2.s.°F	○
○	cal/cm^2.s.°C	○
○	Chu/ft^2.h.°C	○
○	kcal/ft^2.h.°C	○
○	kcal/m^2.h.°C	○
○	kJ/m^2.h.°C	○
○	kW/m^2.K	○
○	pcu/ft^2.h.°C	○
○	W/cm^2.K	○

Result Format
- ● Automatic
- ○ Fixed Decimals
- ○ Fixed with Separators
- ○ Scientific
- ○ Engineering

Significant Digits: 6

Clipboard Contents: 4.40275 Btu/ft^2.h.°F

Fig. 1.34 Uconeer – Units conversion for heat transfer coefficient

There is also facility to copy to clip board and choose the result formats and significant digits. There is a very good 'Help' file, Gas and Liquid Volume/Mass Flow converters, Gas constant converter and Hardness converter. However, there is one 'disadvantage', which does not affect the results anyway: regular popping up of advertisements regarding the products or services provided by the company, as shown in the above screen shot.

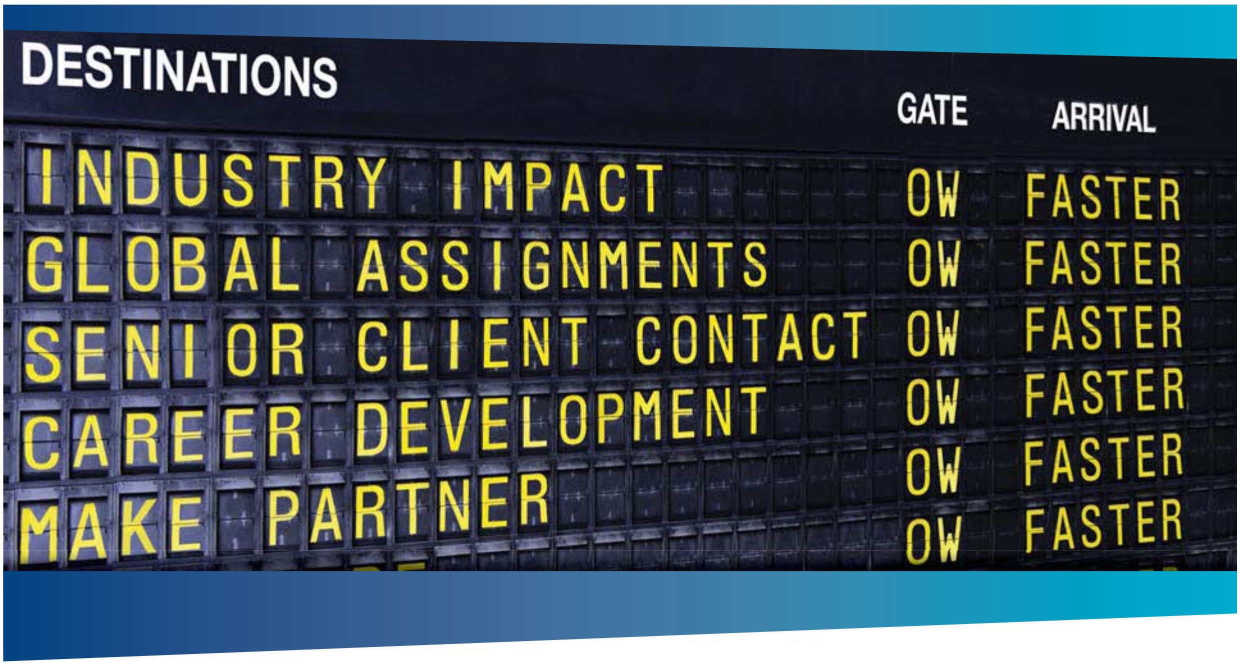
1.4 Summary:

In this chapter, a brief overview was given about three very useful commercial, technical software, viz. Mathcad, EES and TEST, particularly useful to solve problems in Thermodynamics. This chapter is not intended as a tutorial on these software. However, since some examples have been worked out, it is expected that the reader will get sufficient working knowledge on use of these software. As we proceed, more problems will be worked out; all the examples will be thoroughly commented, and the reader should not have any difficulty in understanding the solutions, even if he does not use these software.

In addition, four 'free' software are described, with worked examples. Out of these, two programs are for finding out properties of Steam/Water and one program for psychrometric calculations, and another program for Units conversion.

1.5 References:

1. Y.A.Cengel and M.A.Boles. Thermodynamics – An Engineering Approach. 4th ed. New Delhi: Tata McGraw-Hill, 2003
2. http://physics.nist.gov/cuu/Units/index.html
3. www.ptc.com
4. www.fchart.com
5. www.thermofluids.net
6. www.chemicalogic.com
7. www.figener.com.br
8. www.vaisala.com
9. www.katmarsoftware.com



2 SI Units, Unit Conversion, Pressure, Temperature etc.

Learning objectives:

1. In this chapter, we first describe the **International System of Units** (i.e. SI Units). Authentic information from National Institute of Standards and Technology (NIST), USA, formerly (National Bureau of Standards – NBS – USA) is compiled.
2. **Unit conversion** examples are demonstrated with Uconeer and the Unit converter of TEST software.
3. Then, we discuss about the **pressure measurement with manometers** and work out some examples using Mathcad as well as EES. One example on 'curve fitting' with EES is also explained.
4. **Temperature measurement with Thermocouples** is explained next. Details regarding different types of thermocouples are given. Problems are worked out using both Mathcad and EES.
5. Next, **constant volume gas thermometer** is described and a problem is worked out using EES.
6. Finally, **RTD's and Pt resistance thermometer** are explained; a versatile, free software viz. PRTCalc to make calculations in connection with Pt-100 is introduced and a problem is worked out in Mathcad and verified with PRTCalc.
7. Finally, Temperature vs Resistance characteristics for Pt-100 thermometer are drawn in Mathcad.

2.1 Introduction:

In this chapter, we shall, first describe International System of Units (SI), its proper usage, Unit conversion from one system of units to another and, then work out problems on measurement of pressure with manometers, and measurement of temperature with thermocouples.

2.2 International System of Units (SI):

SI Units are now almost universally adopted in scientific work. National Institute of Standards and Technology (NIST), USA, formerly (National Bureau of Standards – NBS – USA) has brought out authoritative information on SI Units and guide lines for the correct usage of SI Units. An extract of that information is given below:

There are seven **base units** in SI:

Table 2.1. SI base units

	SI base unit	
Base quantity	**Name**	**Symbol**
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Next, **derived units** are defined in terms of these base units:

Table 2.2. Examples of SI derived units

	SI derived unit	
Derived quantity	**Name**	**Symbol**
area	square meter	m^2
volume	cubic meter	m^3
speed, velocity	meter per second	m/s
acceleration	meter per second squared	m/s^2
wave number	reciprocal meter	m^{-1}
mass density	kilogram per cubic meter	kg/m^3
specific volume	cubic meter per kilogram	m^3/kg
current density	ampere per square meter	A/m^2
magnetic field strength	ampere per meter	A/m
amount-of-substance concentration	mole per cubic meter	mol/m^3
luminance	candela per square meter	cd/m^2
mass fraction	kilogram per kilogram, which may be represented by the number 1	kg/kg = 1

22 *SI derived units* have been given special names and symbols, as shown in Table 2.3:

Table 2.3. SI derived units with special names and symbols

	SI derived unit			
Derived quantity	**Name**	**Symbol**	**Expression in terms of other SI units**	**Expression in terms of SI base units**
plane angle	radian (a)	rad	-	$m \cdot m^{-1} = 1$ (b)
solid angle	steradian (a)	sr (c)	-	$m^{2} \cdot m^{-2} = 1$ (b)
frequency	hertz	Hz	-	s^{-1}
force	newton	N	-	$m \cdot kg \cdot s^{-2}$
pressure, stress	pascal	Pa	N/m^{2}	$m^{-1} \cdot kg \cdot s^{-2}$
energy, work, quantity of heat	joule	J	N·m	$m^{2} \cdot kg \cdot s^{-2}$
power, radiant flux	watt	W	J/s	$m^{2} \cdot kg \cdot s^{-3}$
electric charge, quantity of electricity	coulomb	C	-	s·A
electric potential difference, electromotive force	volt	V	W/A	$m^{2} \cdot kg \cdot s^{-3} \cdot A^{-1}$
capacitance	farad	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^{4} \cdot A^{2}$
electric resistance	ohm	Ω	V/A	$m^{2} \cdot kg \cdot s^{-3} \cdot A^{-2}$
electric conductance	siemens	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^{3} \cdot A^{2}$
magnetic flux	weber	Wb	V·s	$m^{2} \cdot kg \cdot s^{-2} \cdot A^{-1}$
magnetic flux density	tesla	T	Wb/m^{2}	$kg \cdot s^{-2} \cdot A^{-1}$

inductance	henry	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
Celsius temperature	degree Celsius	°C	-	K
luminous flux	lumen	lm	cd·sr (c)	$m^2 \cdot m^{-2} \cdot cd = cd$
illuminance	lux	lx	lm/m^2	$m^2 \cdot m^{-4} \cdot cd = m^{-2} \cdot cd$
activity (of a radionuclide)	becquerel	Bq	-	s^{-1}
absorbed dose, specific energy (imparted), kerma	gray	Gy	J/kg	$m^2 \cdot s^{-2}$
dose equivalent (d)	sievert	Sv	J/kg	$m^2 \cdot s^{-2}$
catalytic activity	katal	kat		$s^{-1} \cdot mol$

(a) The radian and steradian may be used advantageously in expressions for derived units to distinguish between quantities of a different nature but of the same dimension; some examples are given in Table 4.
(b) In practice, the symbols rad and sr are used where appropriate, but the derived unit "1" is generally omitted.
(c) In photometry, the unit name steradian and the unit symbol sr are usually retained in expressions for derived units.
(d) Other quantities expressed in sieverts are ambient dose equivalent, directional dose equivalent, personal dose equivalent, and organ equivalent dose.

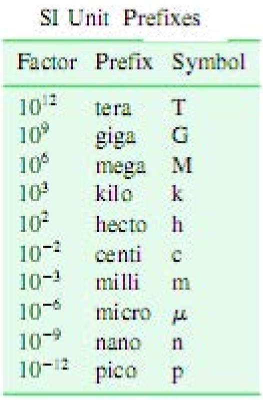
The special names and symbols of the 22 SI derived units with special names and symbols given in Table 2.3 may themselves be included in the names and symbols of *other SI derived units*, as shown in Table 2.4:

Table 2.4. Examples of SI derived units whose names and symbols include SI derived units with special names and symbols

	SI derived unit	
Derived quantity	**Name**	**Symbol**
dynamic viscosity	pascal second	Pa·s
moment of force	newton meter	N·m
surface tension	newton per meter	N/m
angular velocity	radian per second	rad/s
angular acceleration	radian per second squared	rad/s^2
heat flux density, irradiance	watt per square meter	W/m^2
heat capacity, entropy	joule per kelvin	J/K
specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg·K)
specific energy	joule per kilogram	J/kg
thermal conductivity	watt per meter kelvin	W/(m·K)
energy density	joule per cubic meter	J/m^3
electric field strength	volt per meter	V/m
electric charge density	coulomb per cubic meter	C/m^3
electric flux density	coulomb per square meter	C/m^2
permittivity	farad per meter	F/m
permeability	henry per meter	H/m

molar energy	joule per mole	J/mol
molar entropy, molar heat capacity	joule per mole kelvin	J/(mol·K)
exposure (x and γ rays)	coulomb per kilogram	C/kg
absorbed dose rate	gray per second	Gy/s
radiant intensity	watt per steradian	W/sr
radiance	watt per square meter steradian	$W/(m^2 \cdot sr)$
catalytic (activity) concentration	katal per cubic meter	kat/m^3

Prefixes of SI Units are shown below:



SI Unit Prefixes

Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

Correct usage of SI Units:

US Metric Association (USMA) has given guide lines about *correct use of SI Units*:

Important in SI-metric:

1. The short forms for SI units (such as mm for millimeter) are called **symbols**, *not* abbreviations.
2. SI symbols *never end with a period* unless they are the last word in a sentence.
   - **RIGHT:** 20 mm, 10 kg
   - **WRONG:** 20 mm, 10 kg.

3. SI symbols should be preceded by digits and *a space must separate the digits from the symbol.*
    - **RIGHT:** It was 300 mm wide. The millimeter width was given.
    - **WRONG:** It was 300mm wide. The mm width was given.

4. Symbols *always are written in the singular form* (even when more than one is meant).
    - **RIGHT:** 1 mm, 500 mm, 1 kg, 36 kg
    - **WRONG:** 500 mms, 36 kgs
    - **BUT:** It is correct to pluralize written-out metric unit names: 25 kilograms, 250 milliliters

5. The symbol for a compound unit that is *a quotient of two units is indicated by a solidus* or by a negative exponent.
    - **RIGHT:** km/h or km·h^{-1} (for kilometers per hour)
    - **WRONG:** kmph or kph (do *not* use p as a symbol for "per".)
    - **BUT:** It is correct to say or write "kilometers per hour".

6. The meaning of an SI symbol can be changed if you substitute a capital letter for a lower case letter.
    - **RIGHT:** mm (for millimeter, which means 1/1000 of a meter)
    - **WRONG:** MM or Mm (M is the prefix for mega, which means one million; a megameter is a million meters)

Correct Usage	Examples of Incorrect Usage	For
km	Km, km., KM, kms, K, k	kilometer
m	M, m.	meter
mm	Mm, mm., MM	millimeter
L or l	L., l.	liter
mL or ml	ML, Ml, mL., ml., mls	milliliter
kg	KG, KG., Kg, Kg., kgr, kgs, kilo	kilogram
g	G, G., g., gr, gm, GR, GM, GRM, grms	gram
µg	mcg	microgram
h	hr, hrs, HR, h., HR., HRS.	hour
s	sec, S, SEC, sec., s., S.	second
cm^3	cc	cubic centimeter
km/h	KPH, kph, kmph, km/hr	kilometer per hour
kHz	KHz, KHZ, Khz	kilohertz
MHz	MHZ, Mhz	megahertz
hPa	HPa, HPA, Hpa, mb	hectopascal
kPa	KPa, KPA, Kpa	kilopascal
°C	C, deg C, ° C	degree Celsius
K	°K, deg K	kelvin

Table 2.5 Examples of incorrect SI-metric usage:

There is a more detailed *'SI Units rules and style conventions'* (Check list for reviewing manuscripts) published by NIST, USA.

2.3 Conversion of Units:

Even though SI system is now generally adopted for scientific work, still, the old FPS system is used by general public in some countries, especially in the US. So, many times it becomes necessary to convert from FPS to SI or vice-versa.

FPS System:

The fundamental units in the foot-pound-second (fps) system of units are: the foot for length, the pound for weight, and the second for time.

Following Table will be useful for doing unit conversions by hand:

Quantity	**Multiply**	**by**	**to get**
Length	m	3.2808	ft
	ft	0.304804	m
Area	m2	10.7639	ft2
	ft2	0.092903	m2
Volume	m3	35.3147	ft3
	ft3	0.028317	m3
Mass	kg	2.204586	lb
	lb	0.4536	kg
Density	kg/m3	0.062428	lb/ft3
	lb/ft3	16.01845	kg/m3
Temperature	K	0.555556	R
	R	1.8	K
Mass transfer coeff.	m/s	11811	ft/h
	ft/h	8.47E-05	m/s
Vol. Flow rate	m3/s	127130	ft3/h
	ft3/h	7.87E-06	m3/s
Acceleration	m/s2	42520000	ft/h2
	ft/h2	2.35E-08	
Energy	J	0.000948	Btu
	Btu	1054.997	J
Force	N	0.22481	lbf
	lbf	4.448201	N
Heat transfer rate	W	3.4123	Btu/h
	Btu/h	0.293057	W
Heat flux	W/m2	0.317209	Btu/h ft2
	Btu/h ft2	3.152496	W/m2
Heat gen. rate	W/m3	0.096684	Btu/h ft3
	Btu/h ft3	10.34297	W/m3
Heat transfer coeff.	W/m2.K	0.17611	Btu/h ft2 F
	Btu/h ft2 F	5.678269	W/m2.K
Kin. Visc.& diffusvity	m2/s	10.76426	ft2/s
	ft2/s	0.0929	m2/s
Latent heat	J/kg	0.00043	Btu/lb
	Btu/lb	2325.852	J/kg

Mass flow rate	kg/s	7936.6	lbm/h
	lbm/h	0.000126	kg/s
Pressure and stress	N/m2	0.020886	lbf/ft2
	lbf/ft2	47.87896	N/m2
Sp. heat	J/kg.K	0.000239	Btu/lbm.F
	Btu/lbm.F	4186.553	J/kg.K
Thermal conductivity	W/m.K	0.57782	Btu/h ft F
	Btu/h ft F	1.730643	W/m.K
Thermal resistance	K/W	0.5275	F/h.Btu
	F/h.Btu	1.895735	K/W
Dynamic viscosity	kg/m.s	2419.1	lbm/ft.h
	lbm/ft.h	0.000413	kg/m.s

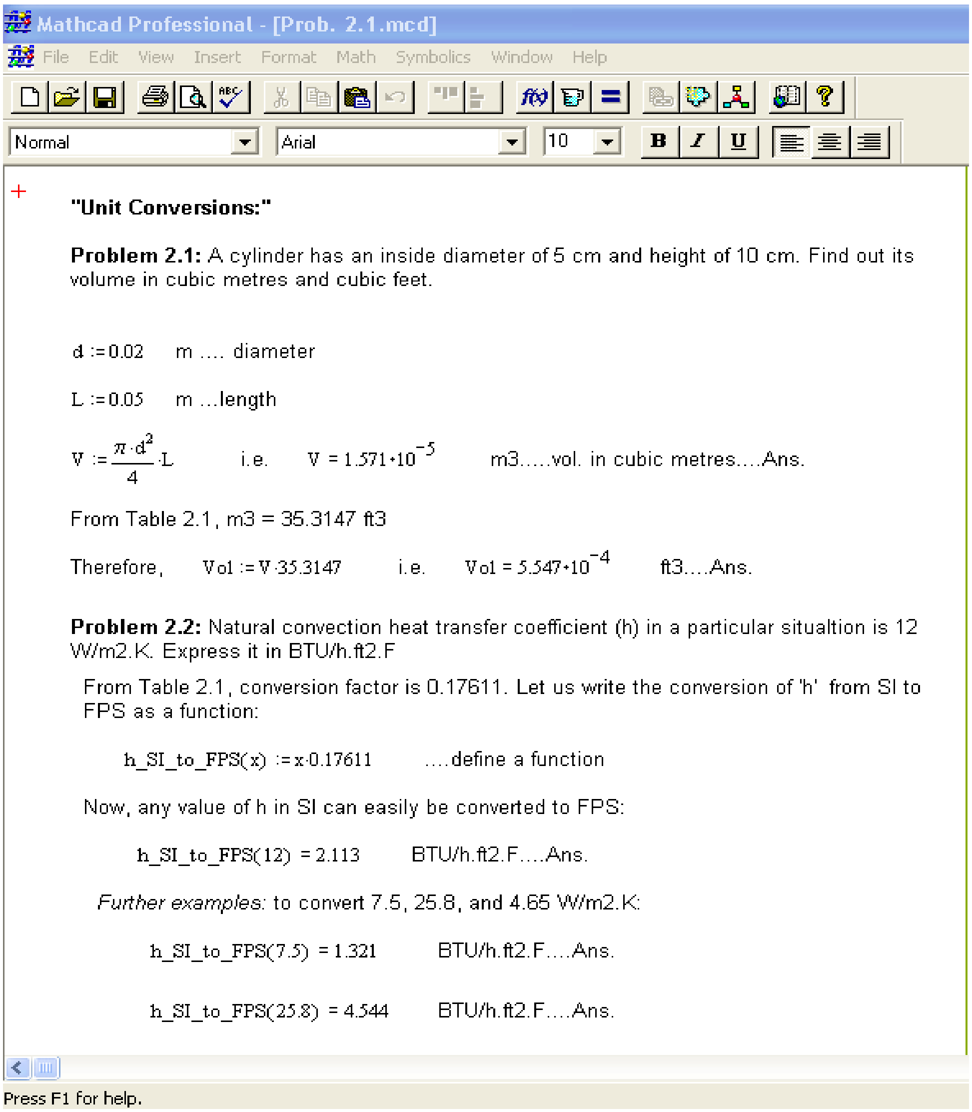
Table 2.6 Conversion Factors

However, if there is access to a computer, it will be convenient, accurate and fast to use a software like Uconeer. AS mentioned earlier, TEST also has a very good ‘Unit converter daemon’ under the heading “Basic daemons’.

2.4 Examples of Unit conversion:

While doing Unit conversions by hand, above Table may be used. If a computer is accessible, it will be quick, accurate and convenient to do unit conversions with the help of one of the softwares. A few examples are shown below.

Mathcad can conveniently be used for quick unit conversions. If the unit conversions have to be done quite a few times in the same worksheet, it will be useful to define the unit conversion factors in a function. See below a Mathcad worksheet example:



"Unit Conversions:"

Problem 2.1: A cylinder has an inside diameter of 5 cm and height of 10 cm. Find out its volume in cubic metres and cubic feet.

$d := 0.02$ m .... diameter

$L := 0.05$ m ...length

$V := \frac{\pi \cdot d^2}{4} \cdot L$ i.e. $V = 1.571 \cdot 10^{-5}$ m3.....vol. in cubic metres....Ans.

From Table 2.1, m3 = 35.3147 ft3

Therefore, $Vol := V \cdot 35.3147$ i.e. $Vol = 5.547 \cdot 10^{-4}$ ft3....Ans.

Problem 2.2: Natural convection heat transfer coefficient (h) in a particular situaltion is 12 W/m2.K. Express it in BTU/h.ft2.F

From Table 2.1, conversion factor is 0.17611. Let us write the conversion of 'h' from SI to FPS as a function:

h_SI_to_FPS(x) := x·0.17611 ....define a function

Now, any value of h in SI can easily be converted to FPS:

h_SI_to_FPS(12) = 2.113 BTU/h.ft2.F....Ans.

Further examples: to convert 7.5, 25.8, and 4.65 W/m2.K:

h_SI_to_FPS(7.5) = 1.321 BTU/h.ft2.F....Ans.

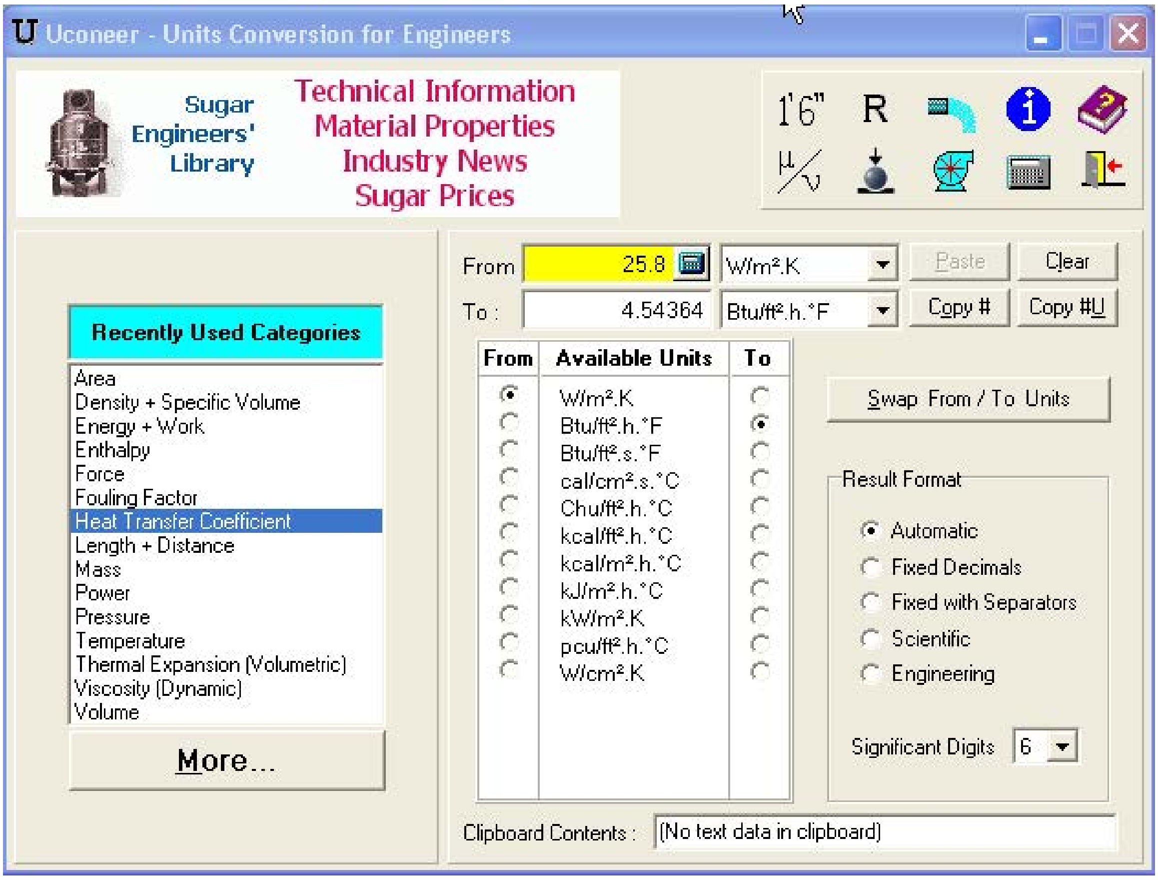
h_SI_to_FPS(25.8) = 4.544 BTU/h.ft2.F....Ans.

Fig. 2.1 Mathcad Worksheet for Unit conversion

However, using the software designed specifically for unit conversions is always advantageous; you need not remember the conversion factors. Just a few clicks of the mouse will do the job.

Prob. 2.3 Convert a value of heat transfer coeff. of 25.8 W/m2.K to BTU/h.ft2.F using Uconeer software.

Open Uconeer, choose the category 'heat transfer coeff.', and click the radio buttons in 'From' and 'To'. Enter 25.8 in the 'From' widget. Immediately, you get the following result:



From 25.8 W/m².K

To : 4.54364 Btu/ft².h.°F

Result Format: ● Automatic

Significant Digits 6

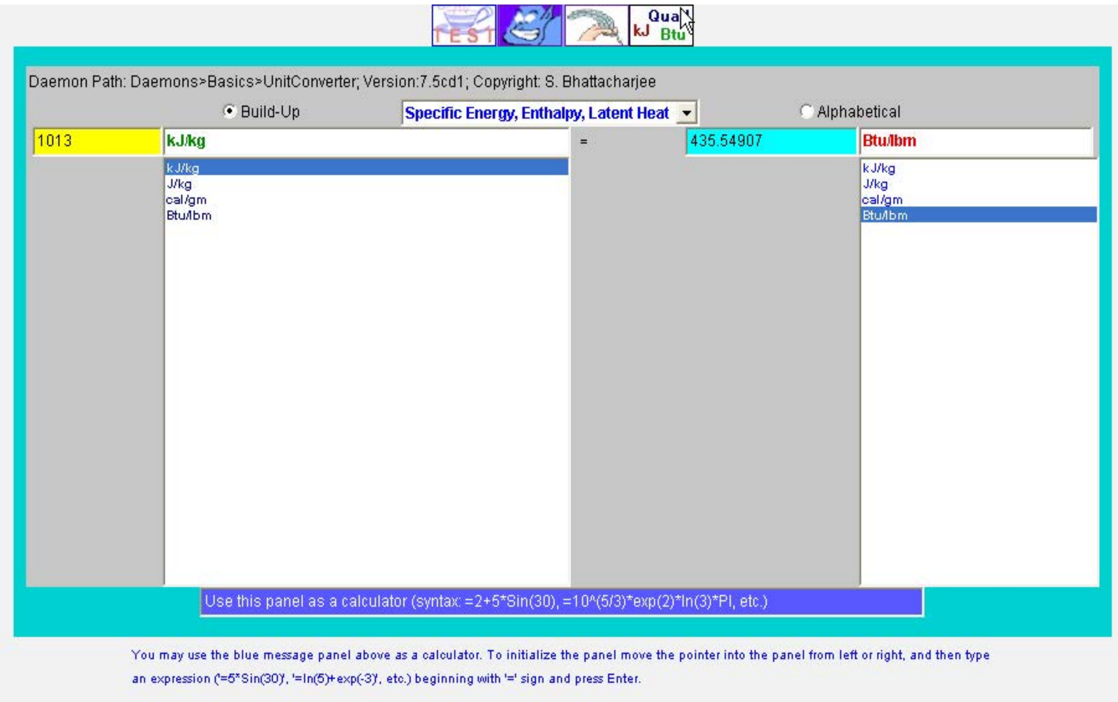
Clipboard Contents : (No text data in clipboard)

Fig. 2.2 Unit conversion with Uconeer

Next, an example of using the 'Unit conversion daemon' from TEST software is given below:

Prob. 2.4 Convert 1013 kJ/kg to BTU/lbm.

Open the Unit converter daemon in TEST. Select the category 'Specific Energy, Enthalpy, Latent Heat'. Enter 1013 on the yellow panel. Select 'kJ/kg' on LHS and select 'BTU/lbm' on RHS, as shown. Immediately the answer appears as 435.54907 BTU/lbm:



Daemon Path: Daemons>Basics>UnitConverter; Version:7.5cd1; Copyright: S. Bhattacharjee

● Build-Up Specific Energy, Enthalpy, Latent Heat ○ Alphabetical

1013 kJ/kg = 435.54907 Btu/lbm

- kJ/kg
- J/kg
- cal/gm
- Btu/lbm

- kJ/kg
- J/kg
- cal/gm
- Btu/lbm

Use this panel as a calculator (syntax: =2+5*Sin(30), =10^(5/3)*exp(2)*ln(3)*PI, etc.)

You may use the blue message panel above as a calculator. To initialize the panel move the pointer into the panel from left or right, and then type an expression ('=5*Sin(30)', '=ln(5)+exp(-3)', etc.) beginning with '=' sign and press Enter.

Fig. 2.3 Unit conversion in TEST software

2.5 Examples of Pressure calculations with Manometers:

Manometers are commonly used in experiments to measure pressures or pressure differentials.

Formulae:

A barometer and a simple U-tube manometer are shown below:

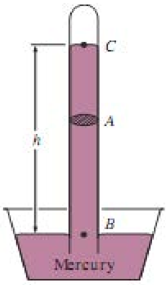


Fig. 2.4 The barmoter

First principle to remember is: if the height of a column of liquid is h, and its density ρ, pressure at the bottom of the column is:

$$P2 = P1 = P_{atm} + \rho \cdot g \cdot h \quad \text{Pa.....eqn.} \qquad (2.2)$$

where, ρ = density of fluid in kg/m3, h = vertical height of fluid column in m, g = accn.

d or, to gravity = 9.81 m/s2 at sea level

Second principle to remember is: in a body of liquid the pressures are the same at all points at the same horizontal level. i.e. in the fig. below, P1 = P2.

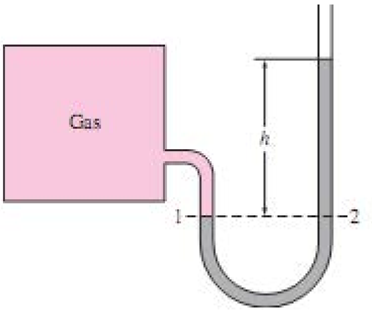


Fig. 2.5 The basic manometer

i.e

$$P2 = P1 = P_{atm} + \rho \cdot g \cdot h \quad .....\text{eqn.} \tag{2.2}$$

or,

$$P1 - P_{atm} = \Delta P = \rho \cdot g \cdot h \quad ....\text{eqn.} \tag{2.3}$$

To improve accuracy and sensitivity of manometers, different arrangements have been devised: simplest one is the *inclined manometer.* Here, the manometer arm is inclined at an angle of say, theta degrees to the horizontal.

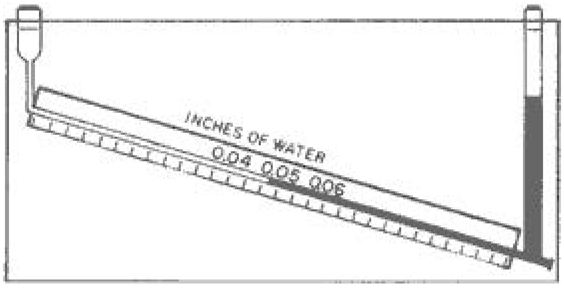
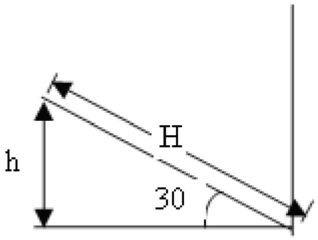


Fig. 2.6 Inclined manometer



Then, if the inclined reading is H, vertical height h is given by:

$$h = H \cdot \sin(\theta) \quad \text{eqn.} \tag{2.4}$$

And, using this 'h', ΔP is calculated from eqn.(2.3)

Another way of improving the accuracy and sensitivity of manometers is to use more than one fluid in the manometer. Fig. below shows a manometer with three working fluids:

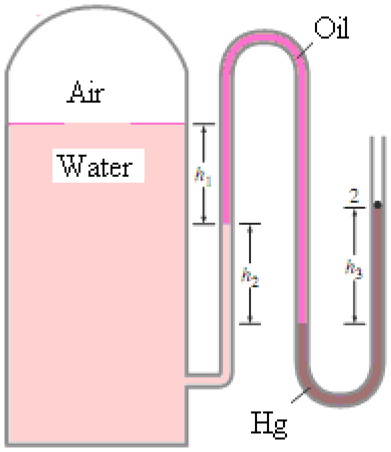
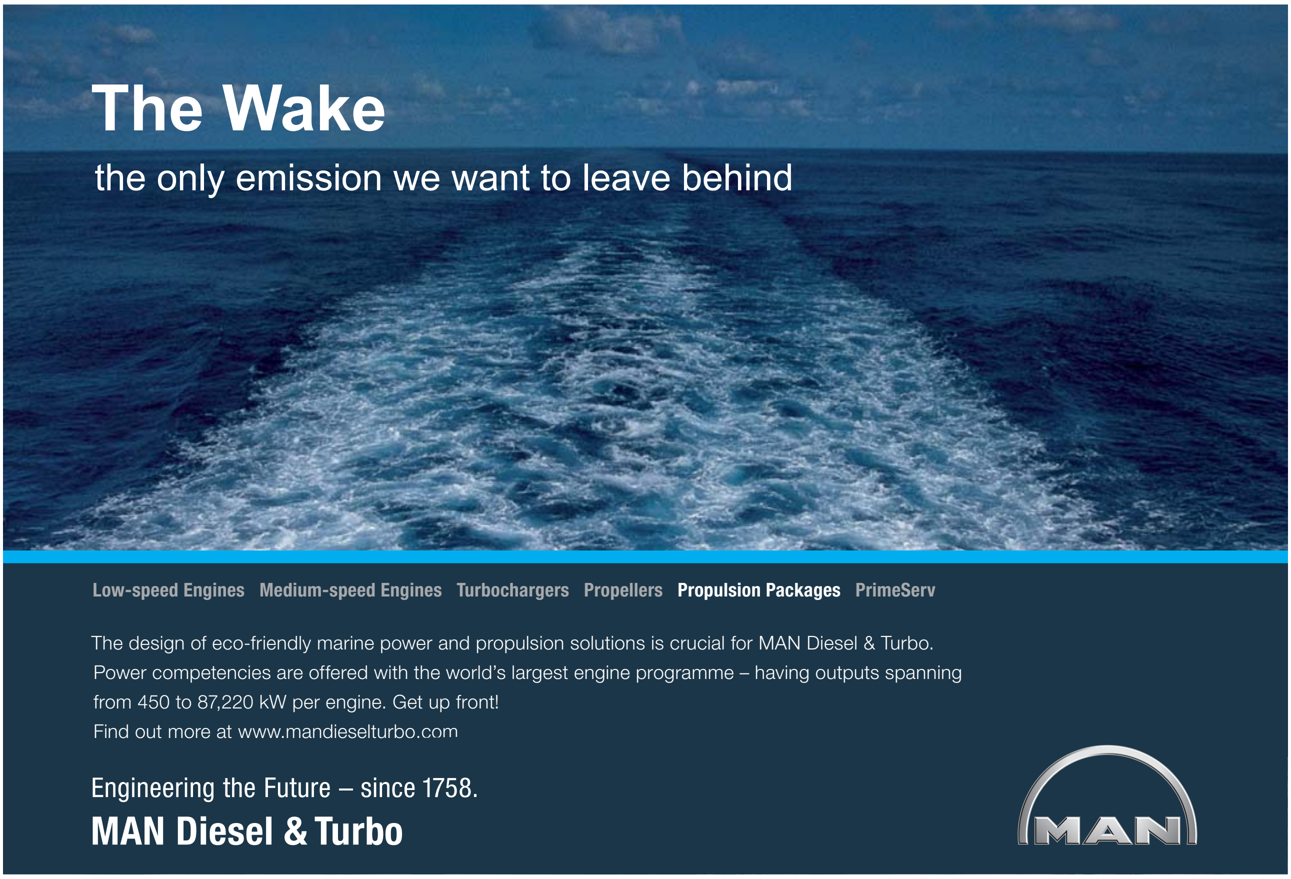


Fig. 2.7 Manometer with 3 fluids

To find the pressure at point 1, follow this procedure: start from point 1 and proceed along the fluid in the manometer applying the two principles stated earlier. Then we can write:

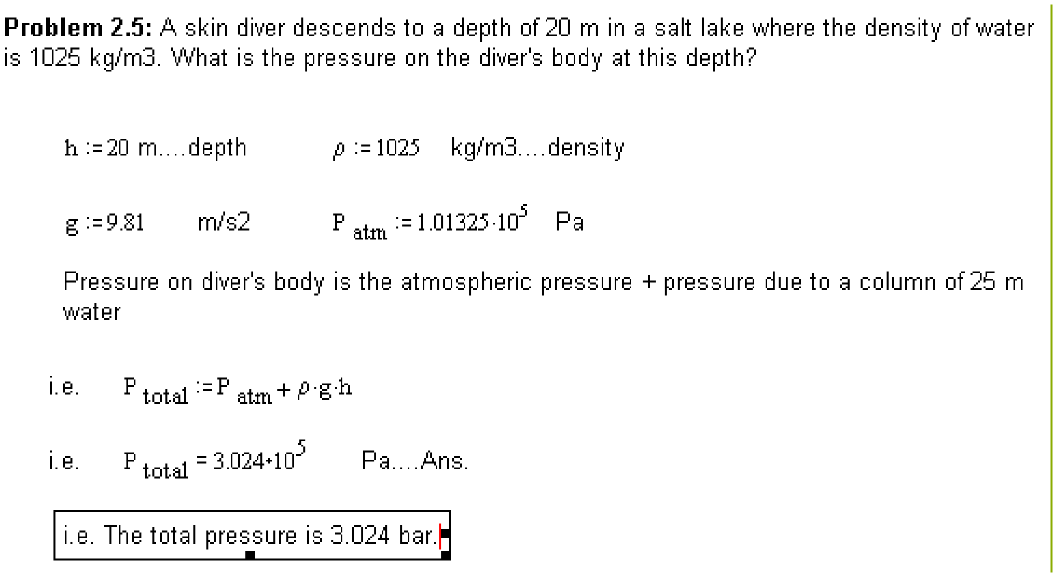
$$P_1 + \rho_{water} \cdot g \cdot h_1 + \rho_{oil} \cdot g \cdot h_2 - \rho_{Hg} \cdot g \cdot h_3 = P_{atm}$$

i.e. $$P_1 = P_{atm} - \rho_{water} \cdot g \cdot h_1 - \rho_{oil} \cdot g \cdot h_2 + \rho_{Hg} \cdot g \cdot h_3 \quad \text{...eqn.} \qquad (2.5)$$



Now, let solve a few problems on pressure measurement.

Following problem is solved in Mathcad.



Problem 2.5: A skin diver descends to a depth of 20 m in a salt lake where the density of water is 1025 kg/m3. What is the pressure on the diver's body at this depth?

$h := 20$ m....depth $\rho := 1025$ kg/m3....density

$g := 9.81$ m/s2 $P_{atm} := 1.01325 \cdot 10^5$ Pa

Pressure on diver's body is the atmospheric pressure + pressure due to a column of 25 m water

i.e. $P_{total} := P_{atm} + \rho \cdot g \cdot h$

i.e. $P_{total} = 3.024 \cdot 10^5$ Pa....Ans.

i.e. The total pressure is 3.024 bar.

Problem 2.6: In the following fig. if the gauge reads 70 kPa, what should be the height of the liquid column in manometer? Liquid sp. gravity = 0.85.

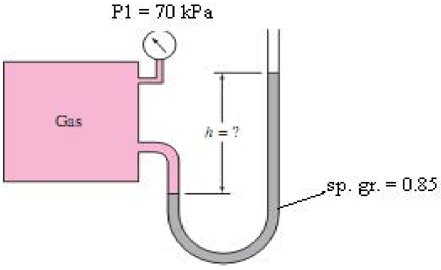


Fig. Prob. 2.6

Pressure inside the Gas tank is equal to the gauge pressure + atmospheric pressure. On the right limb of manometer, atm. pressure is acting. Therefore, h should be equivalent to the gauge pressure, i.e.

$\Delta P := 70 \cdot 1000$ Pa $g := 9.81$ m/s2

$\rho_{liq} := 0.85 \cdot 1000$ kg/m3

$\Delta P = \rho_{liq} \cdot g \cdot h$ ...eqn. for pressure differential

Therefore, $h := \dfrac{\Delta P}{\rho_{liq} \cdot g}$

i.e. $h = 8.395$ m....height of liquid column....Ans.

Note: This height of liquid column is rather too much. So, let us investigate the variation of liquid height with ρliq, say starting from 800m kg/m3 to 13600 kg/m3:

In Mathcad, this is very easy. Define 'h' as a function of ρ and proceed as shown in the following:

$h(\rho_{liq}) := \frac{\Delta P}{\rho_{liq} \cdot g}$ ....define 'h' as a function of ρliq.

$\rho_{liq} := 800, 850 .. 13600$ .....define the range variable for liq. density; Format is: first value, next value and the last value.

Then from the Insert menu, choose: Graph -x-y plot. A blank plot appears with place holders in x and y axes. Fill up rliq for x and h(rliq) for y. Immediately the graph appears. It can then be formatted for better appearance by adding grid lines, titles etc.

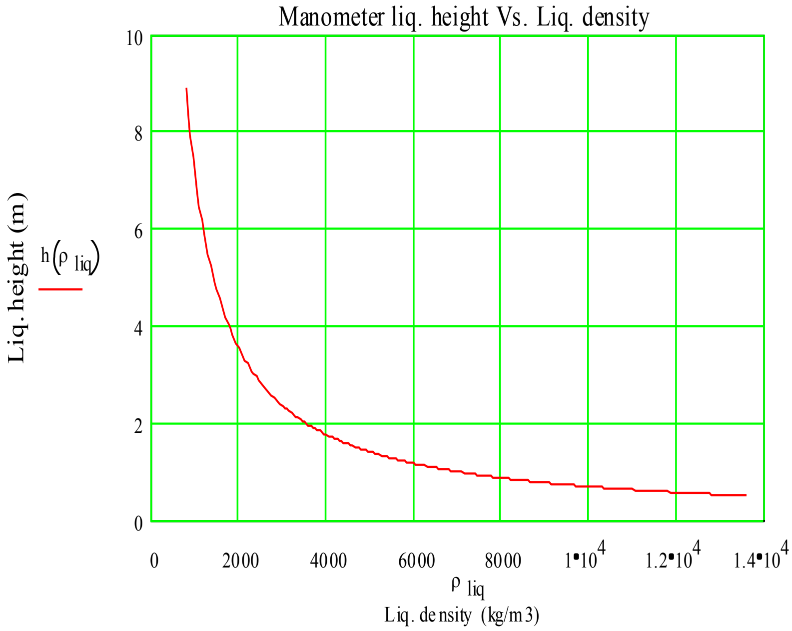


Fig. Prob. 2.6(b)

Note the ease with which this graph is produced. Verify from the graph the liq. column height for Mercury (ρ = 13,600 kg/m3):

$h(13600) = 0.525$ m.... liq. height with Hg as manometric fluid.

Problem 2.7: Calculate the pressure in the Natural gas pipe line in the following arrangement; assume atm. pressure as 101.3 kPa

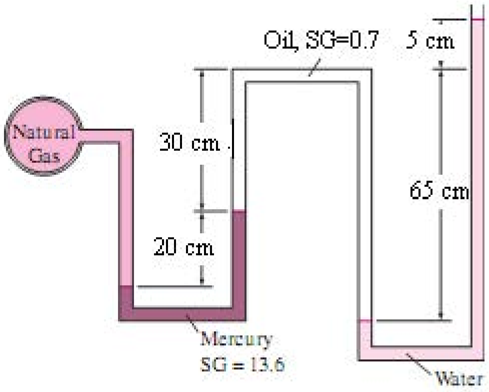
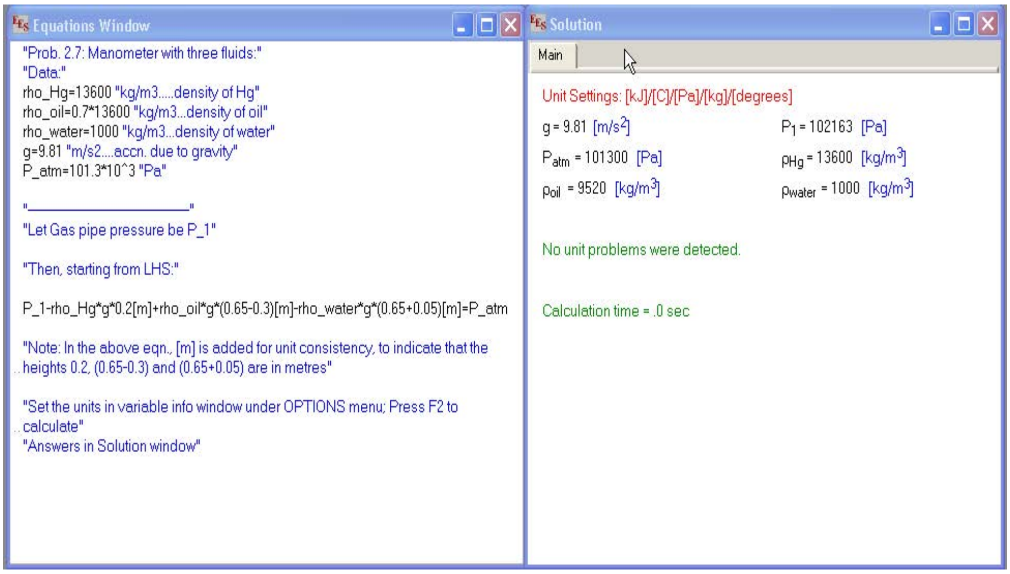


Fig. Prob. 2.7

Right hand end of manometer is open to atmosphere.

Procedure is to start from the LHS (i.e. from natural gas pipe line) and proceed through the manometer fluid.

EES worksheet solution of this problem is shown below:



```
"Prob. 2.7: Manometer with three fluids:"
"Data:"
rho_Hg=13600 "kg/m3.....density of Hg"
rho_oil=0.7*13600 "kg/m3...density of oil"
rho_water=1000 "kg/m3...density of water"
g=9.81 "m/s2....accn. due to gravity"
P_atm=101.3*10^3 "Pa"

"_______________________"
"Let Gas pipe pressure be P_1"

"Then, starting from LHS:"

P_1-rho_Hg*g*0.2[m]+rho_oil*g*(0.65-0.3)[m]-rho_water*g*(0.65+0.05)[m]=P_atm

"Note: In the above eqn., [m] is added for unit consistency, to indicate that the
heights 0.2, (0.65-0.3) and (0.65+0.05) are in metres"

"Set the units in variable info window under OPTIONS menu; Press F2 to
calculate"
"Answers in Solution window"
```

```
Unit Settings: [kJ]/[C]/[Pa]/[kg]/[degrees]
g = 9.81  [m/s2]                  P1 = 102163  [Pa]
Patm = 101300  [Pa]               ρHg = 13600  [kg/m3]
ρoil = 9520  [kg/m3]              ρwater = 1000  [kg/m3]

No unit problems were detected.

Calculation time = .0 sec
```

Thus, the pressure in the gas pipe line is: P_1 = 102163 Pa = 1.02 bar.

Problem 2.8: Change in atm. pressure with the altitude is shown in the following table:
(Ref: http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html)

Altitude Above Sea Level		Absolute Barometer		Absolute Atmospheric Pressure		
feet	**meter**	**in. Hg**	**mm Hg**	**psia**	**kg/cm^2**	**kPa**
-5,000	-1,526	35.58	903.7	17.48	1.229	120.5
-4,500	-1,373	35.00	889.0	17.19	1.209	118.5
-4,000	-1,220	34.42	874.3	16.9	1.188	116.5
-3,500	-1,068	33.84	859.5	16.62	1.169	114.6
-3,000	-915	33.27	845.1	16.34	1.149	112.7
-2,500	-763	32.70	830.6	16.06	1.129	110.7
-2,000	-610	32.14	816.4	15.78	1.109	108.8
-1,500	-458	31.58	802.1	15.51	1.091	106.9
-1,000	-305	31.02	787.9	15.23	1.071	105.0
-500	-153	30.47	773.9	14.96	1.052	103.1
0[1]	0	29.92	760.0	14.696	1.0333	101.33
500	153	29.38	746.3	14.43	1.015	99.49
1,000	305	28.86	733.0	14.16	0.996	97.63
1,500	458	28.33	719.6	13.91	0.978	95.91
2,000	610	27.82	706.6	13.66	0.960	94.19
2,500	763	27.32	693.9	13.41	0.943	92.46
3,000	915	26.82	681.2	13.17	0.926	90.81
3,500	1,068	26.33	668.8	12.93	0.909	89.15
4,000	1,220	25.84	656.3	12.69	0.892	87.49
4,500	1,373	25.37	644.4	12.46	0.876	85.91
5,000	1,526	24.90	632.5	12.23	0.86	84.33
6,000	1,831	23.99	609.3	11.78	0.828	81.22
7,000	2,136	23.10	586.7	11.34	0.797	78.19
8,000	2,441	22.23	564.6	10.91	0.767	75.22
9,000	2,746	21.39	543.3	10.5	0.738	72.40
10,000	3,050	20.58	522.7	10.1	0.71	69.64
15,000	4,577	16.89	429.0	8.29	0.583	57.16
20,000	6,102	13.76	349.5	6.76	0.475	46.61
25,000	7,628	11.12	282.4	5.46	0.384	37.65
30,000	9,153	8.903	226.1	4.37	0.307	30.13
35,000	10,679	7.06	179.3	3.47	0.244	23.93
40,000	12,204	5.558	141.2	2.73	0.192	18.82
45,000	13,730	4.375	111.1	2.15	0.151	14.82
50,000	15,255	3.444	87.5	1.69	0.119	11.65
55,000	16,781	2.712	68.9	1.33	0.094	9.17
60,000	18,306	2.135	54.2	1.05	0.074	7.24
70,000	21,357	1.325	33.7	0.65	0.046	4.49
80,000	24,408	0.8273	21.0	0.41	0.029	2.80
90,000	27,459	0.520	13.2	0.26	0.018	1.76
100,000	30,510	0.329	8.36	0.16	0.011	1.12

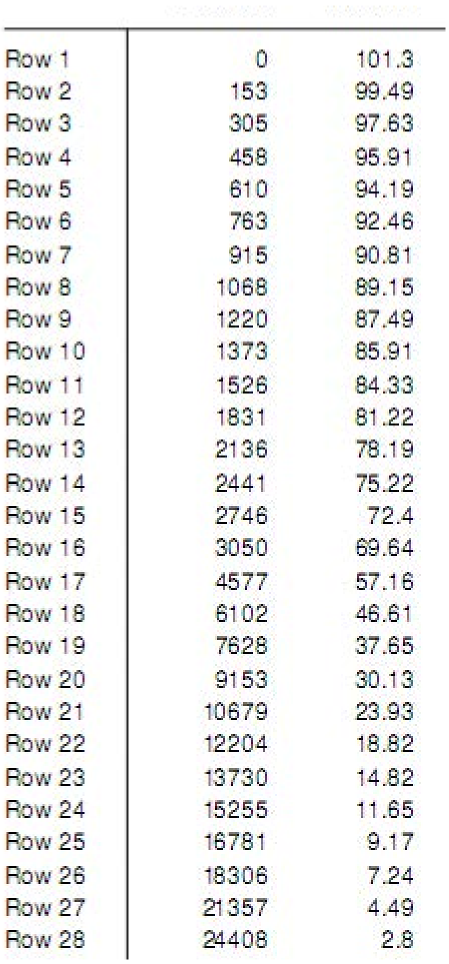
Table 2.7 Atmospheric pressure with Altitude

[1] Sea Level

Find out the atm. pressure in kPa at an altitude of 10000 m.

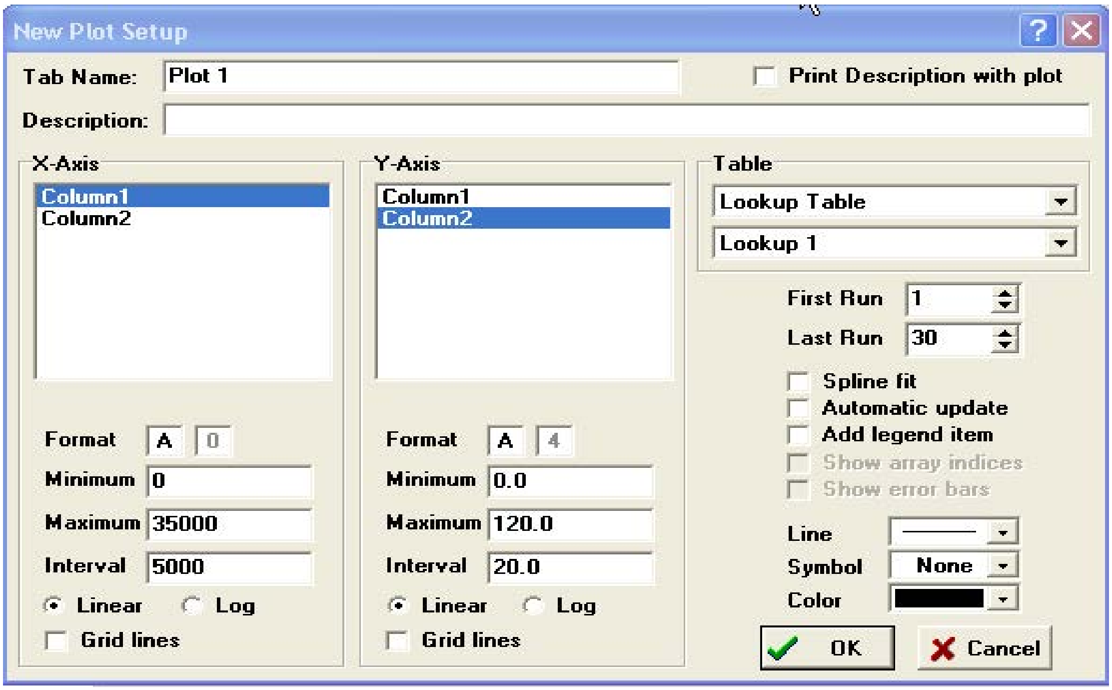
Let us work out this problem in EES. First, we prepare a 'look up table' in EES with altitude (m) in column 1 and pressure (kPa) in column 2; then, plot the pressure against altitude, and then get the curve fit equation and then use it to calculate the pressure at 10000 m altitude in the equations window.

Since ***'curve fit'*** is an important requirement in many problems, let us show the details: After starting EES, go to 'Tables' menu, select 'New look up table', select two columns and 30 rows, and fill up the altitude values in metres in the column 1, and pressure values in kPa in column 2. Look up table is shown below:



Row 1	0	101.3
Row 2	153	99.49
Row 3	305	97.63
Row 4	458	95.91
Row 5	610	94.19
Row 6	763	92.46
Row 7	915	90.81
Row 8	1068	89.15
Row 9	1220	87.49
Row 10	1373	85.91
Row 11	1526	84.33
Row 12	1831	81.22
Row 13	2136	78.19
Row 14	2441	75.22
Row 15	2746	72.4
Row 16	3050	69.64
Row 17	4577	57.16
Row 18	6102	46.61
Row 19	7628	37.65
Row 20	9153	30.13
Row 21	10679	23.93
Row 22	12204	18.82
Row 23	13730	14.82
Row 24	15255	11.65
Row 25	16781	9.17
Row 26	18306	7.24
Row 27	21357	4.49
Row 28	24408	2.8

Next, go to Plots menu, select 'New Plot' – x y plot – you get the following dialog window:



New Plot Setup

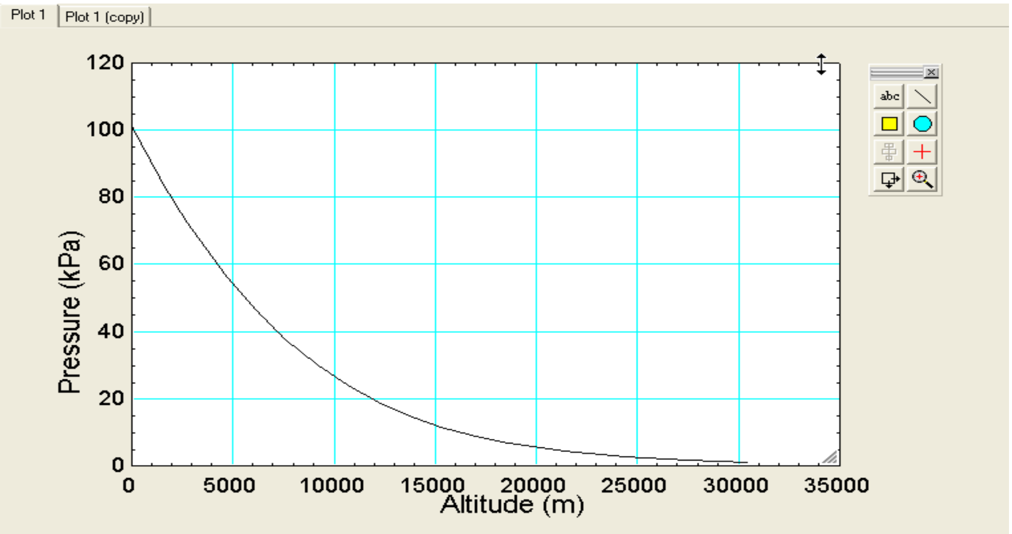
Tab Name: Plot 1
☐ Print Description with plot
Description:

X-Axis: Column1, Column2
Format: A 0
Minimum: 0
Maximum: 35000
Interval: 5000
● Linear ○ Log
☐ Grid lines

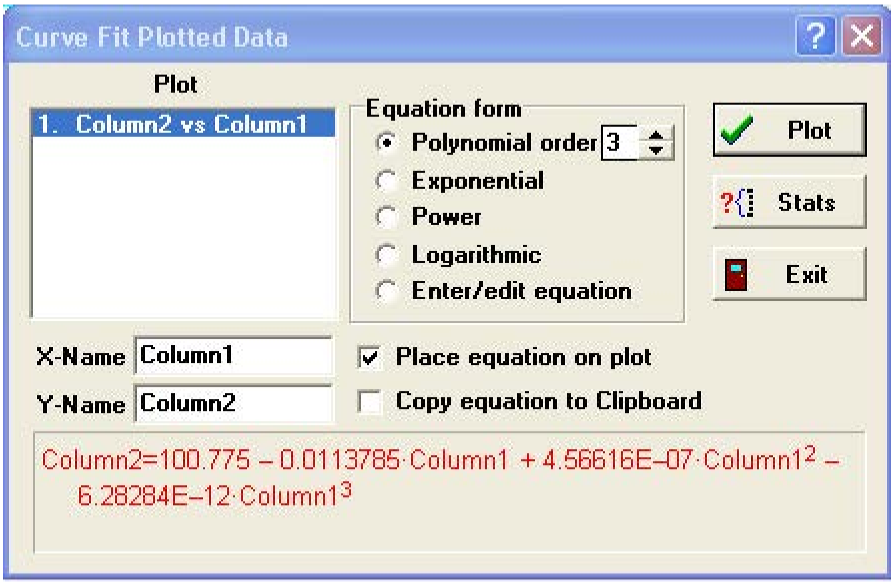
Y-Axis: Column1, Column2
Format: A 4
Minimum: 0.0
Maximum: 120.0
Interval: 20.0
● Linear ○ Log
☐ Grid lines

Table: Lookup Table
Lookup 1
First Run: 1
Last Run: 30
☐ Spline fit
☐ Automatic update
☐ Add legend item
☐ Show array indices
☐ Show error bars
Line
Symbol: None
Color

Choose column 1 for x-axis and column 2 for y-axis; press OK. Graph appears. You can format the graph by right clicking on the graph, x-axis and y-axis. Graph obtained is shown below:



Now, to do curve *fitting*: Go to 'Plots' menu and choose 'curve fit'; choose 'polynomial order 3', curve fit eqn. appears at the bottom of that window as shown:



1. Column2 vs Column1

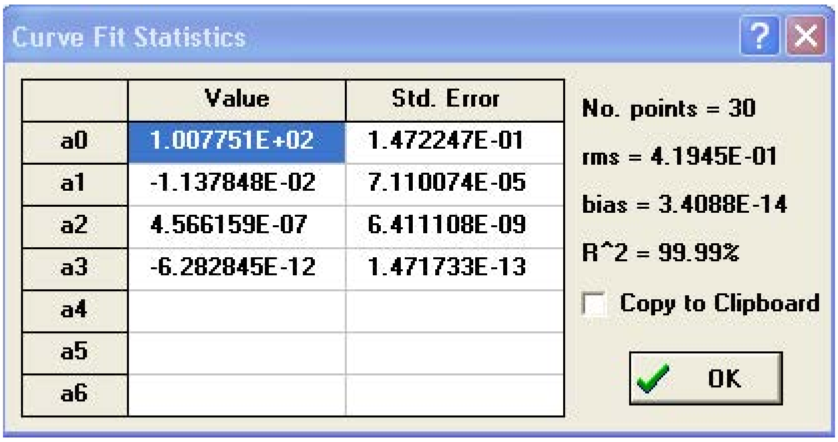
● Polynomial order 3
○ Exponential
○ Power
○ Logarithmic
○ Enter/edit equation

X-Name Column1
Y-Name Column2

☑ Place equation on plot
☐ Copy equation to Clipboard

$$\text{Column2} = 100.775 - 0.0113785 \cdot \text{Column1} + 4.56616\text{E}{-07} \cdot \text{Column1}^2 - 6.28284\text{E}{-12} \cdot \text{Column1}^3$$

Statistics regarding the plot (to find how good is the curve fit) can be obtained by clicking on 'Stats':



	Value	Std. Error
a0	1.007751E+02	1.472247E-01
a1	-1.137848E-02	7.110074E-05
a2	4.566159E-07	6.411108E-09
a3	-6.282845E-12	1.471733E-13
a4		
a5		
a6		

No. points = 30

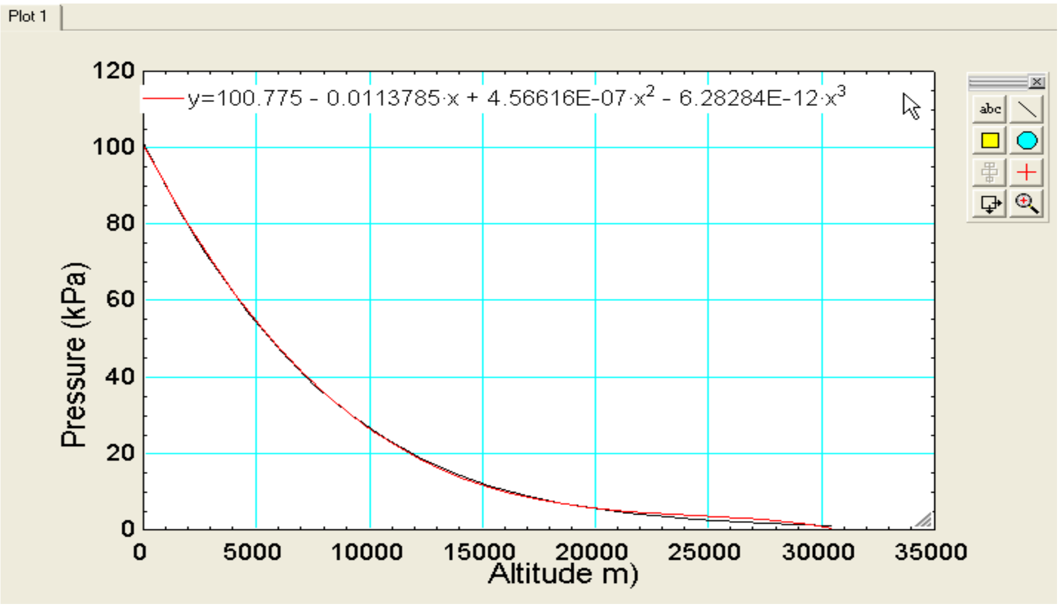
rms = 4.1945E-01

bias = 3.4088E-14

R^2 = 99.99%

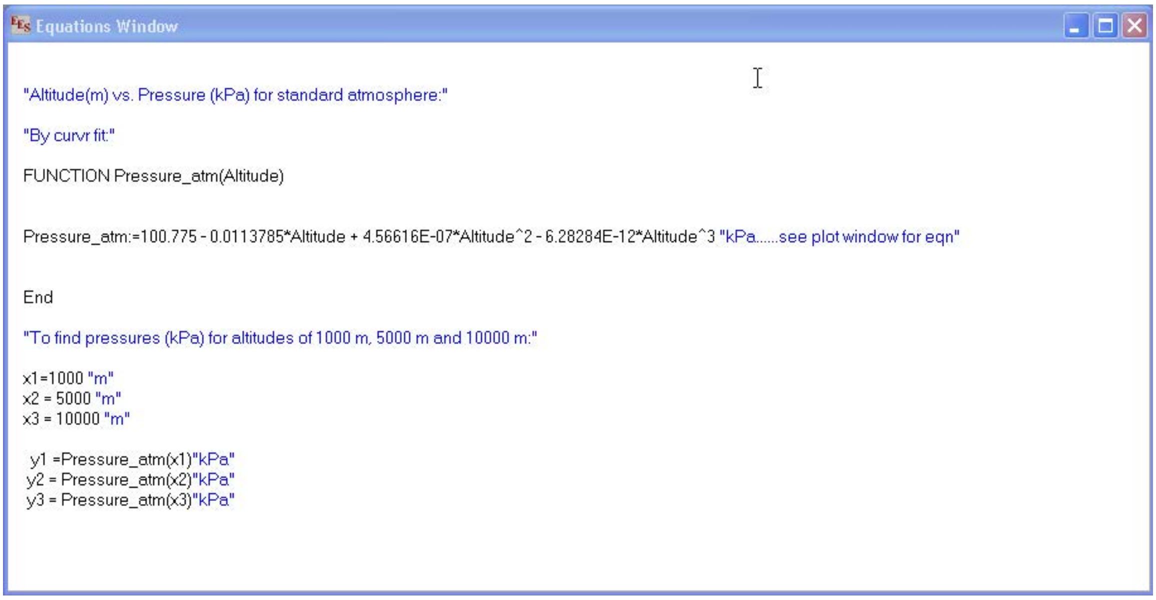
☐ Copy to Clipboard

Press OK in the above screen. Now, click on ‘Plot’ on the earlier screen and the eqn. is placed on the plot. Right click on the eqn. and format it. Following is the screen shot after formatting:



Note that plot shows one curve for the data in the table and a second curve for the results as per the curve fit equation.

Next, to find the pressure at an altitude of 10000 m: Use the curve fit eqn. In the Equation window of EES, you can type this eqn, substitute for x = 10000 and get the value of pressure (= y). In the following screen, we have written an EES function using the curve fit eqn. so that pressures can be calculated conveniently for any altitudes, say for x1 = 1000 m, x2 = 5000 m and x3 = 10000 m:



```
"Altitude(m) vs. Pressure (kPa) for standard atmosphere:"

"By curvr fit:"

FUNCTION Pressure_atm(Altitude)

Pressure_atm:=100.775 - 0.0113785*Altitude + 4.56616E-07*Altitude^2 - 6.28284E-12*Altitude^3 "kPa......see plot window for eqn"


End

"To find pressures (kPa) for altitudes of 1000 m, 5000 m and 10000 m:"

x1=1000 "m"
x2 = 5000 "m"
x3 = 10000 "m"

 y1 =Pressure_atm(x1)"kPa"
y2 = Pressure_atm(x2)"kPa"
y3 = Pressure_atm(x3)"kPa"
```

Now, pressing F2 produces the following Solution:

```
SOLUTION
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
x1 = 1000                 x2 = 5000                 x3 = 10000                y1 = 89.85
y2 = 54.51                y3 = 26.37

No unit problems were detected.
```

We note from the solution that the pressures for altitudes of 1000, 5000 and 10000 m are: 89.85, 54.51 and 26.37 kPa respectively.

Prob. 2.9: Find the differential pressure P_B in Pa and the head in metres of water in the following arrangement. Given: Rm = 60 cm, h = 75 cm, Δz = 30 cm, $P_A = 5 * 10^4$ Pa.

Let us work out this problem in Mathcad.

The method is: to start the known pressure and work the way through the manometer fluid. Mathcad worksheet is shown below:

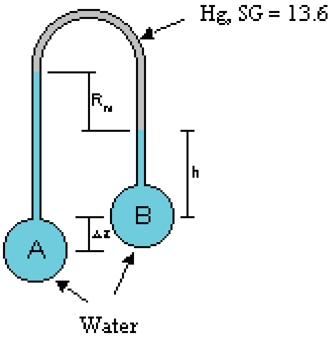


Fig. Prob 2.9

$R_m := 0.6$ m $h := 0.75$ m $\Delta z := 0.3$ m $P_A := 5 \cdot 10^4$ Pa

$\rho_{water} := 1000$ kg/m3 $\rho_{Hg} := 13600$ kg/m3 $g := 9.81$ m/s2

Find out P_B:

Write down the pressures, starting from bulb A:

$$P_B := \left[P_A - \rho_{water} \cdot g \cdot \left(R_m + h + \Delta z\right) + \left(\rho_{Hg} \cdot g \cdot R_m\right) + \left(\rho_{water} \cdot g \cdot h\right)\right]$$

i.e. $P_B = 1.212 \cdot 10^5$ Pa.....Ans.

To find the head in metres of water:

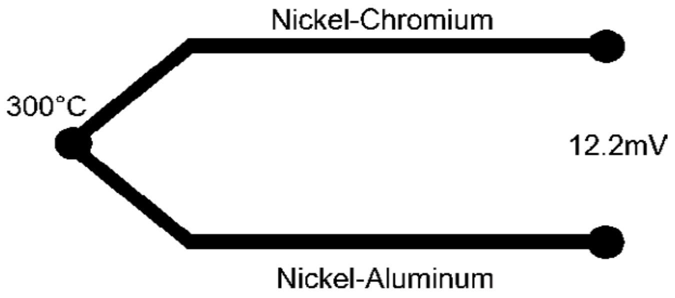
$$P_B = \rho_{water} \cdot g \cdot head$$

i.e. $$head := \frac{P_B}{\rho_{water} \cdot g}$$

i.e. head=12.357 m of water....Ans.

2.6 Examples of Temperature calculations with Thermocouples:

Thermocouple works on the basis of 'Seebeck effect' discovered by Thomas Johann Seebeck in 1821: i.e. when a junction formed out of two dis-similar metals/alloys is kept at a temperature different from the other ends, an emf is generated between those ends as shown below:



Thermocouple is a popular device for temperature measurement.

Its *advantages* are: it is cost effective, easy and convenient to use and is suitable for a wide range of temperatures. Because of low thermal mass of the thermocouple junction, it is quite suitable to measure varying temperatures with fast response.

However, its *disadvantages* are non-linear characteristics of output (i.e. milli-Volts against temperature) and very low values of voltage output, which needs amplification; also, 'cold junction compensation' is required for accuracy.

Voltage developed in thermocouple is a function of temperature difference between junctions. It varies from 1 to 70 microvolts per degree Celsius.

Thermocouples popularly used in industry are:

Type	Materials	Typical Range (deg.C)	Comments
T	Copper/Constantan	-200 to 400	Non-magnetic; sensitivity of about 43 μV/°C.
J	Iron/Constantan	-40 to 750	Limited range; sensitivity: approx. 50 μV/°C
K	Chromel/Alumel	-200 to 1300	General purpose; most commonly used. Sensitivity: approx. 41 μV/°C.
E	Chromel/Constantan	-200 to 900	Suitable for cryogenic use; high sensitivity: 68 μV/°C
S	Pt-10%Rh vs Pt	-50 to 1760	Costly; used for high temp; Low sensitivity:10 μV/deg.C
B	(Pt-13%Rh) vs (Pt-6% Rh)	100 to 1800	--do--
R	(Pt-13%Rh) vs Pt	-50 to 1760	--do--
N	(Ni-Cr-Si) vs (Ni-Si-Mg)	-200 to 1300	For high temp. exceeding 1200^0 C. Sensitivity is about 39 μV/°C at 900°C.

Table 2.8 Thermocouple types

Correct method of connecting a thermocouple is shown below:

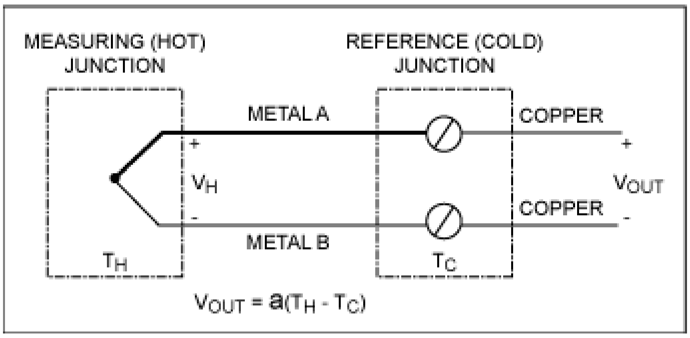
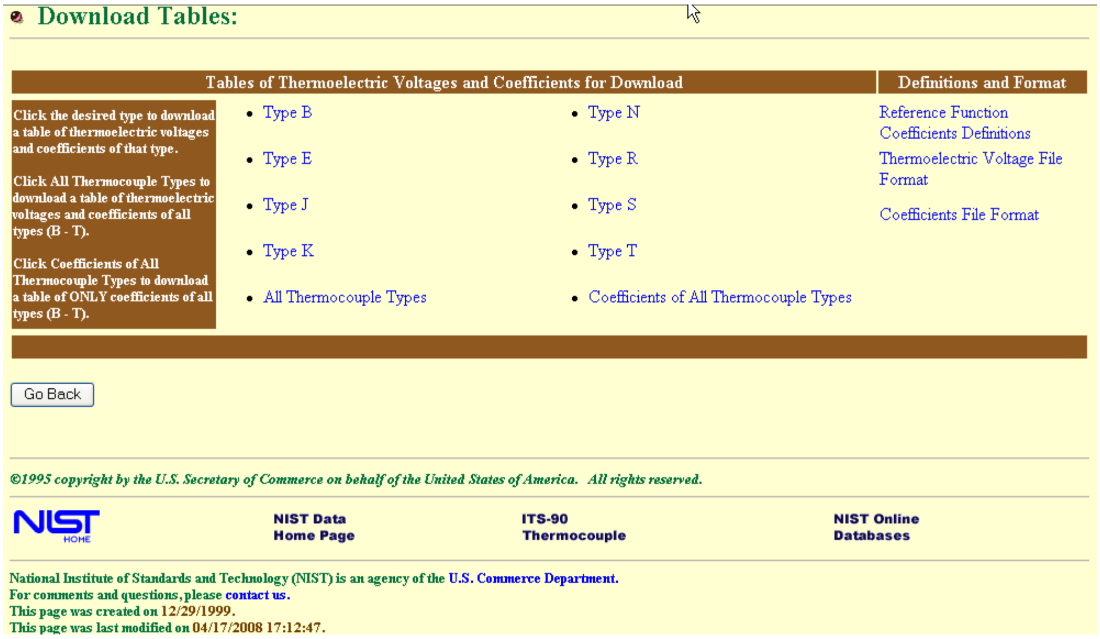


Fig. 2.8 Using Reference junction for thermocouples

Reference junction is normally at 0 deg. C. However, if it is difficult to maintain 0 deg. C reference in practice, by suitable electronic circuitry, 'cold junction compensation' is provided.

Standard reference tables for Thermocouples are normally referenced to 0 deg.C cold junction. NIST reference functions and tables of thermocouple electromotive force (emf) versus temperature have been adopted as standards by the American Society for Testing and Materials (ASTM) and the International Electrotechnical Commission (IEC). Distributed by Standard Reference Data Program of the National Institute of Standards and Technology. NIST look up tables and polynomial coefficients for different Types of thermocouples are available for download from the web site: http://srdata.nist.gov/its90/download/

This website presents the following screen:



Download Tables:

Tables of Thermoelectric Voltages and Coefficients for Download

Definitions and Format

Click the desired type to download a table of thermoelectric voltages and coefficients of that type.

Click All Thermocouple Types to download a table of thermoelectric voltages and coefficients of all types (B - T).

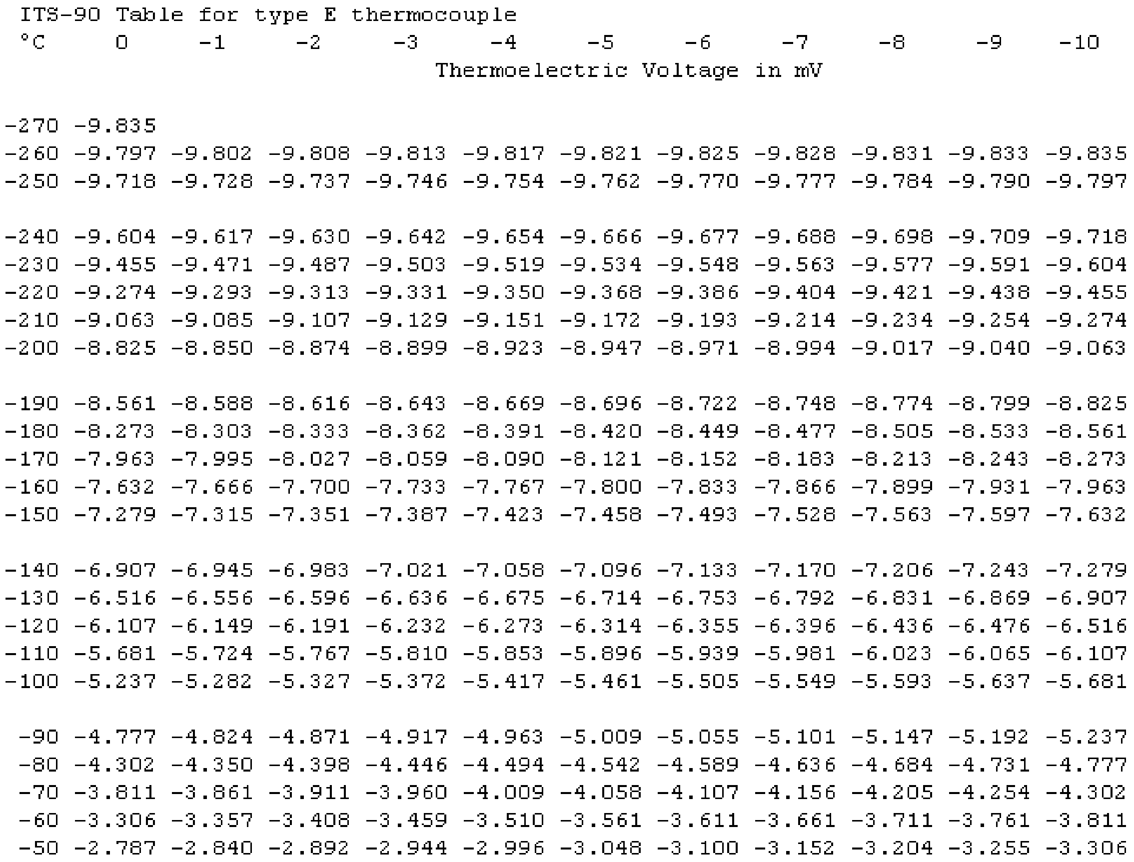
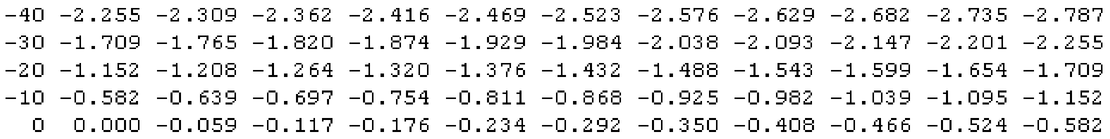
Click Coefficients of All Thermocouple Types to download a table of ONLY coefficients of all types (B - T).

©1995 copyright by the U.S. Secretary of Commerce on behalf of the United States of America. All rights reserved.

National Institute of Standards and Technology (NIST) is an agency of the U.S. Commerce Department.
For comments and questions, please contact us.
This page was created on 12/29/1999.
This page was last modified on 04/17/2008 17:12:47.

By clicking at the required type of thermocouple, one can download the look up table for that type. For example, a partial extract (-270 deg.C to 90 deg.C) of the look up table given by NIST for Type E thermocouple in their website is shown below. Note that the table is given in the temperature range: (-270 deg.C to1000 deg.C).

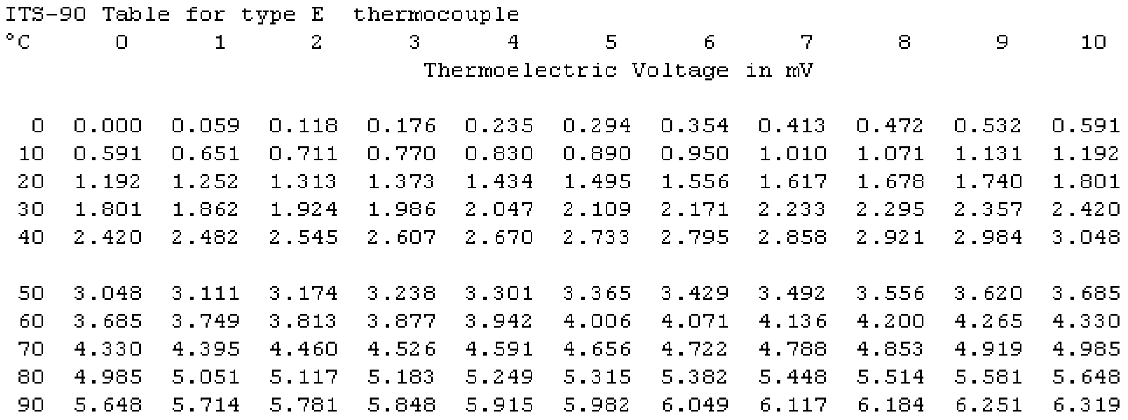
(Ref: (http://srdata.nist.gov/its90/download/type_e.tab)

ITS-90 Table for type E thermocouple

Thermoelectric Voltage in mV

°C	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10
-270	-9.835										
-260	-9.797	-9.802	-9.808	-9.813	-9.817	-9.821	-9.825	-9.828	-9.831	-9.833	-9.835
-250	-9.718	-9.728	-9.737	-9.746	-9.754	-9.762	-9.770	-9.777	-9.784	-9.790	-9.797
-240	-9.604	-9.617	-9.630	-9.642	-9.654	-9.666	-9.677	-9.688	-9.698	-9.709	-9.718
-230	-9.455	-9.471	-9.487	-9.503	-9.519	-9.534	-9.548	-9.563	-9.577	-9.591	-9.604
-220	-9.274	-9.293	-9.313	-9.331	-9.350	-9.368	-9.386	-9.404	-9.421	-9.438	-9.455
-210	-9.063	-9.085	-9.107	-9.129	-9.151	-9.172	-9.193	-9.214	-9.234	-9.254	-9.274
-200	-8.825	-8.850	-8.874	-8.899	-8.923	-8.947	-8.971	-8.994	-9.017	-9.040	-9.063
-190	-8.561	-8.588	-8.616	-8.643	-8.669	-8.696	-8.722	-8.748	-8.774	-8.799	-8.825
-180	-8.273	-8.303	-8.333	-8.362	-8.391	-8.420	-8.449	-8.477	-8.505	-8.533	-8.561
-170	-7.963	-7.995	-8.027	-8.059	-8.090	-8.121	-8.152	-8.183	-8.213	-8.243	-8.273
-160	-7.632	-7.666	-7.700	-7.733	-7.767	-7.800	-7.833	-7.866	-7.899	-7.931	-7.963
-150	-7.279	-7.315	-7.351	-7.387	-7.423	-7.458	-7.493	-7.528	-7.563	-7.597	-7.632
-140	-6.907	-6.945	-6.983	-7.021	-7.058	-7.096	-7.133	-7.170	-7.206	-7.243	-7.279
-130	-6.516	-6.556	-6.596	-6.636	-6.675	-6.714	-6.753	-6.792	-6.831	-6.869	-6.907
-120	-6.107	-6.149	-6.191	-6.232	-6.273	-6.314	-6.355	-6.396	-6.436	-6.476	-6.516
-110	-5.681	-5.724	-5.767	-5.810	-5.853	-5.896	-5.939	-5.981	-6.023	-6.065	-6.107
-100	-5.237	-5.282	-5.327	-5.372	-5.417	-5.461	-5.505	-5.549	-5.593	-5.637	-5.681
-90	-4.777	-4.824	-4.871	-4.917	-4.963	-5.009	-5.055	-5.101	-5.147	-5.192	-5.237
-80	-4.302	-4.350	-4.398	-4.446	-4.494	-4.542	-4.589	-4.636	-4.684	-4.731	-4.777
-70	-3.811	-3.861	-3.911	-3.960	-4.009	-4.058	-4.107	-4.156	-4.205	-4.254	-4.302
-60	-3.306	-3.357	-3.408	-3.459	-3.510	-3.561	-3.611	-3.661	-3.711	-3.761	-3.811
-50	-2.787	-2.840	-2.892	-2.944	-2.996	-3.048	-3.100	-3.152	-3.204	-3.255	-3.306
-40	-2.255	-2.309	-2.362	-2.416	-2.469	-2.523	-2.576	-2.629	-2.682	-2.735	-2.787
-30	-1.709	-1.765	-1.820	-1.874	-1.929	-1.984	-2.038	-2.093	-2.147	-2.201	-2.255
-20	-1.152	-1.208	-1.264	-1.320	-1.376	-1.432	-1.488	-1.543	-1.599	-1.654	-1.709
-10	-0.582	-0.639	-0.697	-0.754	-0.811	-0.868	-0.925	-0.982	-1.039	-1.095	-1.152
0	0.000	-0.059	-0.117	-0.176	-0.234	-0.292	-0.350	-0.408	-0.466	-0.524	-0.582



ITS-90 Table for type E thermocouple

Thermoelectric Voltage in mV

°C	0	1	2	3	4	5	6	7	8	9	10
0	0.000	0.059	0.118	0.176	0.235	0.294	0.354	0.413	0.472	0.532	0.591
10	0.591	0.651	0.711	0.770	0.830	0.890	0.950	1.010	1.071	1.131	1.192
20	1.192	1.252	1.313	1.373	1.434	1.495	1.556	1.617	1.678	1.740	1.801
30	1.801	1.862	1.924	1.986	2.047	2.109	2.171	2.233	2.295	2.357	2.420
40	2.420	2.482	2.545	2.607	2.670	2.733	2.795	2.858	2.921	2.984	3.048
50	3.048	3.111	3.174	3.238	3.301	3.365	3.429	3.492	3.556	3.620	3.685
60	3.685	3.749	3.813	3.877	3.942	4.006	4.071	4.136	4.200	4.265	4.330
70	4.330	4.395	4.460	4.526	4.591	4.656	4.722	4.788	4.853	4.919	4.985
80	4.985	5.051	5.117	5.183	5.249	5.315	5.382	5.448	5.514	5.581	5.648
90	5.648	5.714	5.781	5.848	5.915	5.982	6.049	6.117	6.184	6.251	6.319

Table 2.9 Extract of NIST look up table for Type E thermocouple

Or, if a polynomial equation is desired, coefficients can be downloaded by clicking 'Coeff. of all thermocouple types'.

Polynomial function is defined as follows:

Reference Function Coefficients Definitions:

The general form for the emf, E, as a function of t90 for all except type K thermocouples is:

$$E = \sum_{i=0}^{n} c_i \, (t_{90})^i$$

where E is in mV and t90 is in °C. For type K thermocouples above 0°C, there is an additional term to account for a magnetic ordering effect:

$$E = \sum_{i=0}^{n} c_i \, (t_{90})^i + a_0 e^{a_1 (t_{90} - a_2)^2}$$

where e is the natural logarithm constant, E is in mV, and t_{90} is in °C. The constants a_0, a_1, and a_2 have the values:

$a_0 = 0.118597600000 \text{x} 10^0$

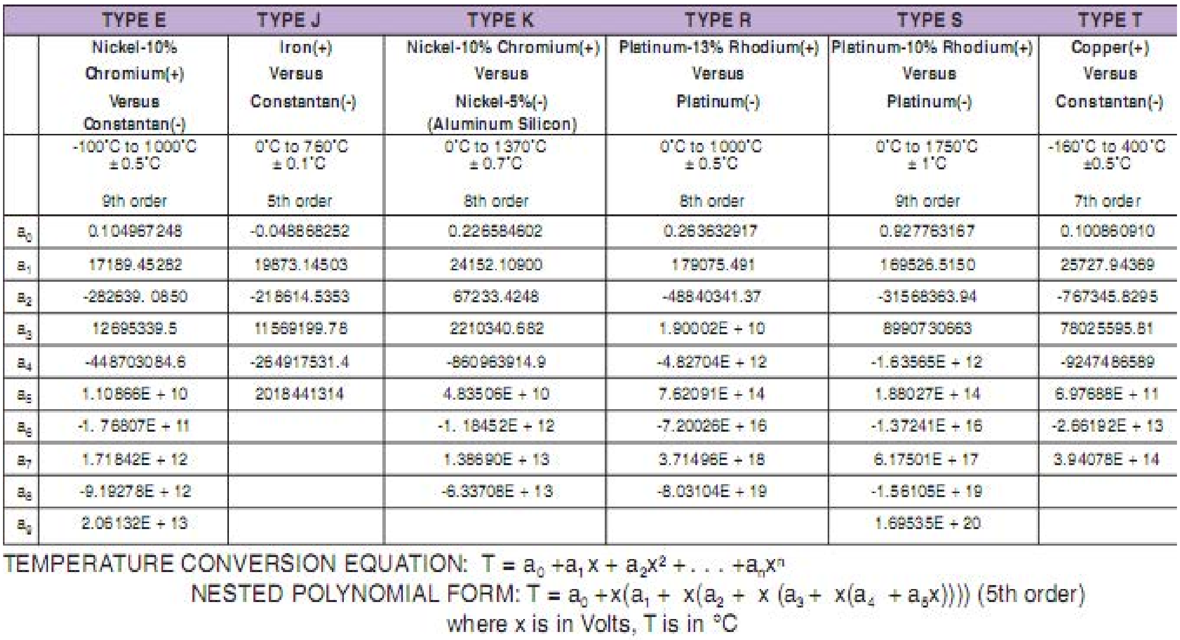
$a_1 = – 0.118343200000 \text{x} 10^{-3}$

$a_2 = 0.126968600000 \text{x} 10^3$

As an example, coefficients for E type thermocouple are downloaded and shown below: Note that polynomial coefficients for E type are given for two temperature ranges, i.e. from -170 to 0 deg.C and 0 to 1000 deg.C:

```
*************************************
* This section contains coefficients for type E thermocouples for
* the two subranges of temperature listed below.  The coefficients
* are in units of °C and mV and are listed in the order of constant
* term up to the highest order.  The equation is of the form
* E = sum(i=0 to n) c_i t^i.
*
*     TemperatureRange (°C)
*        -270.000 to 0.000
*         0.000 to 1000.000
*************************************
name: reference function on ITS-90
type: E
temperature units: °C
emf units: mV
range:  -270.000,      0.000, 13
 0.000000000000E+00
 0.586655087080E-01
 0.454109771240E-04
-0.779980486860E-06
-0.258001608430E-07
-0.594525830570E-09
-0.932140586670E-11
-0.102876055340E-12
-0.803701236210E-15
-0.439794973910E-17
-0.164147763550E-19
-0.396736195160E-22
-0.558273287210E-25
-0.346578420130E-28
range:     0.000,   1000.000, 10
 0.000000000000E+00
 0.586655087100E-01
 0.450322755820E-04
 0.289084072120E-07
-0.330568966520E-09
 0.650244032700E-12
-0.191974955040E-15
-0.125366004970E-17
 0.214892175690E-20
-0.143880417820E-23
0.359608994810E-27
```

Polynomial equations for voltage developed: Voltage developed in a thermocouple is a non-linear function of temperature. Normally a 5th or 7th or 9th order polynomial describes the voltage output. Following Table gives the polynomial coefficients (NBS) for a few types of thermocouples (Ref: www.omega.com):



	TYPE E	TYPE J	TYPE K	TYPE R	TYPE S	TYPE T
	Nickel-10% Chromium(+) Versus Constantan(-)	Iron(+) Versus Constantan(-)	Nickel-10% Chromium(+) Versus Nickel-5%(-) (Aluminum Silicon)	Platinum-13% Rhodium(+) Versus Platinum(-)	Platinum-10% Rhodium(+) Versus Platinum(-)	Copper(+) Versus Constantan(-)
	-100°C to 1000°C ± 0.5°C 9th order	0°C to 760°C ± 0.1°C 5th order	0°C to 1370°C ± 0.7°C 8th order	0°C to 1000°C ± 0.5°C 8th order	0°C to 1750°C ± 1°C 9th order	-160°C to 400°C ±0.5°C 7th order
a_0	0.104967248	-0.048868252	0.226584602	0.263632917	0.927763167	0.100860910
a_1	17189.45282	19873.14503	24152.10900	179075.491	169526.5150	25727.94369
a_2	-282639. 0850	-218614.5353	67233.4248	-48840341.37	-31568363.94	-767345.8295
a_3	12695339.5	11569199.78	2210340.682	1.90002E + 10	8990730663	78025595.81
a_4	-448703084.6	-264917531.4	-860963914.9	-4.82704E + 12	-1.63565E + 12	-9247486589
a_5	1.10866E + 10	2018441314	4.83506E + 10	7.62091E + 14	1.88027E + 14	6.97688E + 11
a_6	-1. 76807E + 11		-1. 18452E + 12	-7.20026E + 16	-1.37241E + 16	-2.66192E + 13
a_7	1.71842E + 12		1.38690E + 13	3.71496E + 18	6.17501E + 17	3.94078E + 14
a_8	-9.19278E + 12		-6.33708E + 13	-8.03104E + 19	-1.56105E + 19	
a_9	2.06132E + 13				1.69535E + 20	

TEMPERATURE CONVERSION EQUATION: $T = a_0 + a_1 x + a_2 x^2 + \ldots + a_n x^n$

NESTED POLYNOMIAL FORM: $T = a_0 + x(a_1 + x(a_2 + x(a_3 + x(a_4 + a_5 x))))$ (5th order)

where x is in Volts, T is in °C

Table 2.10 NBS polynomial coefficients for Thermocouples

Note: Polynomial equations should be used strictly within the temperature ranges indicated.

Thermocouple voltage vs temperature for different types of thermocouples is shown graphically in Fig. 2.10 below. From this graph, one can easily compare the sensitivities of different types of thermocouples:

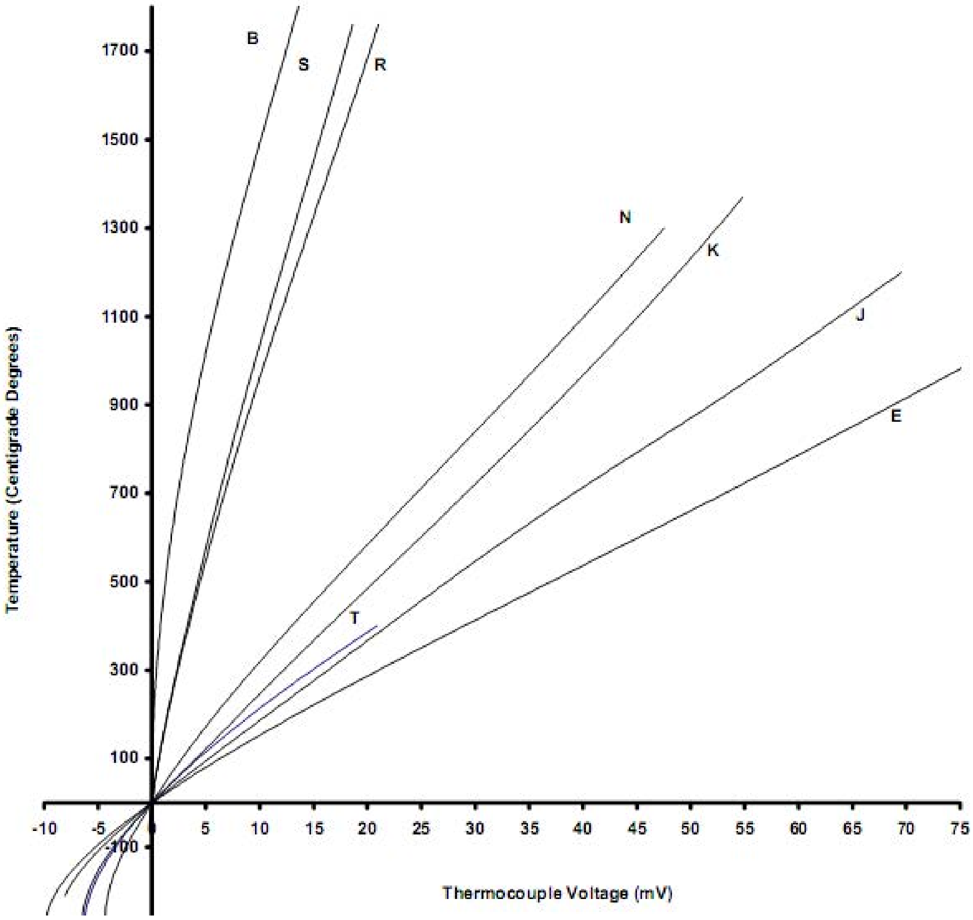


Fig. 2.10 Thermocouple voltage vs temperature for different types of thermocouples

Following problem is worked out in Mathcad:

Prob.2.10: EMF in a Thermocouple, with test junction at t deg.C on gas thermometer scale and reference junction at ice point is given by: $\varepsilon = 0.2*t - 5*10^{-4}\,t^2$, mV. The milli-voltmeter is calibrated at ice point and steam points. What will this thermometer read in a place where gas thermometer reads 50 deg. C? [M.U.]

Solution:

$\varepsilon(t) := 0.2\cdot t - 5\cdot 10^{-4}\cdot t^2$ ....define ε as a function of t

Therefore: $\varepsilon(0) = 0$ ...value of ε at t = 0 C

$\varepsilon(100) = 15$ ...value of ε at t = 100 C

$\varepsilon(50) = 8.75$ ...value of ε at t = 50 C

Then $T := \frac{100}{15}\cdot 8.75$ ...value of T at ε = 8.75 mV

i.e. T=58.333 C......Ans.

Problem 2.11: A temperature T on a thermometric scale is defined in terms of property P by the relation: T = a. ln(P) + b where a and b are constants. The temperatures at ice point and steam point are 0 deg.C and 100 deg.C respectively. Instrument gives values of P as 1.86 and 6.81 at ice and steam point respectively. Evaluate temperature corresponding to a reading of P = 2.5 [M.U.].

Here, we set up two equations from the given data and solve them simultaneously.

We use the 'Solve block' of Mathcad.

First, we write the trial values for a and b; then write the Solve block, i.e. type: Given, and below that write the two constraint equations; then write 'Find (a, b) =' ; then, values of a and b are given in a vector:

$a := 1$ $b := 1$ ...trial values

Given

$0 = a\cdot \ln(1.86) + b$

$100 = a\cdot \ln(6.81) + b$

$$\text{Find}(a,b) = \begin{bmatrix} 77.053 \\ -47.817 \end{bmatrix}$$

i.e. $a := 77.053$ $b := -47.817$

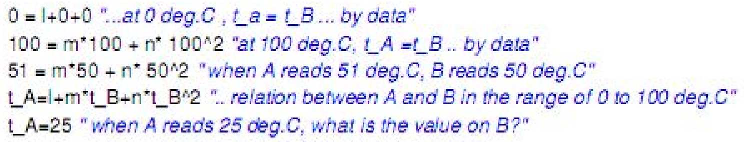
When p=2.5: $T(p) := a\cdot \ln(p) + b$

T(2.6)=25.808 C.....Ans.

Problem 2.12: The readings t_A and t_B of two Celsius thermometers A and B agree at the Ice point (0 deg.C) and Steam point (100 deg.C), but elsewhere are related by the equation: $t_A = l + m^* t_A + n^* t_B^2$, where l, m and n are constants. When both the thermometers are immersed in a well stirred oil bath, A registers 51 deg.C, while B registers 50 deg.C. Determine the reading on B when A reads 25 deg.C [M.U.]

This problem is now solved in EES:

First, enter the constraints in the 'Equation window'. See the comments against each line in the screen shot below. Next press F2 and the solution appears in the 'Solutions window'.



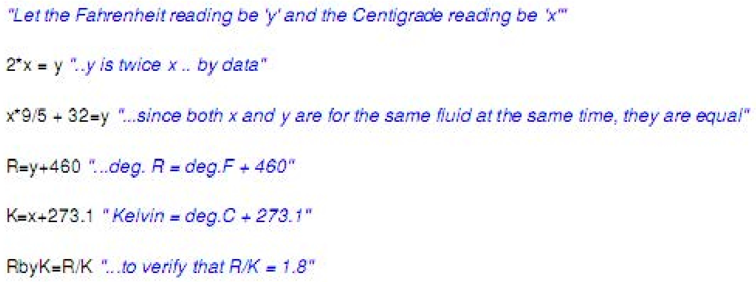
```
0 = l+0+0 "...at 0 deg.C , t_a = t_B ... by data"
100 = m*100 + n* 100^2 "at 100 deg.C, t_A =t_B .. by data"
51 = m*50 + n* 50^2 "when A reads 51 deg.C, B reads 50 deg.C"
t_A=l+m*t_B+n*t_B^2 ".. relation between A and B in the range of 0 to 100 deg.C"
t_A=25 "when A reads 25 deg.C, what is the value on B?"
```

```
SOLUTION
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
l = 0                  m = 1.04                  n = -0.0004                  tA = 25
tB = 24.26

No unit problems were detected.
```

We get the solution as: t_B = 24.26 deg.C when t_A = 25 deg.C

Problem 2.13: Fahrenheit and Centigrade thermometers are both immersed in a fluid. Fahrenheit reading is numerically twice that of the Centigrade reading. What is the temperature of the fluid expressed on degree Rankine and Kelvin?

This problem is also easily solved in EES. See the screen prints of 'Equation window' and 'Solution window' below. Read the comments against each eqn. in the Eqns. Window.



```
"Let the Fahrenheit reading be 'y' and the Centigrade reading be 'x'"

2*x = y "..y is twice x .. by data"

x*9/5 + 32=y "...since both x and y are for the same fluid at the same time, they are equal"

R=y+460 "...deg. R = deg.F + 460"

K=x+273.1 "Kelvin = deg.C + 273.1"

RbyK=R/K "...to verify that R/K = 1.8"
```

```
SOLUTION
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
K = 433.1                R = 780                  RbyK = 1.801                  x = 160
y = 320

No unit problems were detected.
```

Note the answers as: x = 160 deg.C, y = 320 deg.F;

R = 780 deg. Rankine; K = 433.1 K; (R/K = 1.8 …verified).

Problem 2.14: A Pt vs Pt-Rh thermocouple gave following readings during its calibration: at 630.74 C, emf = 5550 microvolts; at 961.93 C, emf = 9150 microvolts, and at 1064.3 C, emf = 10335 microvolts. If the polynomial relation between emf and temperature is emf = A.T + B.T^2 + C.T^3, determine the constants A, B and C. Also, find the temperature corresponding to an emf of 7300 microvolts.

Solution is done in EES.

In the Eqn. window, write the equations for the three temperatures as shown. Solving them simultaneously, one gets polynomial coefficients A, B and C. Then use the polynomial eqn. to get temperature corresponding to emf = 7300 microvolts. Press F2 to get solution. Results are shown below:

```
"We have:
emf = A.T + B.T^2 + C.T^3"
"From data:"
5550 = A*630.74 + B*(630.74)^2 + C*(630.74)^3 "...at 630.74 deg.C"
9150 = A*961.93 + B*(961.93)^2 + C*(961.93)^3 "...at 961.93 deg.C"
10335 = A*1064.3 + B*(1064.3)^2 + C*(1064.3)^3 "...at 1064.3 deg.C"
"When emf = 7300 microvolts:"
 7300 = A*T + B*T^2 + C*T^3  "....finds T in deg.C"

SOLUTION
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
A = 7.142                 B = 0.002938               C = -4.931E-07              T = 796.2

No unit problems were detected.
```

We note the results:

Polynomial coeffs: A = 7.142, B = 0.002938 and C=-4.931E-07, and
At emf = 7300 microvolts, Temperature T = 796.2 deg.C

2.7 Constant volume gas thermometer:

A constant volume thermometer, as the name implies, has a constant bulb volume and as the temperature is changed, pressure inside the bulb also will change. Temperature and pressure are related by the Perfect gas law, viz. P.V = m. R .T where P is the absolute pressure and T is the absolute temperature.

A schematic diagram of a constant volume thermometer is shown below:

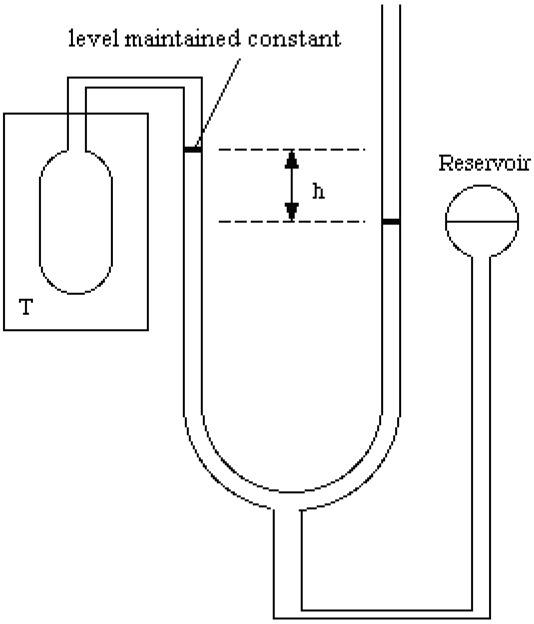


Fig. 2.11 Constant volume gas thermometer

Volume is maintained constant by maintaining the level at the mark as shown in Fig. above, by moving the reservoir up or down.

First, place the bulb in a bath maintained at a constant, known temperature of triple point of water (i.e. 273.16 K) and measure the pressure. Since RHS of manometer is open to atm. pressure, pressure inside the bulb is:

$$P_{TP} = P_{atm} - \rho \cdot g \cdot h \tag{2.7}$$

where pressures are Pa.

Now, place the bulb in the environment of the temperature to be measured (say, T Kelvin); maintain constant volume by maintaining the level in the manometer at the mark, and again measure the pressure = P, say.

Then, applying the Gas Law:

$$\frac{P}{P_{TP}} = \frac{T}{T_{TP}} = \frac{T}{273.16} \qquad \text{....(2.8)}$$

$$\text{i.e.} \qquad T = 273.16 \cdot \frac{P}{P_{TP}} \qquad \text{....(2.9)}$$

Problem 2.15: A constant volume gas thermometer is filled with Hydrogen gas. When it is brought in contact with a system at triple point of water, pressure reading is -175 mm Hg; when the same thermometer is brought in contact with a system at an unknown temperature of T, the pressure reading is -105 mm Hg. If barometric pressure is 750 mm Hg, what is the unknown temperature in Kelvin?

Solution: We shall solve this problem in EES:

Equations are entered in the Eqn. Window. Take care to see that pressures are absolute pressures, and temperatures are in Kelvin. Apply the Gas law, as indicated earlier.

Press F2 to get Solutions.

Screen shot of Equations and Solution window are shown below:

```
P_atm = 750 "mm Hg"
T_TP = 273.16 "K"
P_TP = P_atm -175 "mm Hg"
P_T = P_atm-105 "mm Hg"
P_T/P_TP = T/T_TP "...finds T in Kelvin"

SOLUTION
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
Patm  = 750               PT = 645               PTP  = 575               T  = 306.41
TTP  = 273.16

No unit problems were detected.
```

So, the result is: Unknown temperature, T = 306.41 K

2.8 Resistance Thermometer Detectors (RTD):

RTD's work on the principle that electrical resistances of many metals such as Platinum, Copper, Aluminium, Lead, Indium, Gold and Silver change with temperature.

Generally, Platinum is used because of its *advantages:*

i. it has a wide range and non-reactive upto high temperatures of around 850 deg. C,
ii. it has good accuracy
iii. it has good interchangeability
iv. it has long term stability
v. it can be drawn into wires
vi. it is not too soft
vii. it gives reproducible results, and
viii. it is not affected by corrosion and oxidation

Disadvantages of Pt are:

i. expensive
ii. influenced by lead wire resistance
iii. slow thermal response, and
iv. low resistance to shock and vibration

Pure Pt (99.99%) is used, since impurities in the resistor will affect the electrical resistance. Pt-resistance thermometers are known as PRT. According to the IEC and DIN Standards, temperature coefficient of the resistance wire must be 0.003850^0C^{-1} (i.e. mean resistance change referred to the nominal resistance at zero deg.C) and it should have a resistance of 100 ohms at 0 deg.C; so, it is known as PT-100. Its resistance changes approximately 0.4 ohms/degree C. Following graph shows the variation of resistance with temperature:

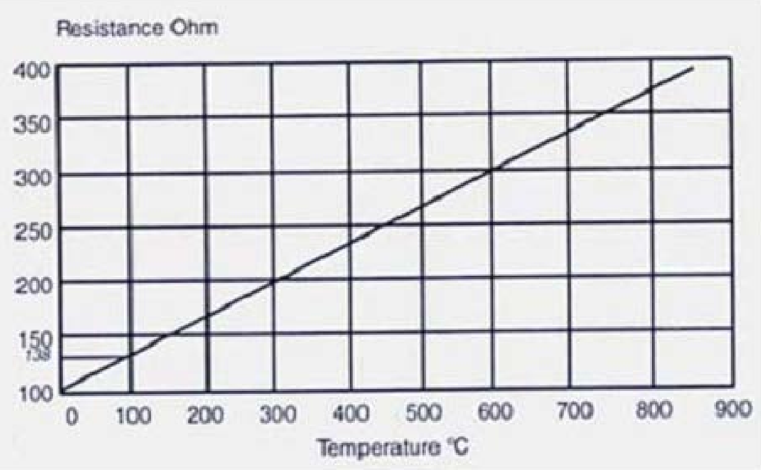


Fig. 2.12 Resistance – Temperature characteristics of Pt-100

For analytical calculations, the resistance – temperature characteristics is expressed as follows:

A third order polynomial in the temperature range (-200 deg.C to 0 deg.C):

$$R(t) = R_0 \cdot \left[\left(1 + A \cdot t + B \cdot t^2\right) + C \cdot (t - 100) \cdot t^3 \right] \qquad \text{....(2.10)}$$

A second order polynomial for the temperature range: (0 to 850 deg.C):

$$R(t) = R_0 \cdot \left(1 + A \cdot t + B \cdot t^2\right) \qquad \text{...(2.11)}$$

Here, constants A, B and C are given by:

$$A = 3.9083 \times 10^{-3}\ {}^{\circ}C^{-1}$$

$$B = -5.775 \times 10^{-7}\ {}^{\circ}C^{-2}$$

$$C = -4.183 \times 10^{-12}\ {}^{\circ}C^{-4}$$

Free software to quickly determine temperature for a given resistance and vice-versa:

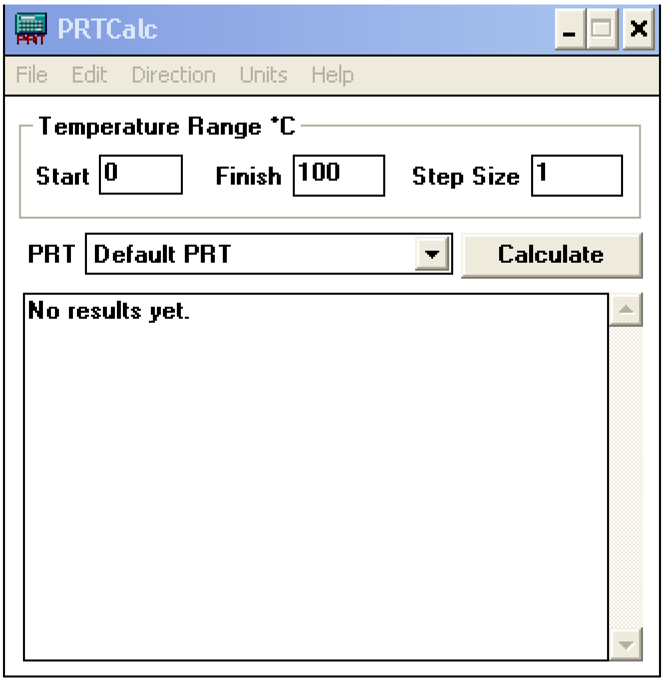
For those who use Pt 100 very often, there is a very versatile free software to make calculations, known as PRTCalc., available for download from http://www.isotech.co.uk/prtcalc/prtcalc.html. According to its supplier: "It allows for the accurate conversion of resistance to temperature or temperature to resistance. PRTCalc is a small utility that can sit on the desk top alongside other applications. The calculated results can easily be imported to spreadsheets or other applications for presentation, storage or whatever. Output data can also be saved as a text file".

Important features of PRTCalc are:

1. Can Generate Large Tables or Single Values
2. Convert Temperature to Resistance with high accuracy
3. Convert Resistance to Temperature to approx. 0.01°C
4. Allows very large lists of data
5. Output Can be Saved as a text file
6. Allows marking and copying of result data
7. Stores coefficients for user entered probes
8. Probe Management.
9. Unit Choice – *Celsius, Fahrenheit or Kelvin*

Using PRTCalc:

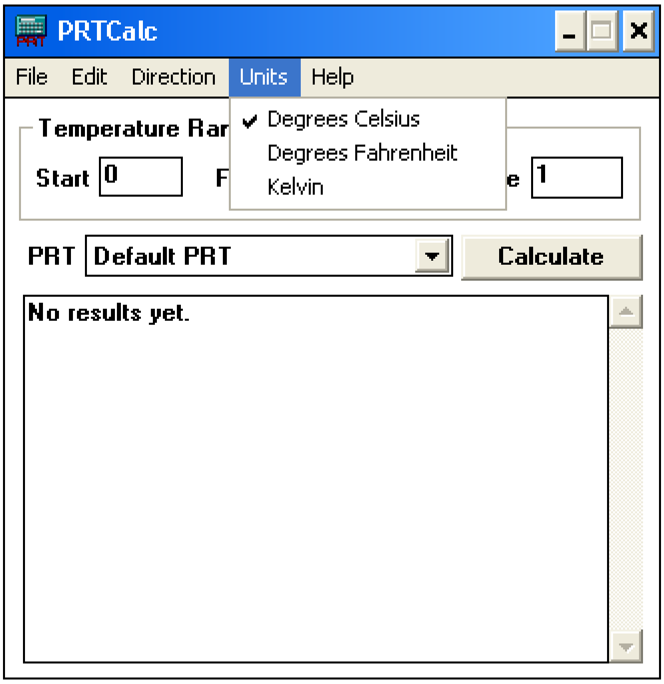
As you start PRTCalc, following screen is presented:



Start: 0
Finish: 100
Step Size: 1
PRT: Default PRT

No results yet.

Then, select °C, °F or Kelvin from the **Units** menu:



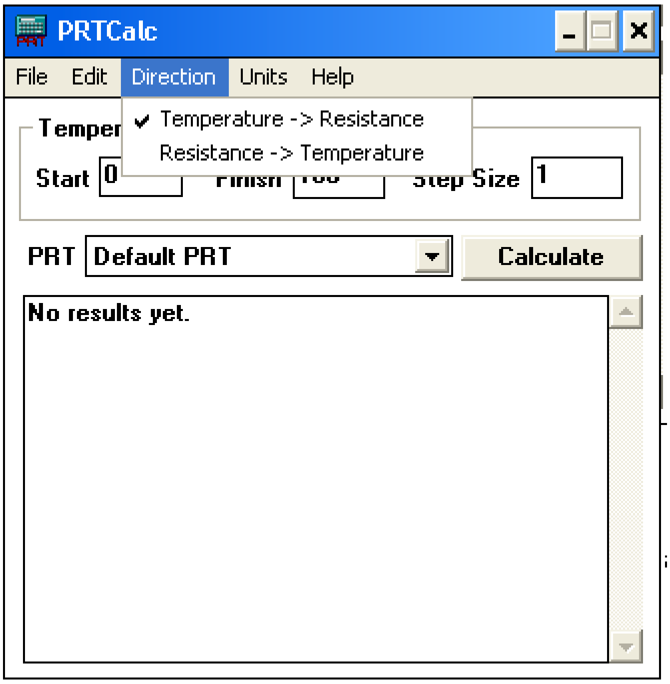
Start 0

e 1

PRT Default PRT

No results yet.

Choose between calculating from resistance to temperature or temperature to resistance from the **Direction** menu:



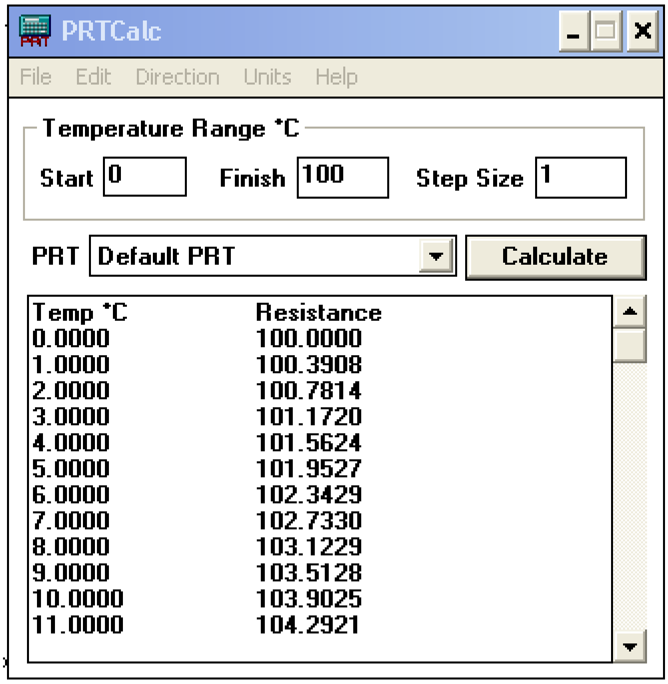
Start 0

Step Size 1

PRT Default PRT

No results yet.

Press **'Calculate'** and the table of Temp vs Resistance appears as shown:



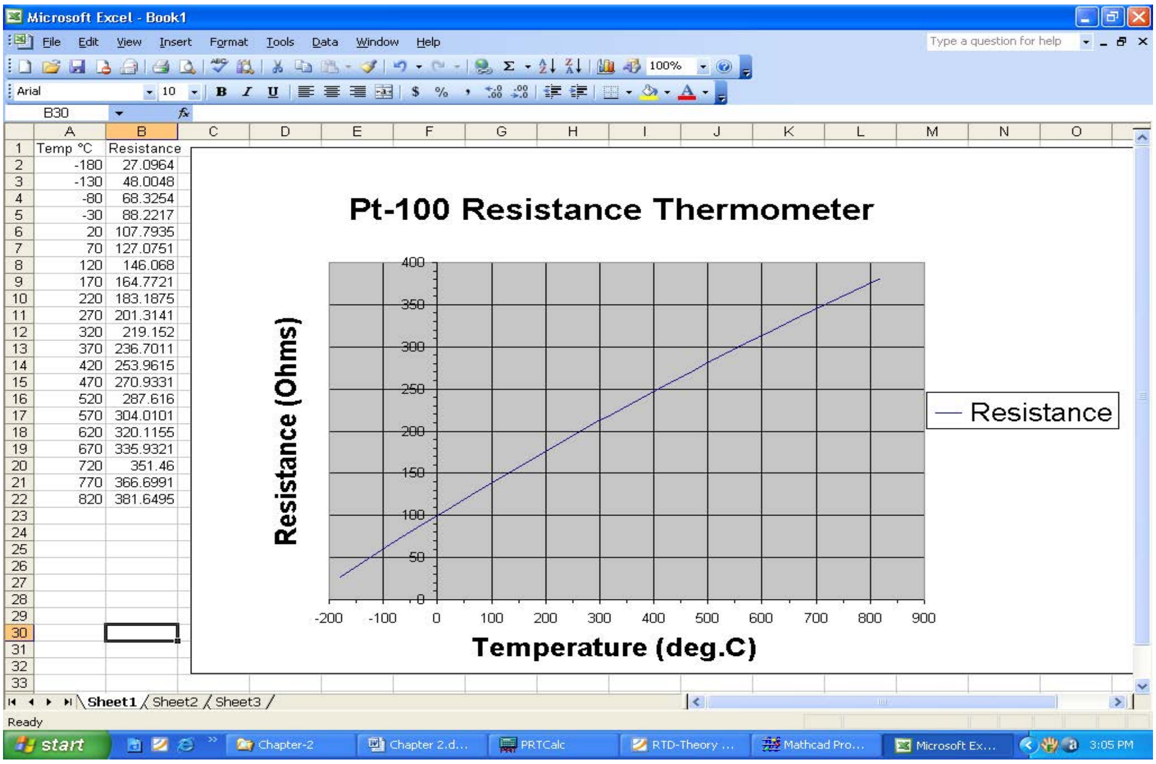
Temperature Range °C

Start 0
Finish 100
Step Size 1

PRT Default PRT

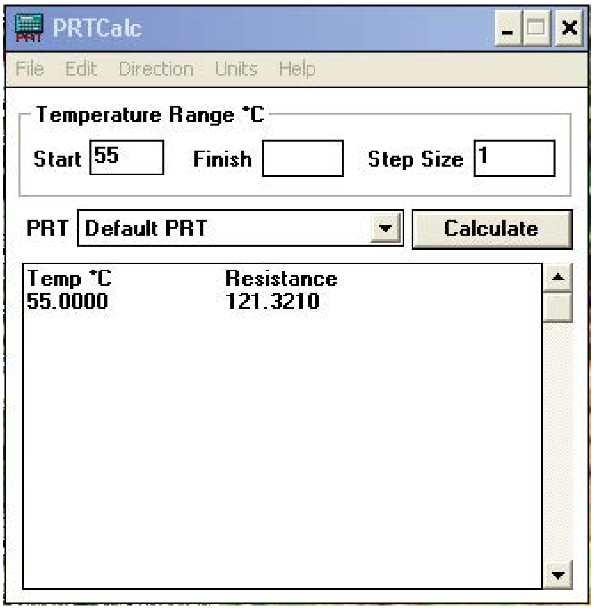
Temp °C	Resistance
0.0000	100.0000
1.0000	100.3908
2.0000	100.7814
3.0000	101.1720
4.0000	101.5624
5.0000	101.9527
6.0000	102.3429
7.0000	102.7330
8.0000	103.1229
9.0000	103.5128
10.0000	103.9025
11.0000	104.2921

Use the **Edit** menu to copy data to the clipboard; the data can then be pasted into a spreadsheet to produce a graph. As an example, values of resistances are calculated in the temperature range -180 deg.C to 820 deg.C and the table produced is copied to Excel; then, the Temperature vs Resistance chart is produced in Excel, and is shown below:



Temp °C	Resistance
-180	27.0964
-130	48.0048
-80	68.3254
-30	88.2217
20	107.7935
70	127.0751
120	146.068
170	164.7721
220	183.1875
270	201.3141
320	219.152
370	236.7011
420	253.9615
470	270.9331
520	287.616
570	304.0101
620	320.1155
670	335.9321
720	351.46
770	366.6991
820	381.6495

If you wish to calculate a single value only, say the value of resistance at 55 deg.C, then, leave the Finish box empty, and click on 'Calculate'; you read the resistance as 121.321 ohms.:



Start 55
Finish
Step Size 1
PRT Default PRT

```
Temp °C        Resistance
55.0000        121.3210
```

Note: You can run multiple copies of PRTCalc simultaneously to see the effects of different coefficients or for multiple thermometers.

Problem 2.16: A Pt-100 RTD shows a resistance of 38.6 ohms. Find out the temperature.

We shall solve this problem in Mathcad.

Since the resistance is less than 100 ohms, temperature is less than 0 deg.C, and we use the eqn:

$$R(t) = R_0 \cdot \left[\left(1 + A \cdot t + B \cdot t^2 \right) + C \cdot (t - 100) \cdot t^3 \right] \quad \text{....(2.10)}$$

where $R_0 := 100$ ohms

$A := 3.9083 \cdot 10^{-3}$ deg.C/C

$B := -5.775 \cdot 10^{-7}$ deg.C/C^2

$C := -4.183 \cdot 10^{-12}$ deg.C/c^4

We use the 'Solve block' to solve this. First, assume a trial value for temperature, say -10 deg.C. Then, type Given, and under 'Given' write the constraint eqn. i.e. R(t) is equal to 38.6 ohms. Now, simply type 'Find(t) =' and the answer appears immediately as -152.694 deg.C

$t := -10$ deg.C......trial value

Given

$$38.6 = R_0 \cdot \left[\left(1 + A \cdot t + B \cdot t^2 \right) + C \cdot (t - 100) \cdot t^3 \right]$$

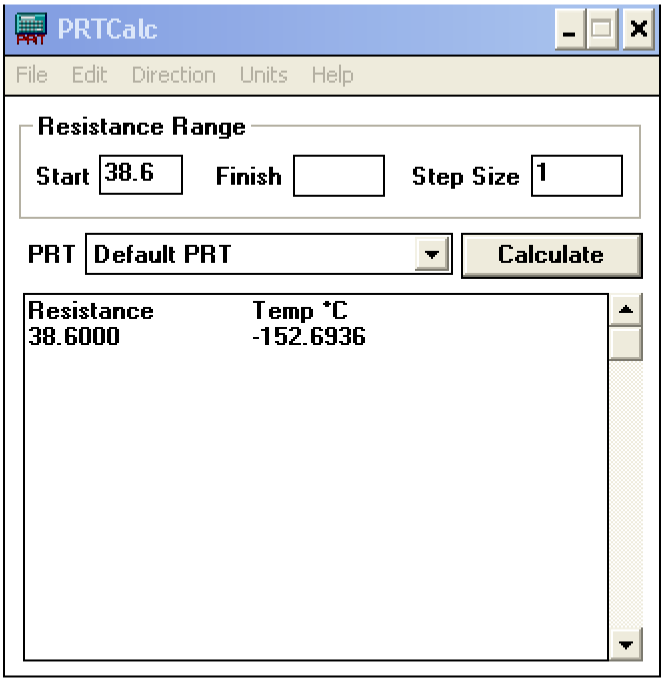
$\text{Find}(t) = -152.694$

Now, the same problem can be solved quickly in PRTCalc.

First choose 'Resistance to Temperature' from the **Direction** menu.

Then, enter Resistance = 38.6 and click on 'Calculate'.

Immediately, answer appears: T = -152.6936 deg.C. This matches with the value of T calculated in Mathcad. Screen shot of PRTCalc is shown below:

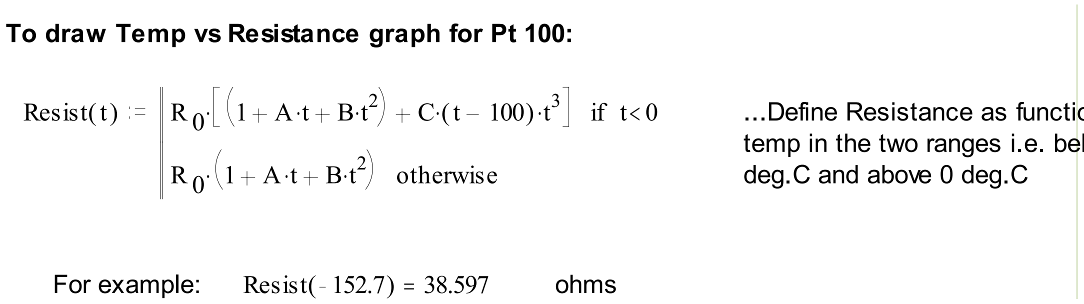


Start 38.6 Finish Step Size 1

PRT Default PRT

```
Resistance          Temp °C
38.6000             -152.6936
```

Finally, let us produce a **graph of Temperature vs Resistance** for Pt-100 thermometer, in Mathcad, in the temperature range: -200 deg.C to 850 deg.C:



To draw Temp vs Resistance graph for Pt 100:

$$\text{Resist}(t) := \begin{array}{|l} R_0\cdot\left[\left(1+A\cdot t+B\cdot t^2\right)+C\cdot(t-100)\cdot t^3\right] \ \text{ if } \ t<0 \\ R_0\cdot\left(1+A\cdot t+B\cdot t^2\right) \ \text{ otherwise} \end{array}$$

...Define Resistance as function of temp in the two ranges i.e. below 0 deg.C and above 0 deg.C

For example: $\text{Resist}(-152.7) = 38.597$ ohms

In the above, we first define a function to calculate resistance for any temperature. Since there are two different equations to determine the resistance depending on the temperature range, we have written a small Mathcad program using 'if…otherwise' construct. First line in the above program gives the value of resistance if the temperature 't' is less than 0 deg.C and the next line gives the value of resistance 'otherwise' i.e. if the value of temperature is more than 0 deg.C. To check the working of the program, resistance at -152.7 deg.C is calculated, which is 38.597 ohms, same value obtained earlier.

Next, to draw the graph, first define a range variable ‘t’ to vary from -200 deg.C to 850 deg.C with an increment of 5 deg.C. Then, from the ‘Insert’ menu in Mathcad, click ‘graph-x-y plot’ and a blank plot appears with one ‘place holder’ on the x-axis and another ‘place holde’r on the y-axis. On the x-axis place holder type ‘t’ and on the y-axis place holder type ‘Resist(t)’ and the graph appears immediately. To format the graph for grid lines, titles, axis limits etc, double click on the graph and the formatting menu table appears where the choices can be selected. The Mathcad worksheet with graph is shown below:

$t := -200, -195 .. 850$ ...define a range variable t from -200 C to 850 C with an increment of 5 deg.C

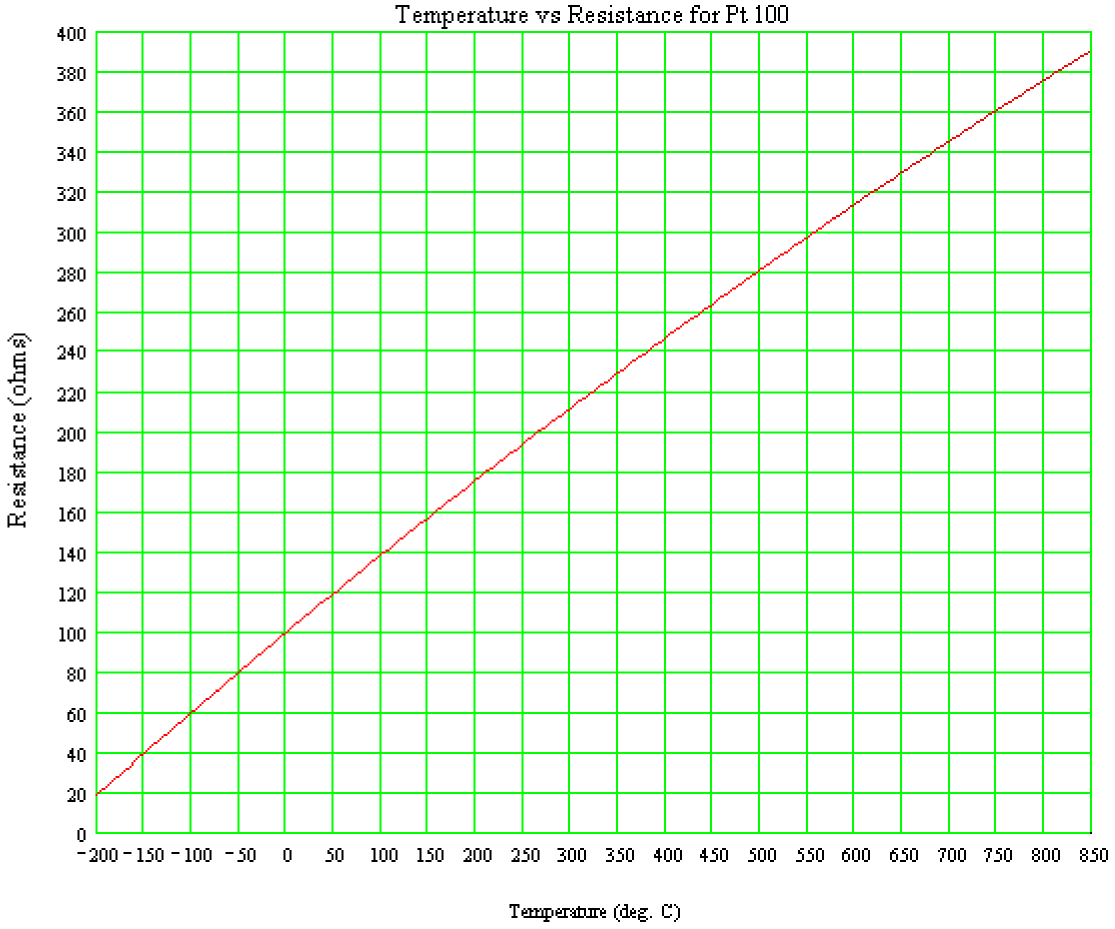


Fig. 2.1 Pt 100 Resistance Thermometer characteristics

2.9 Summary:

In this chapter, we first described the International System of Units (i.e. SI Units). Unit conversion examples were worked out using Uconeer and the Unit converter of TEST software. Then, we discussed about the pressure measurement with manometers and worked out some examples using Mathcad as well as EES. One example on 'curve fitting' with EES was also explained. Temperature measurement with Thermocouples was explained next. Details regarding different types of thermocouples were given. Problems were worked out using both Mathcad and EES. Next, constant volume gas thermometer was described and a problem was worked out using EES. Finally, RTD's and Pt resistance thermometer were explained; a versatile, free software viz. PRTCalc to make calculations in connection with Pt-100 was introduced and a problem was worked out in Mathcad and verified with PRTCalc. Finally, Temperature vs Resistance characteristics for Pt-100 thermometer were drawn in Mathcad.

2.10 References:

1. Y.A. Cengel and M.A. Boles. Thermodynamics – An Engineering Approach. 4th ed. New Delhi: Tata McGraw-Hill, 2003
2. I. Granet and M. Bluestein. Thermodynamics and Heat Power. 6th ed. Delhi: Pearson Education Asia, 2001
3. C.P.Arora. Thermodynamics. New Delhi: Tata McGraw-Hill, 1998
4. http://srdata.nist.gov/its90/main/
5. www.efunda.com
6. http://www.minco.com/tools/sensorcalc/
7. www.temperatures.com
8. www.omega.com
9. www.peaksensors.com
10. www.dataforth.com
11. www.picotech.com
12. www.maxim-ic.com
13. http://www.isotech.co.uk/prtcalc/prtcalc.html

3 Properties Of Pure Substances

Learning objectives:

1. In this chapter, we study about 'pure substances' i.e. substances which have a fixed chemical composition throughout.
2. Various property diagrams are explained, with particular reference to water.
3. Use of EES, TEST and many 'free' and online software to determine properties and plot property diagrams for different substances is demonstrated.
4. Methods of finding out property values and generating property tables are also shown using different software.
5. Determination of dryness fraction (or quality) of steam with **'throttling calorimeter'** as well as **'separating and throttling calorimeter'** is explained.

3.1 Introduction:

A substance may exist in solid, liquid or gaseous state, and a *'pure substance'*, by definition, is homogeneous and has the same chemical composition in all the states. For example, water has the same chemical composition whether it exists as ice (i.e. solid), or liquid water or steam (i.e. gaseous state). Sometimes, a mixture of gases, such as air is also treated as *pure substance* as far as it does not change phase. (When air changes phase, it has different compositions in gaseous and liquid phases).

In engineering, we frequently use water, air and refrigerants as important working substances. Water/steam is used in boilers, turbines and power plants. Air is used in Internal combustion engines and in numerous other applications. Many different types of refrigerants are in use in refrigeration and air-conditioning applications.

We shall study the properties of simple, compressible systems (i.e. systems where surface effects, magnetic effects and electrical effects are insignificant), where changes in pressure (P), volume (v) and temperature (T) are important. While studying the properties of pure substances, it is worthwhile to remember the 'State principle', which states as follows: ***'For a simple, compressible substance specifying the values of any two independent, intensive properties will fix the values of all of the others'.*** *Here, the term 'independent' is important. Thus, for example, pressure (P) and temperature (T) are two independent properties for liquid water or gaseous steam, and given P and T fix the state for liquid water or gaseous steam. But, when the water is boiling, P and T are dependent on each other; so, one more independent property such as 'quality' is to be specified to fix the state.*

We shall present our discussion mainly for water, but in general, the principles are valid for other fluids too.

3.2 Property diagrams for Water:

Following are the important property diagrams: P-v, T-v, P-T (or phase diagram), T-s and h-s. Of these, T-s and h-s diagrams are very useful in analyzing power cycles and refrigeration cycles.

Some sample diagrams are shown below:

3.2.1 T-v diagram: (Ref: 1)

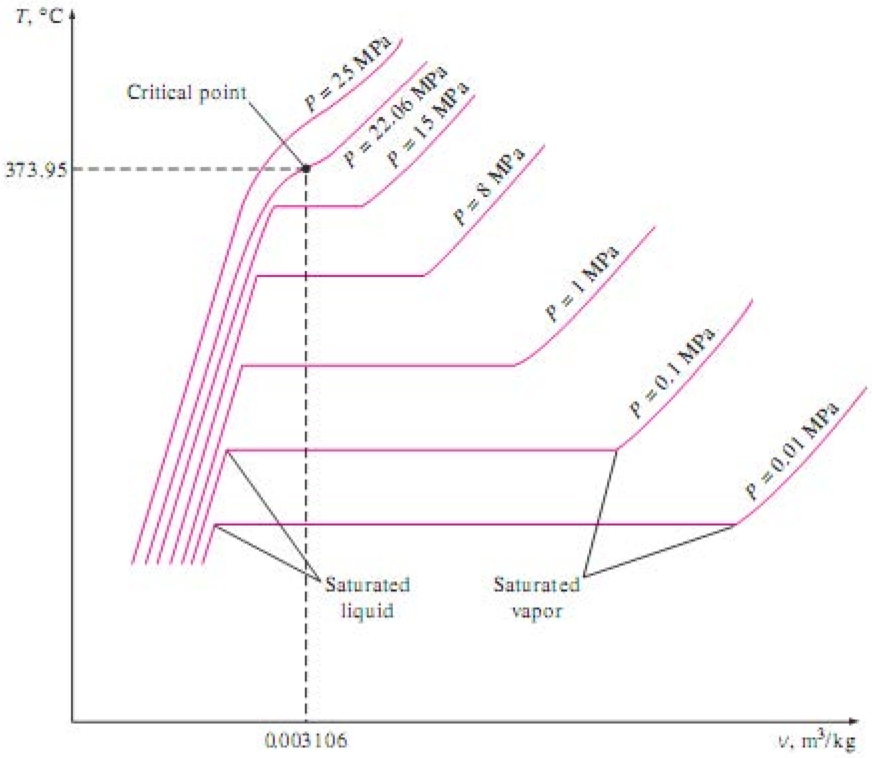


Fig. 3.1 T-v diagram for Water at different pressures

Note that with increasing pressures, the two phase region becomes shorter and shorter and at a 'critical pressure' of 22.06 MPa, it is just a point. This is called 'critical point' and the value of 'critical temperature' is 373.95 K.

Locus of points such as 3 and 5 give the 'saturated liquid line' and 'saturated vapour line' as shown below. Both these lines meet at the critical point.

3.2.2 P-v diagram: (Ref: 1)

Note the various regions and the nature of constant temperature lines in the following P-v diagram.

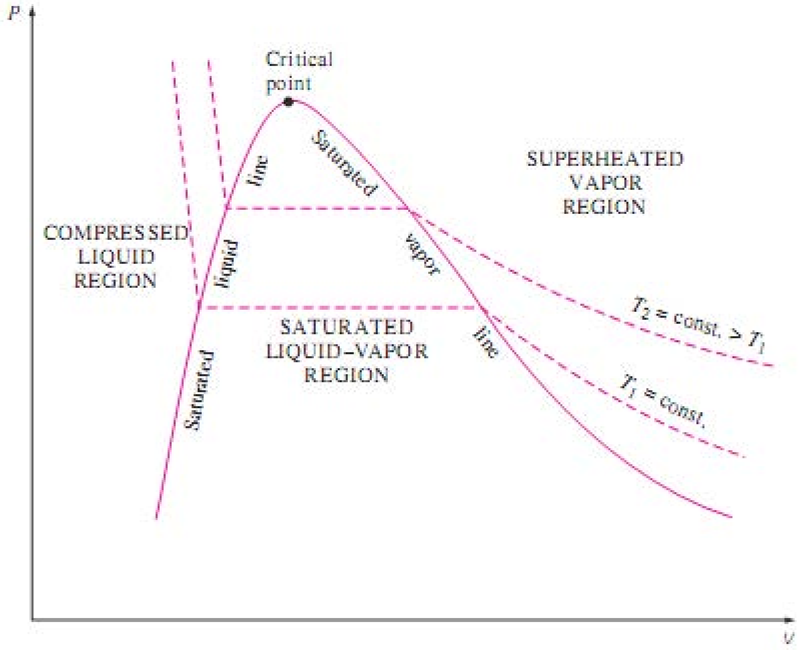


Fig. 3.2 P-v diagram for Pure substance

It is a ***specialty with water*** that as it freezes, the volume increases, whereas for most of other substances, volume decreases as temperature decreases.

If the solid region is also included, P-v diagram for water (which *expands* on freezing) will appear as follows:

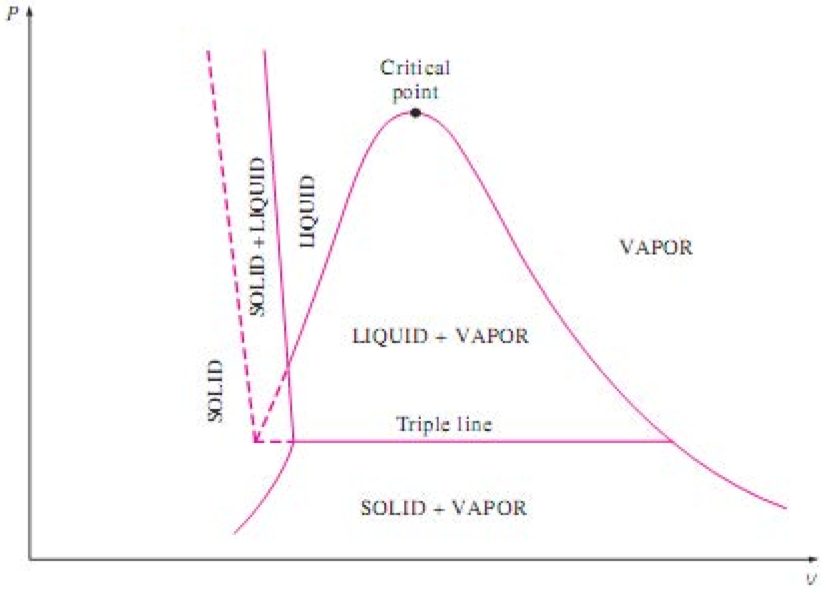


Fig. 3.3 P-v diagram for water (which expands on freezing)

And for substances which *contract* on freezing, P-v diagram will be as follows:

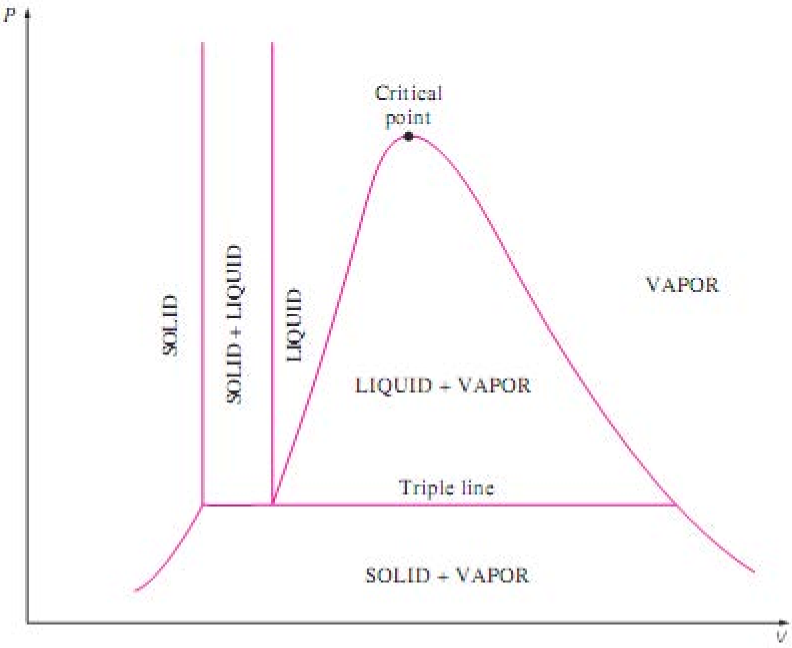
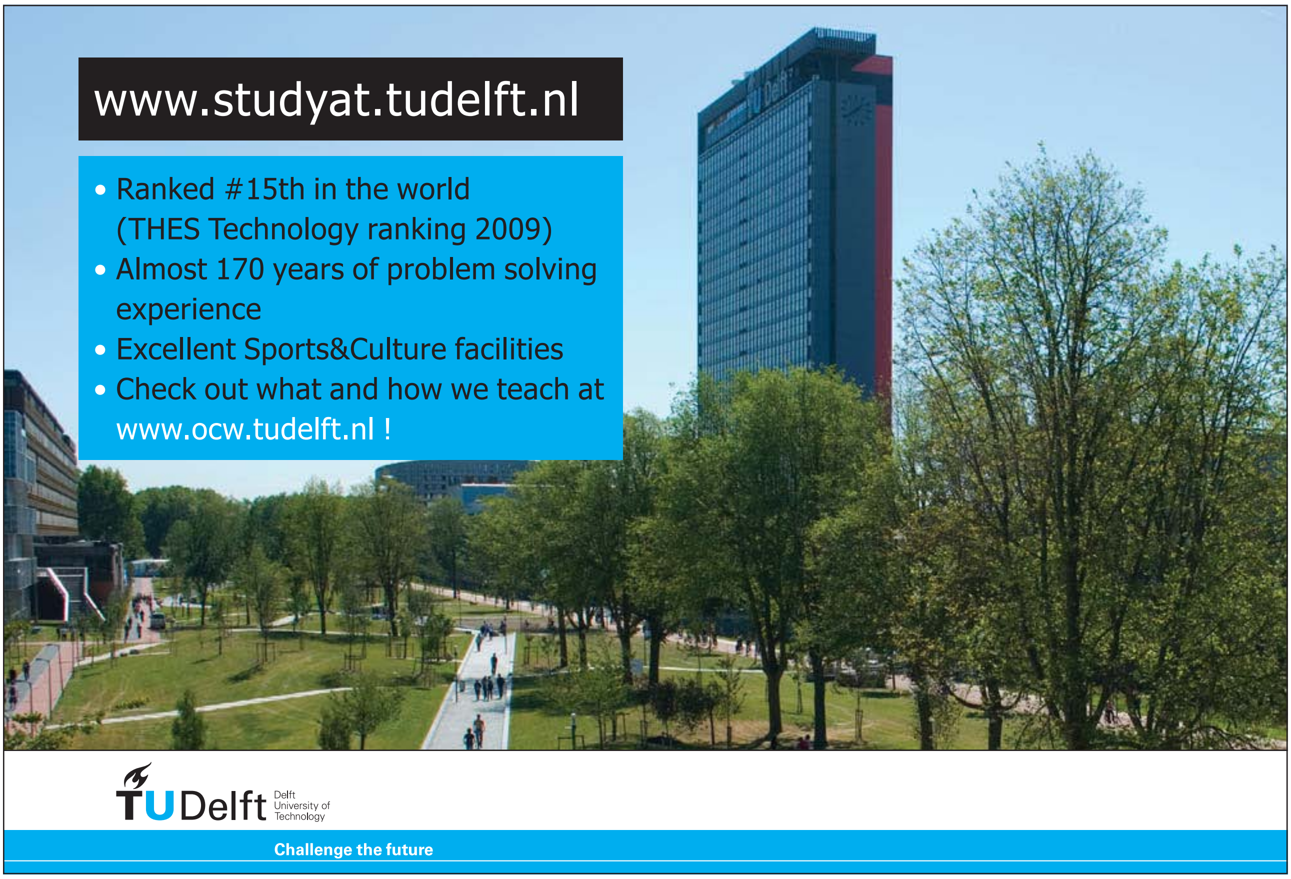


Fig. 3.4 P-v diagram for substances which contract on freezing



3.2.3 P-T diagram (or, Phase diagram): [Ref:12]

A pressure-temperature diagram is called a 'phase diagram' since all the three phases of a substance are shown therein.

P-T diagram for water, which expands on freezing, is shown below; all the three phases are shown and also the melting or fusion (from solid to liquid), vaporization (from liquid to vapor) and sublimation (from solid to vapor) lines are shown. C is the critical point. And, T is the triple point, where all the three phases are present. Note that for water, melting line has a negative slope.

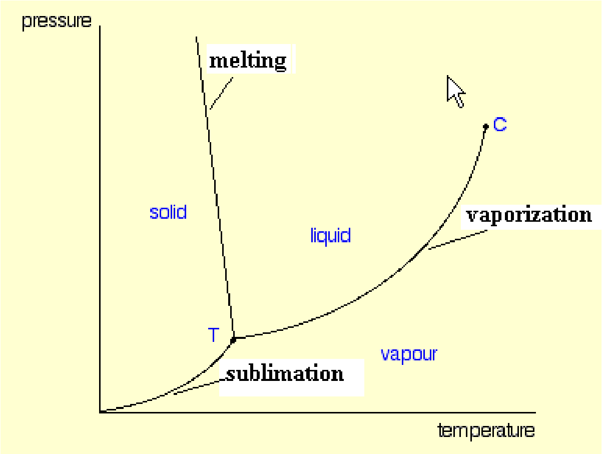


Fig. 3.5a. P-T diagram for water

Following diagram indicates the Triple point, critical point, normal melting point and normal boiling point parameters for water:

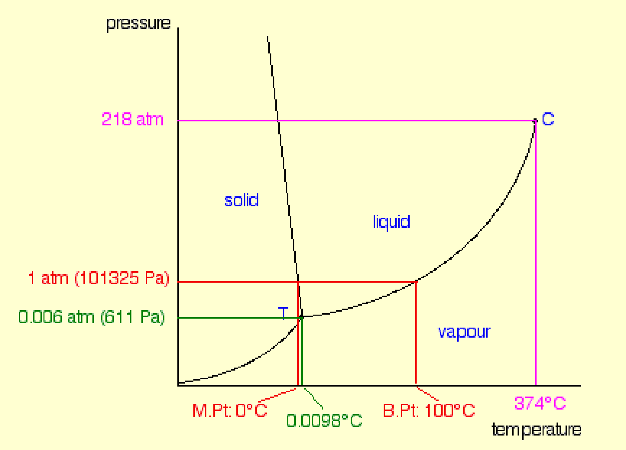


Fig. 3.5b. P-T diagram for water

Note that for water, as a consequence of negative slope of the melting line, freezing temperature decreases with an increase in pressure; also, at a temperature below the Triple point, as the pressure is increased vertically along the constant temperature line, vapor will first become a solid and then liquid! At a temperature above the critical temperature, it is impossible to condense a vapor into liquid by increasing the pressure.

For a substance **other than water**, i.e. which *contracts* on freezing, the phase diagram will look as follows:

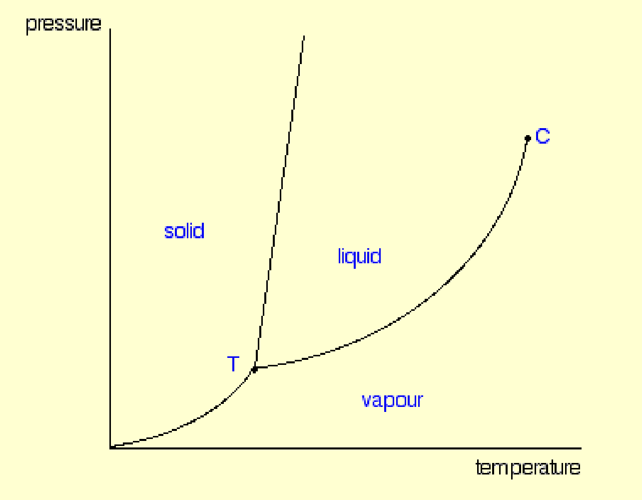


Fig. 3.6 P-T diagram for a substance which contracts on freezing

Note that in the above fig. melting line has a positive slope. As a consequence, freezing temperature increases with an increase in pressure; also, at a temperature below the triple point, as the pressure is increased vertically along the constant temperature line, vapor will first become a solid and will not become a liquid!

For water, values corresponding to the sublimation curve are given below:

***T* (K)**	***P* (mm Hg)**	***T* (K)**	***P* (mm Hg)**	***T*(K)**	***P* (mm Hg)**
190	0.00025	261	1.632	271	3.880
200	0.0012	262	1.785	272	4.217
210	0.0053	263	1.950	272.5	4.40
220	0.026	264	2.131	273	4.579
230	0.074	265	2.326		
240	0.25	266	2.537		
245	0.351	267	2.765		
250	0.58	268	3.103		
255	0.939	269	3.280		
260	1.49	270	3.568		

Table 3.1 Vapor pressure of Ice

Similarly, vaporization curve for water is a plot of vapor pressure against temperature. Values of P and T for vaporization curve of water are shown below in Table 3.2.

***T* (K)**	***P*(kPa)**	***T* (K)**	***P* (kPa)**	***T* (K)**	***P* (*kPa*)**
273	0.6105	310	6.2751	370	90.9349
274	0.6567	320	10.6124	371	94.2947
275	0.7058	330	17.3079	372	97.7570
280	1.0016	340	27.3257	373	101.3247
290	1.9372	350	41.8764	374	105.0004
300	3.5650	360	62.4974	375	108.7721

Table 3.2 Vapor pressure of Water

Note: Triple point: 273 K, Normal boiling point: 373 K, Critical point: 674 K.

Vapor pressure of water is represented graphically in Fig. 3.7 below:

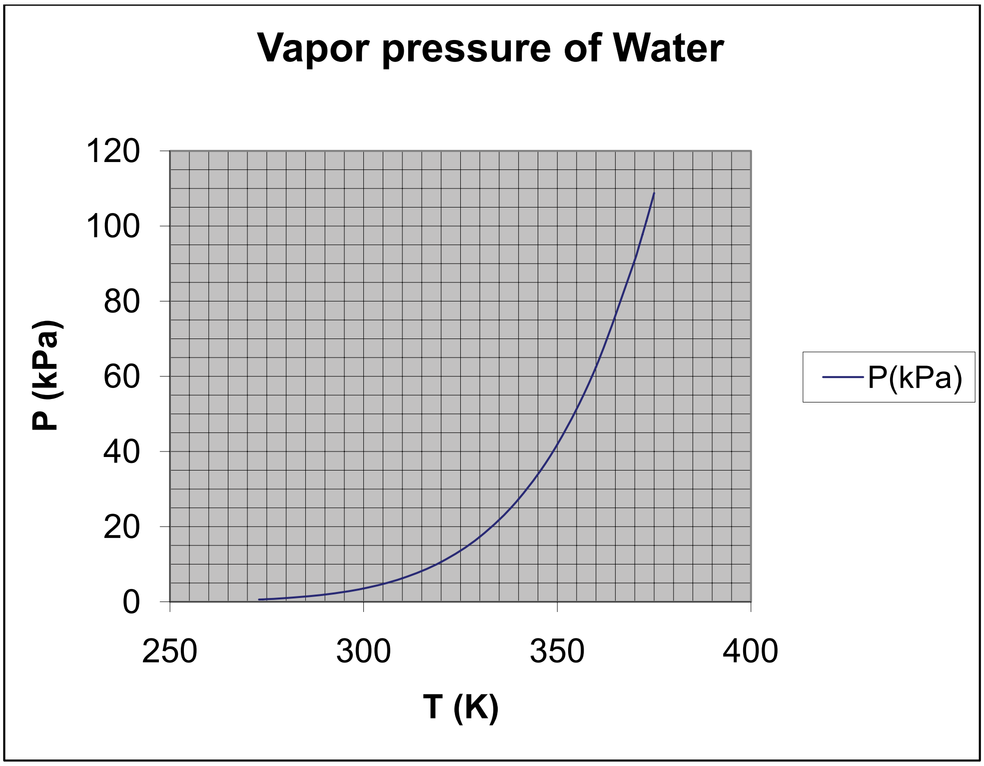


Fig. 3.7 Vapor pressure curve for Water

3.2.4 P-v-T surface [Ref: 11]:

P-v-T surface for water (which *expands* on freezing) is shown in Fig. 3.8. It may be observed that other diagrams such as T-v and P-v diagrams described above are the projections of this three-dimensional P-v-T surface on respective coordinate planes. Note that single phase regions appear as curved surfaces on the P-v-T surface, and the two phase regions are surfaces perpendicular to the P-T plane.

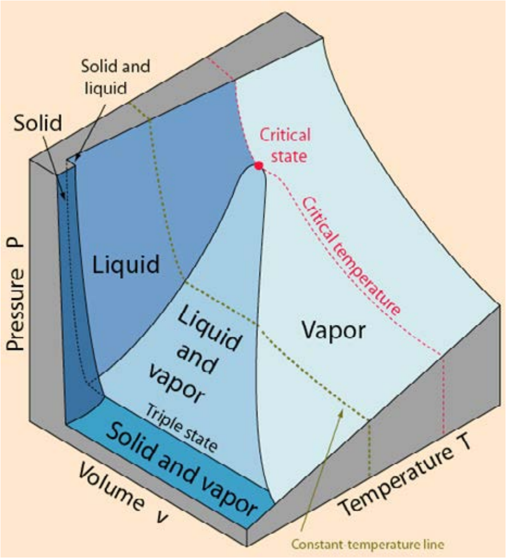


Fig. 3.8 P-v-T surface for Water

For a substance that *contracts* on freezing, the P-v-T surface will be as shown in Fig. 3.9 below:

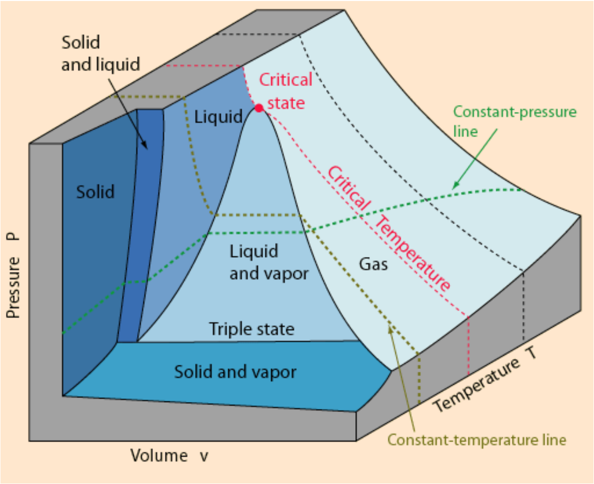


Fig. 3.9 P-v-T surface for a substance that contracts on freezing

3.3 Property Diagrams from Software:

Property diagrams can be obtained very accurately and conveniently from software like EES and TEST. EES gives presentation quality property diagrams for several fluids with just a few clicks of the mouse, whereas TEST gives property diagrams which are indicative while solving the problems or determining the states. However, TEST also gives 'plot data' which can be copied to a spreadsheet like EXCEL and then good quality diagrams can be drawn. We shall illustrate the use of EES as well as TEST to draw a few representative property diagrams.

3.3.1 Property diagrams using EES:

It is very easy and convenient to draw property diagrams using EES.

As you start EES, welcome screen appears; dismiss it and, then, from the 'Plot' menu, choose 'Property plot' as shown below:

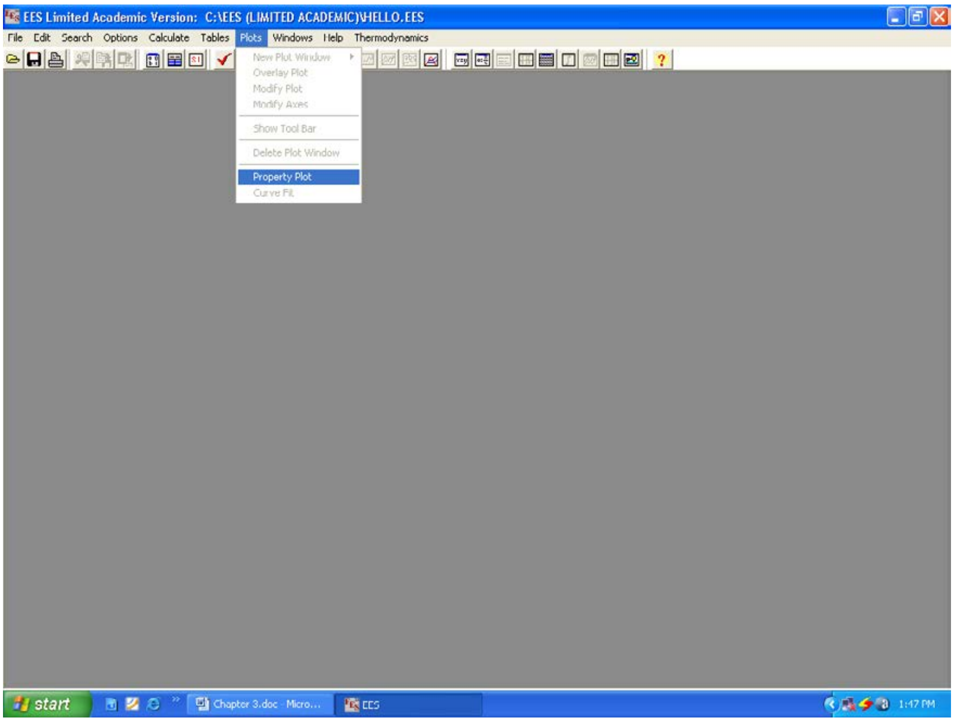
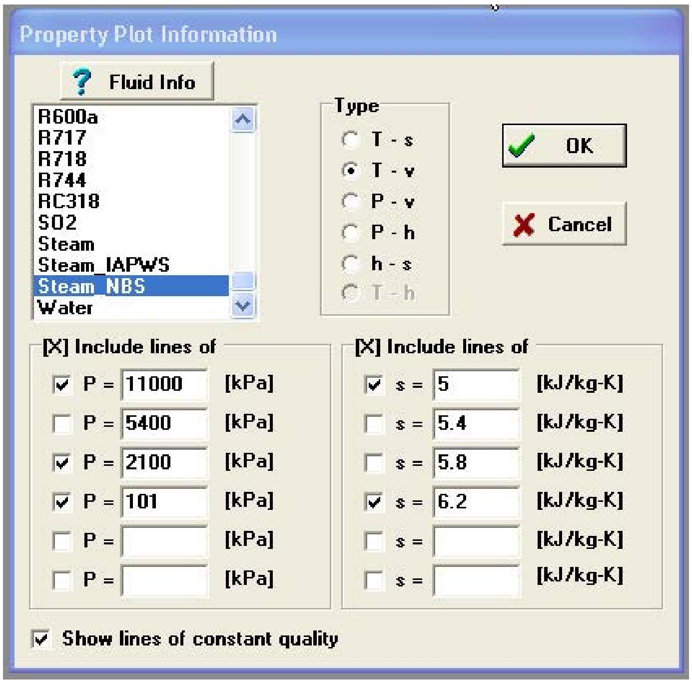


Fig. 3.10a. Drawing Property plot with EES

Then, the 'Property plot information' window appears. Here, you choose the fluid (Steam_NBS), Type of plot (say, T-v plot), and constant pressure, entropy and quality lines, as shown below in Fig. 3.10 b.



Property Plot Information

Fluid Info

R600a
R717
R718
R744
RC318
SO2
Steam
Steam_IAPWS
Steam_NBS
Water

Type
○ T - s
● T - v
○ P - v
○ P - h
○ h - s
○ T - h

OK
Cancel

[X] Include lines of
☑ P = 11000 [kPa]
☐ P = 5400 [kPa]
☑ P = 2100 [kPa]
☑ P = 101 [kPa]
☐ P = [kPa]
☐ P = [kPa]

[X] Include lines of
☑ s = 5 [kJ/kg-K]
☐ s = 5.4 [kJ/kg-K]
☐ s = 5.8 [kJ/kg-K]
☑ s = 6.2 [kJ/kg-K]
☐ s = [kJ/kg-K]
☐ s = [kJ/kg-K]

☑ Show lines of constant quality

Fig. 3.10b. Drawing Property plot with EES

Click OK and the T-v plot appears immediately. Format the graph for scale, captions, gridlines etc. by 'right clicking' on the item to be formatted and a presentation quality graph is produced as shown below:

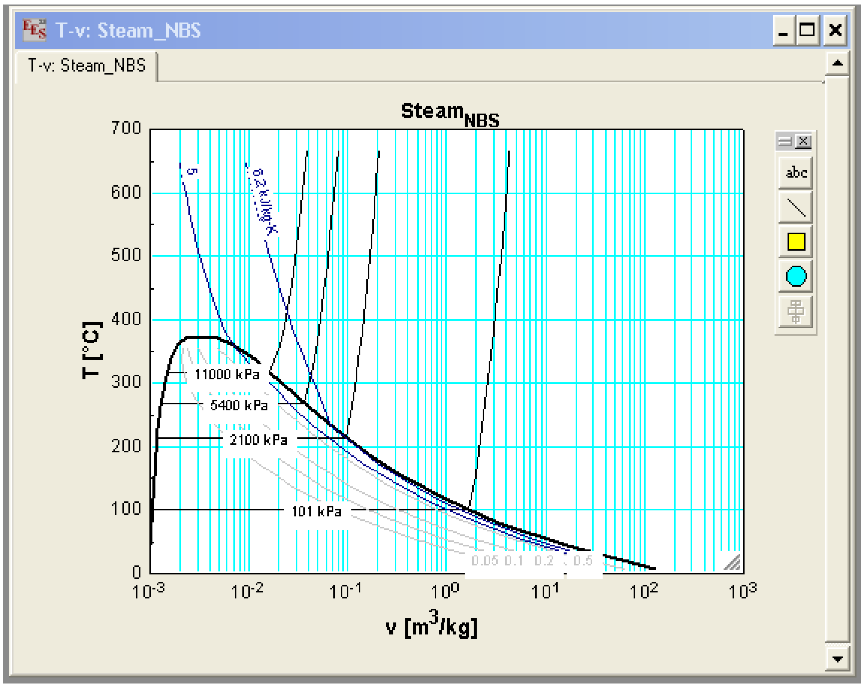


Fig. 3.10c. Drawing Property plot with EES

In a similar manner, P-v diagram for Water (i.e. Steam_NBS) is drawn, and the same is shown below:

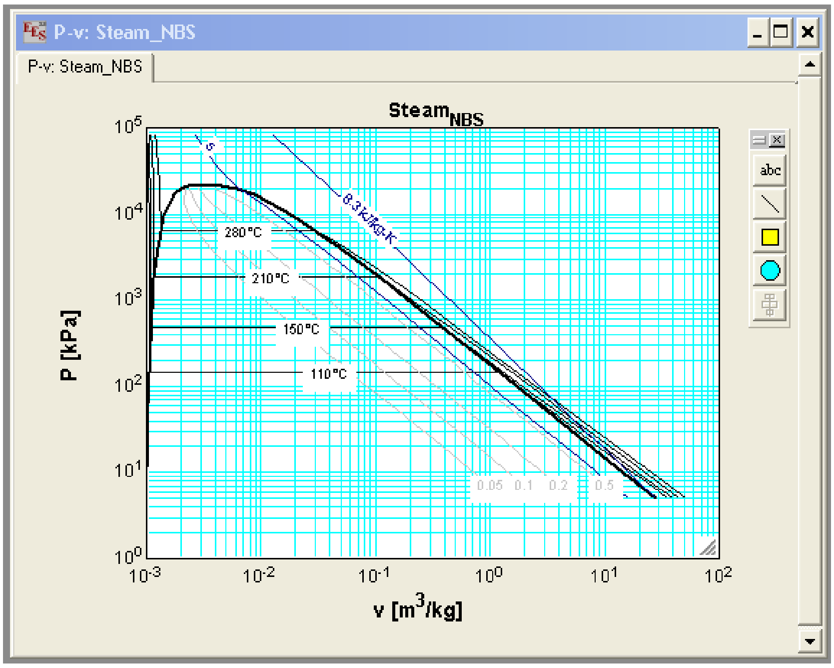
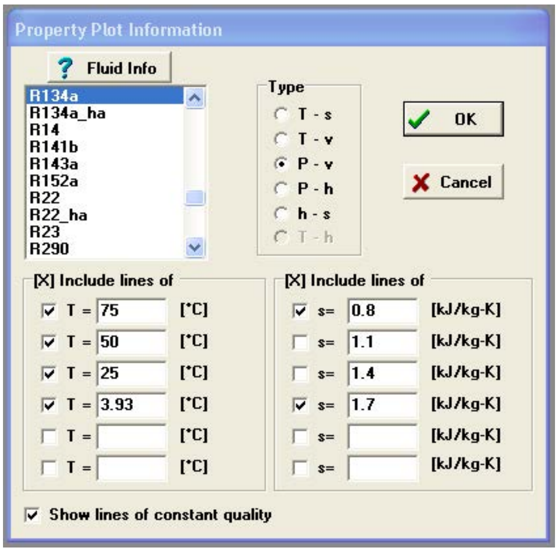


Fig. 3.11 P-v plot for Steam with EES

If we wish to draw Property plot for, say R134a refrigerant, follow a similar procedure. Select the fluid as 'R134a' in the property plot info window; choose the type of plot (say, P-v plot), choose the lines of constant temperature, entropy and quality and click OK.



R134a
R134a_ha
R14
R141b
R143a
R152a
R22
R22_ha
R23
R290

Type
○ T - s
○ T - v
● P - v
○ P - h
○ h - s
○ T - h

[X] Include lines of
☑ T = 75 [°C]
☑ T = 50 [°C]
☑ T = 25 [°C]
☑ T = 3.93 [°C]
☐ T = [°C]
☐ T = [°C]

[X] Include lines of
☑ s= 0.8 [kJ/kg-K]
☐ s= 1.1 [kJ/kg-K]
☐ s= 1.4 [kJ/kg-K]
☑ s= 1.7 [kJ/kg-K]
☐ s= [kJ/kg-K]
☐ s= [kJ/kg-K]

☑ Show lines of constant quality

Fig. 3.12a. Drawing P-v plot for R134a with EES

The plot appears immediately. Format the plot by 'right clicking' on the item to be formatted and the plot produced is shown below:

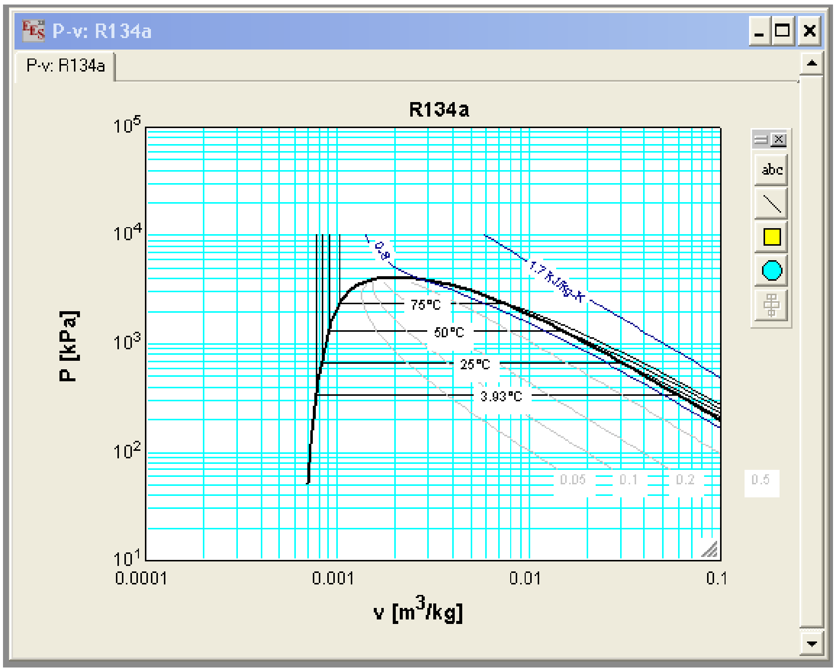


Fig. 3.12b. Drawing P-v plot for R134a with EES

Other three property plots which are very much useful are: Temperature-Entropy (T-s), Enthalpy-Entropy (h-s), and Pressure-Enthalpy (P-h) diagrams. Of these, (T-s) and (h-s) or Mollier diagrams are used in connection with steam cycles and the (P-h) diagram is used to analyze refrigeration cycles. We shall, at this stage, just present these charts drawn with EES as already explained. We shall deal with these charts again later, when we study the steam cycles and refrigeration.

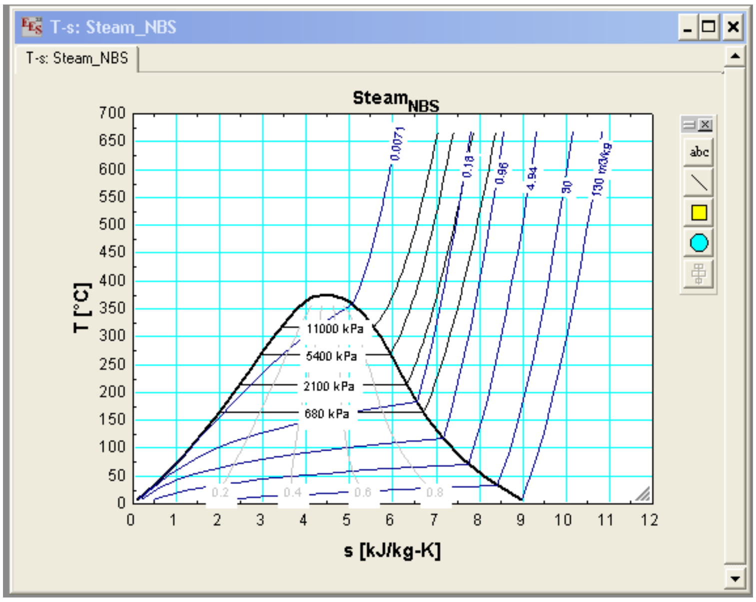


Fig. 3.13 T-s plot for Steam with EES

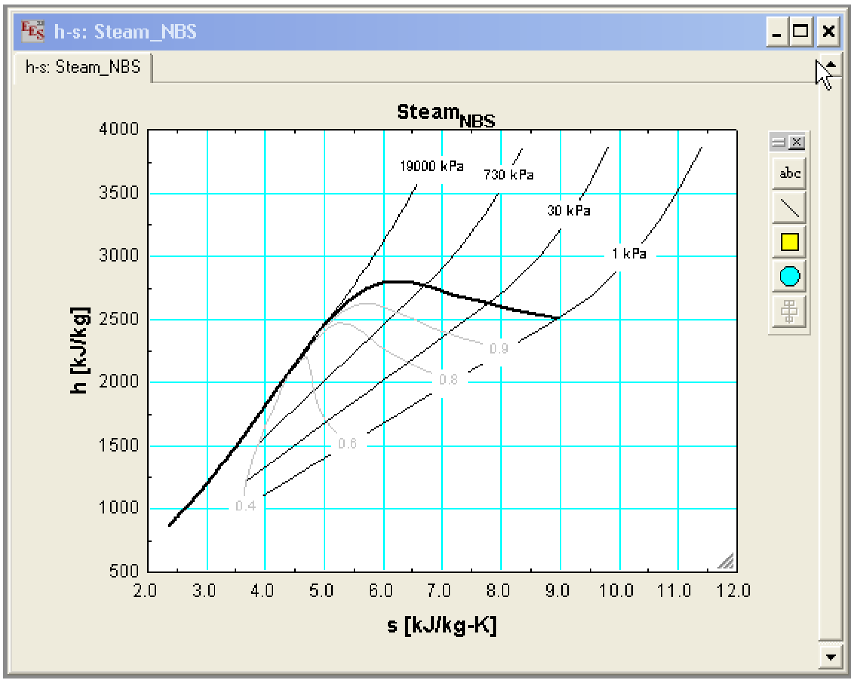


Fig. 3.14a. h-s plot for Steam with EES

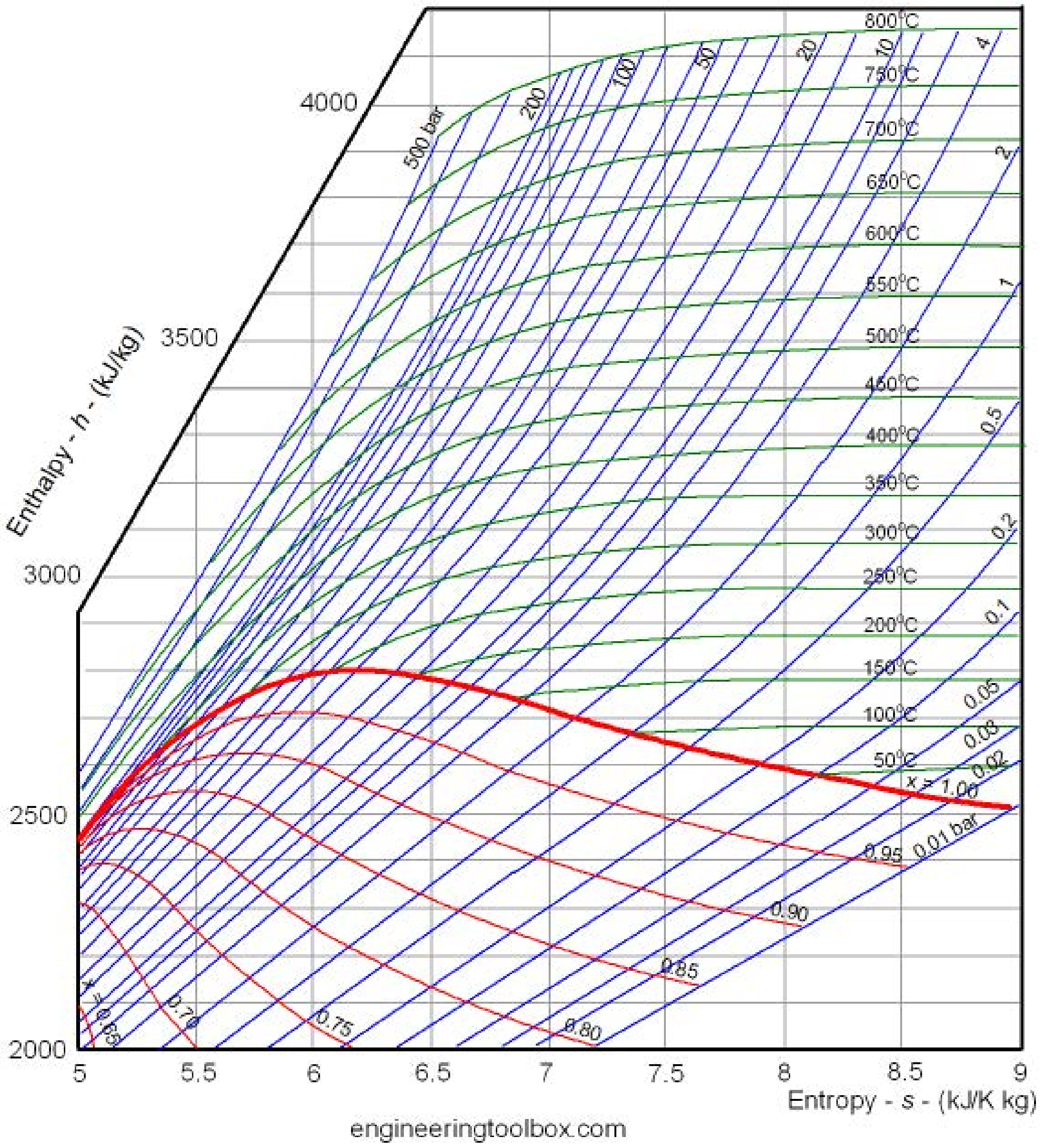


Fig. 3.14b. h-s plot for Steam (from www.Engineeringtoolbox.com)

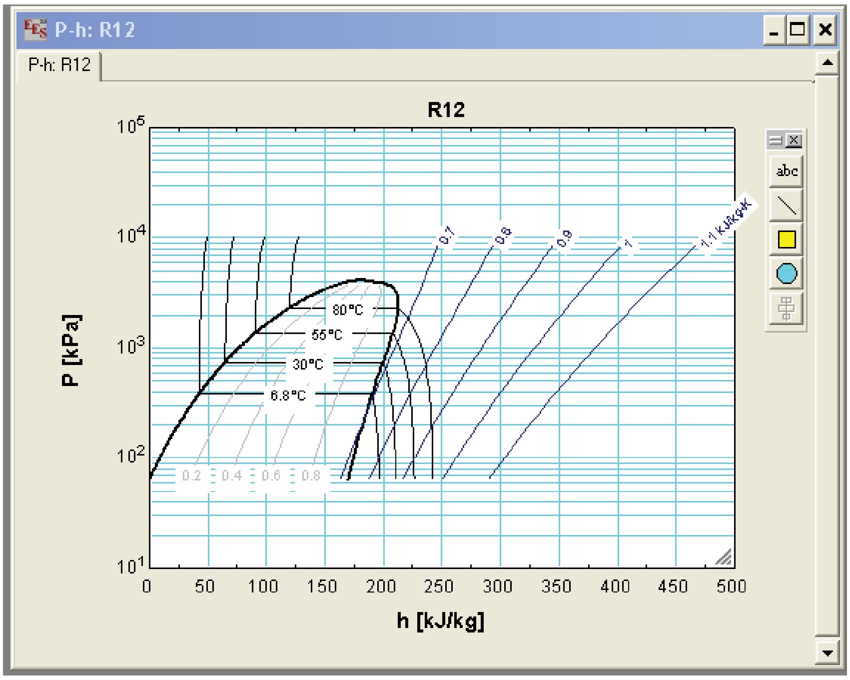


Fig. 3.15a. P-h plot for R12 with EES

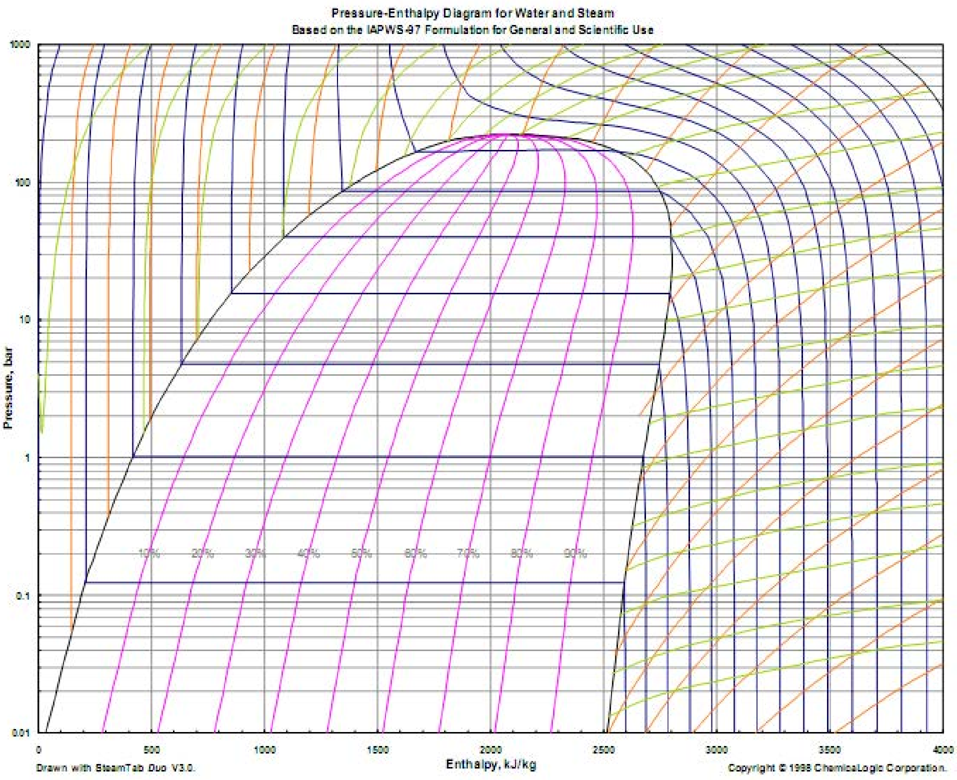


Fig. 3.15a. P-h plot for Steam (from www.ChemicaLogic.com)

3.3.2 Property diagrams using TEST:

With TEST, one can draw the property diagram in an instant, with just one click. However, if presentation quality graph is required, it is recommended that the plot data supplied in the TEST software, be exported to a spreadsheet like EXCEL and the plots drawn there. Procedure is illustrated below:

Go to the Home page of TEST. Click on 'Daemons' and choose 'States & Properties – Uniform System':

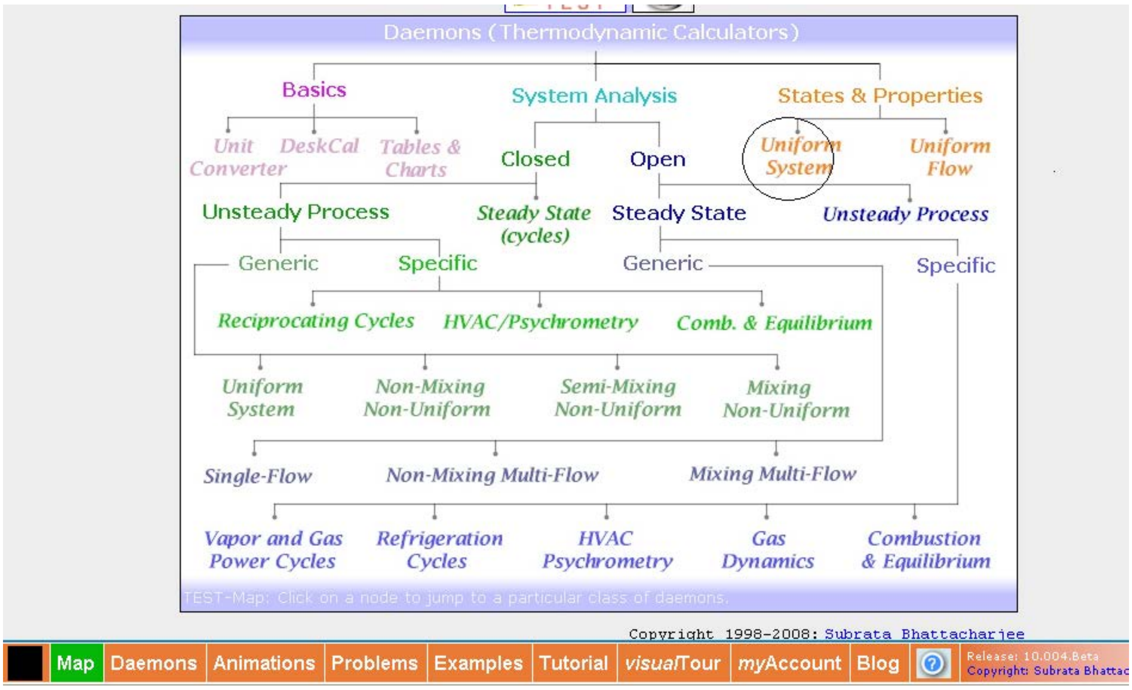
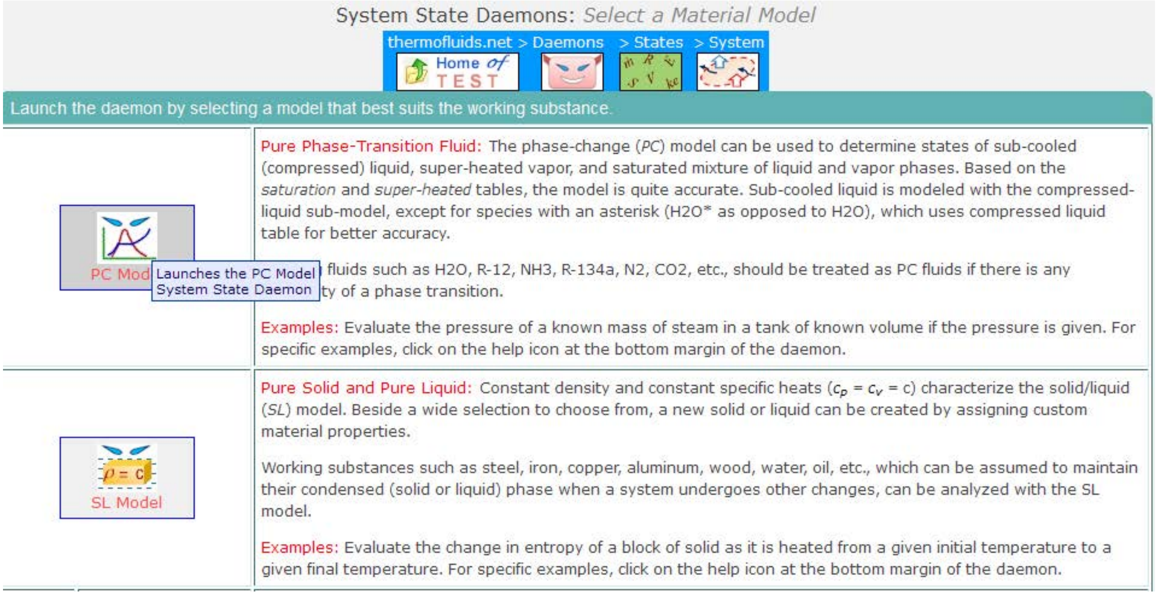


Fig. 3.16a. Drawing P-v plot for H2O with TEST

You get the following screen; choose PC model (i.e. Phase Change Model), since we want to get property diagram for Water/Steam.



Launch the daemon by selecting a model that best suits the working substance.

Pure Phase-Transition Fluid: The phase-change (*PC*) model can be used to determine states of sub-cooled (compressed) liquid, super-heated vapor, and saturated mixture of liquid and vapor phases. Based on the *saturation* and *super-heated* tables, the model is quite accurate. Sub-cooled liquid is modeled with the compressed-liquid sub-model, except for species with an asterisk (H2O* as opposed to H2O), which uses compressed liquid table for better accuracy.

fluids such as H2O, R-12, NH3, R-134a, N2, CO2, etc., should be treated as PC fluids if there is any ty of a phase transition.

Examples: Evaluate the pressure of a known mass of steam in a tank of known volume if the pressure is given. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Solid and Pure Liquid: Constant density and constant specific heats ($c_p = c_v = c$) characterize the solid/liquid (*SL*) model. Beside a wide selection to choose from, a new solid or liquid can be created by assigning custom material properties.

Working substances such as steel, iron, copper, aluminum, wood, water, oil, etc., which can be assumed to maintain their condensed (solid or liquid) phase when a system undergoes other changes, can be analyzed with the SL model.

Examples: Evaluate the change in entropy of a block of solid as it is heated from a given initial temperature to a given final temperature. For specific examples, click on the help icon at the bottom margin of the daemon.

Fig. 3.16b. Drawing P-v plot for H2O with TEST

Then, following screen appears. Choose H2O for the substance, and click on 'P-v' for the plot.

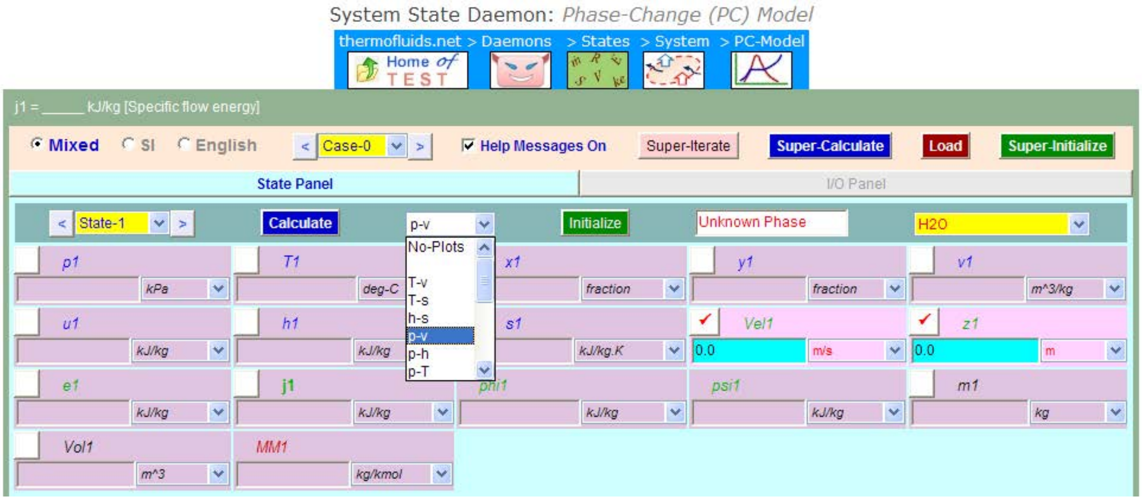
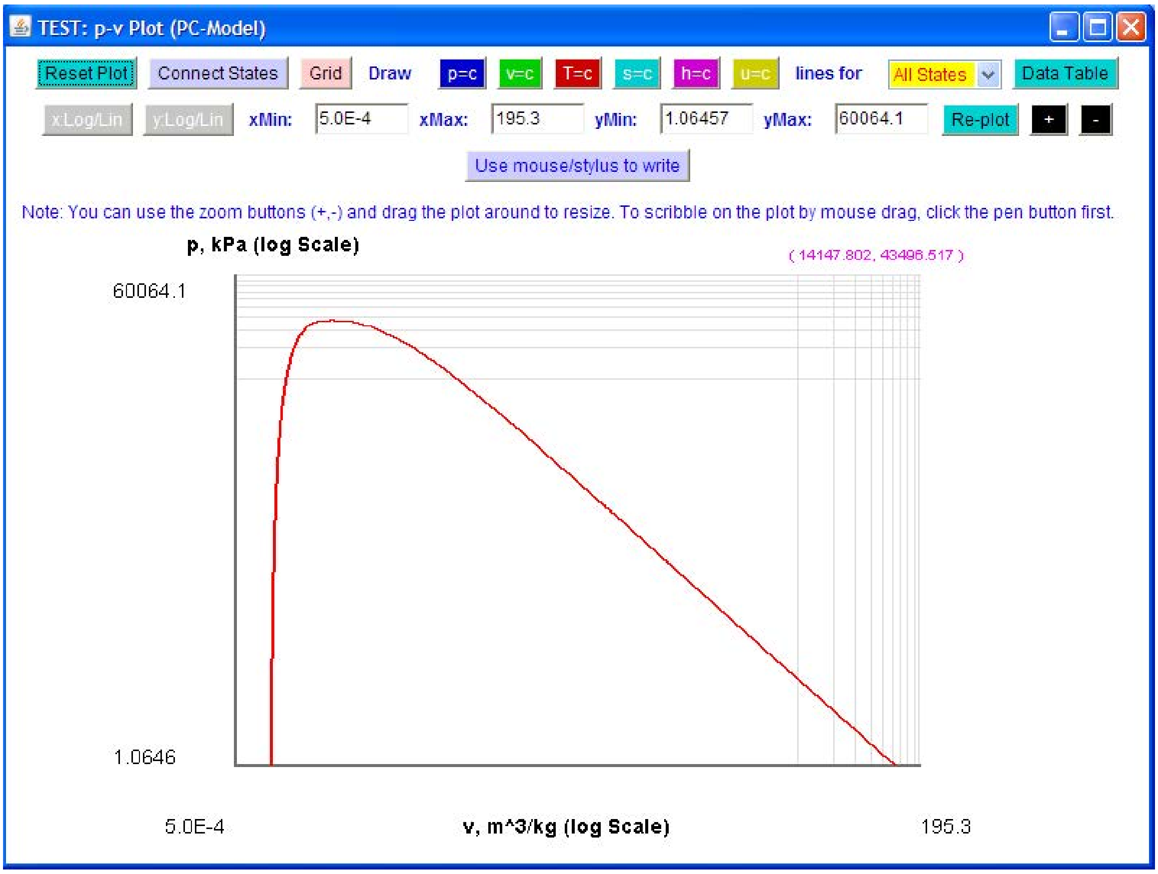


Fig. 3.16c. Drawing P-v plot for H2O with TEST

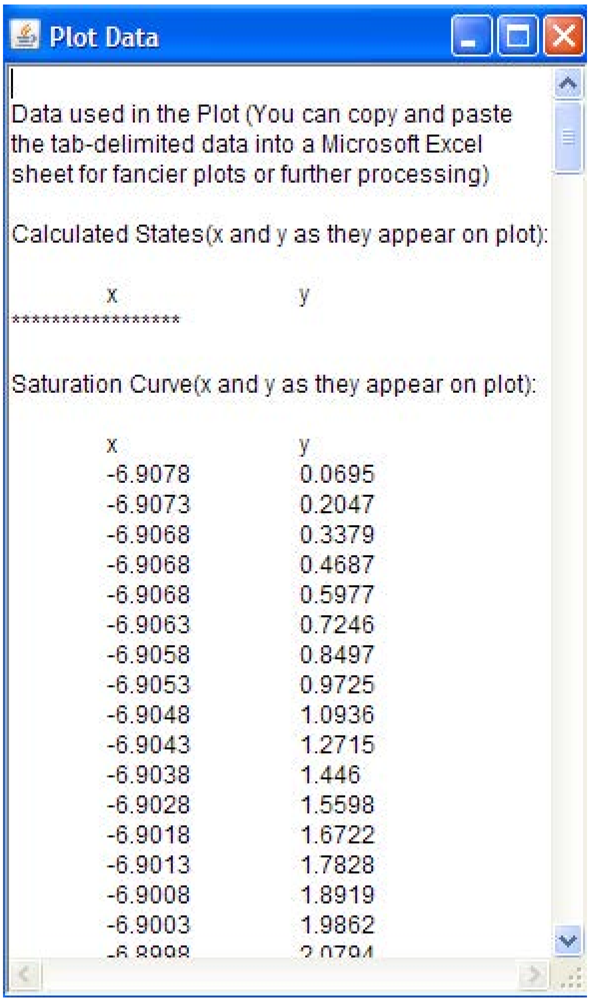
Immediately, the P-v plot appears:



Note: You can use the zoom buttons (+,-) and drag the plot around to resize. To scribble on the plot by mouse drag, click the pen button first.

Fig. 3.16d. Drawing P-v plot for H2O with TEST

This plot is rather indicative; to draw a 'presentation quality' plot it is recommended that you get the plot data, export it to EXCEL and then plot it there. So, click on 'Data Table' tab on the right hand top corner, and you get the following window:



```
Data used in the Plot (You can copy and paste
the tab-delimited data into a Microsoft Excel
sheet for fancier plots or further processing)

Calculated States(x and y as they appear on plot):

         x                 y
*****************

Saturation Curve(x and y as they appear on plot):

         x                 y
         -6.9078           0.0695
         -6.9073           0.2047
         -6.9068           0.3379
         -6.9068           0.4687
         -6.9068           0.5977
         -6.9063           0.7246
         -6.9058           0.8497
         -6.9053           0.9725
         -6.9048           1.0936
         -6.9043           1.2715
         -6.9038           1.446
         -6.9028           1.5598
         -6.9018           1.6722
         -6.9013           1.7828
         -6.9008           1.8919
         -6.9003           1.9862
         -6.8998           2.0794
```

Fig. 3.16e. Drawing P-v plot for H2O with TEST

Copy the x-y data to EXCEL and draw the graph. Resulting plot is shown below:

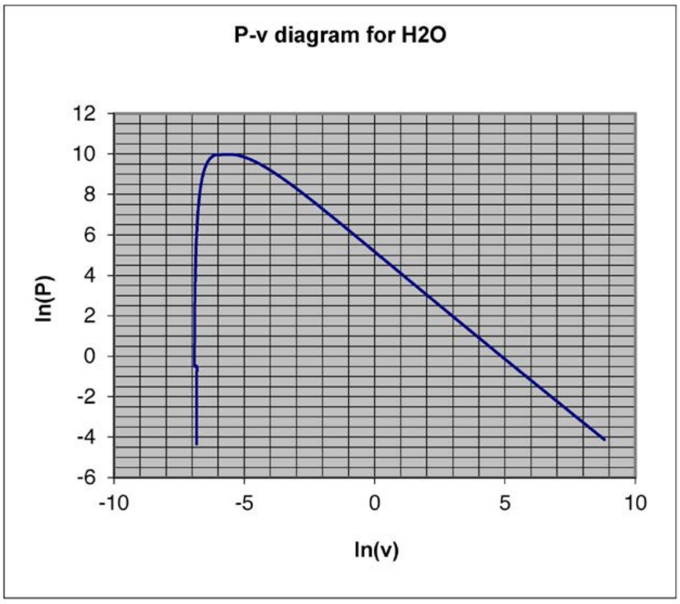
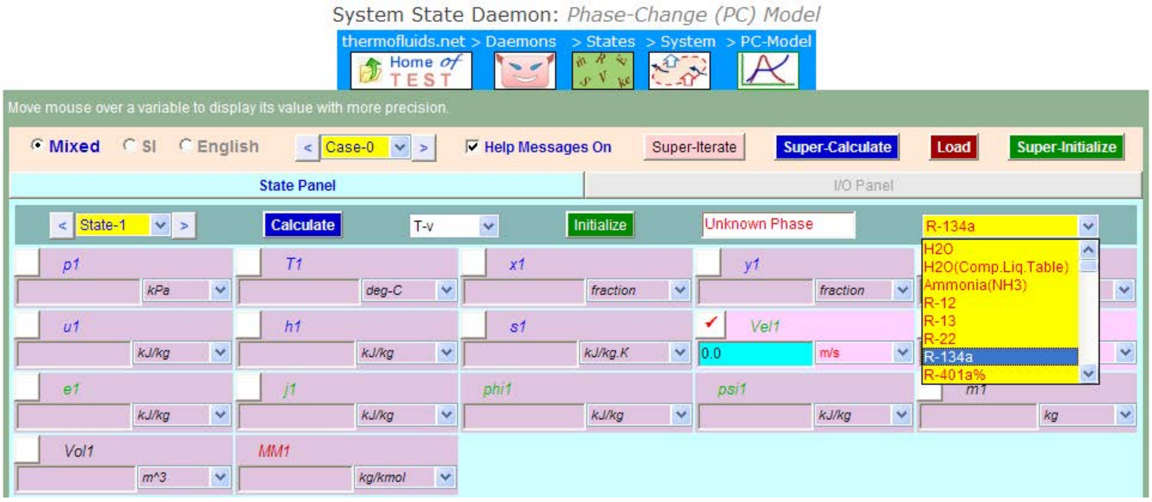


Fig. 3.16f. P-v plot for H2O drawn in EXCEL with data from TEST

Similarly, we can draw other diagrams by choosing the type of plot required (see Fig.3.18c).

As another example, if we wish to draw T-v plot for R134a, choose the substance as R134a, and the plot type as T-v as shown below:



Move mouse over a variable to display its value with more precision.

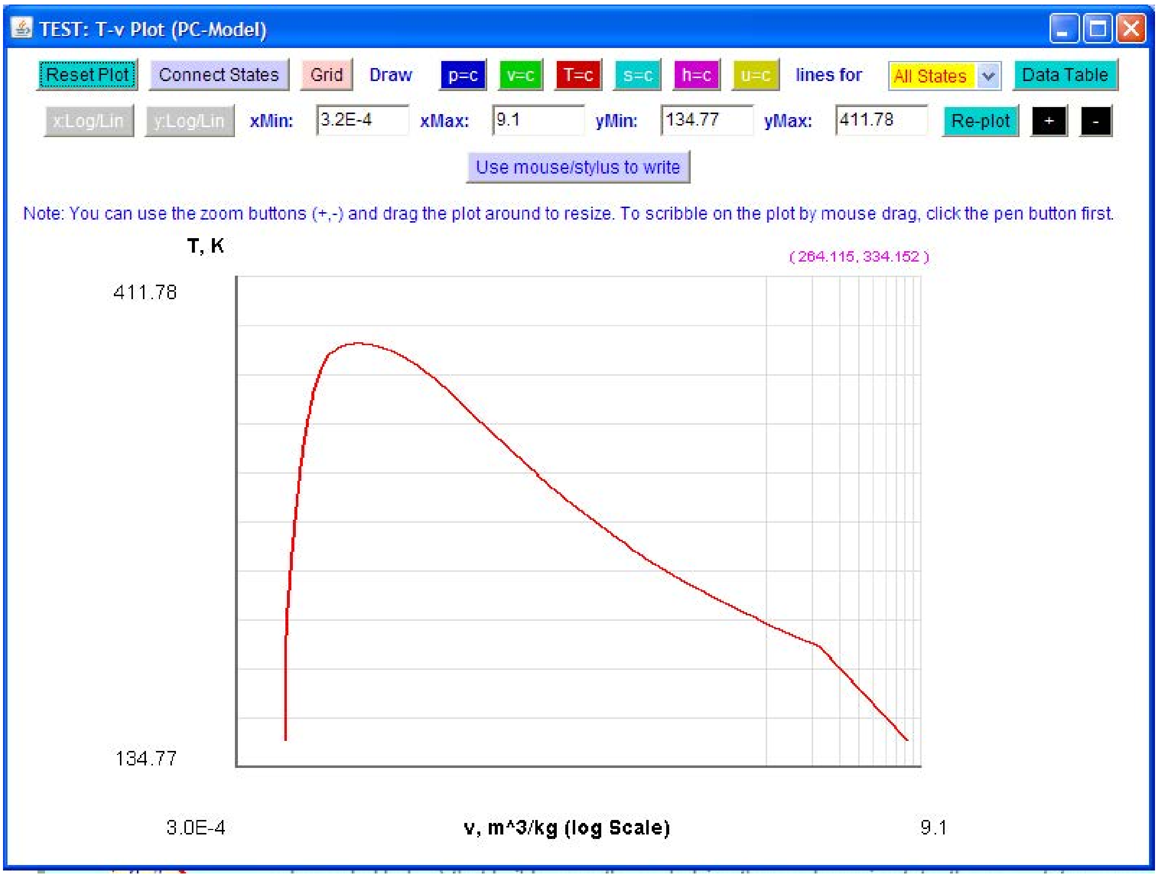
● Mixed ○ SI ○ English Case-0 ☑ Help Messages On

State-1 T-v Unknown Phase R-134a

☑ Vel1: 0.0 m/s

Fig. 3.17a. Drawing T-v plot for R134a with TEST

Immediately following plot appears:



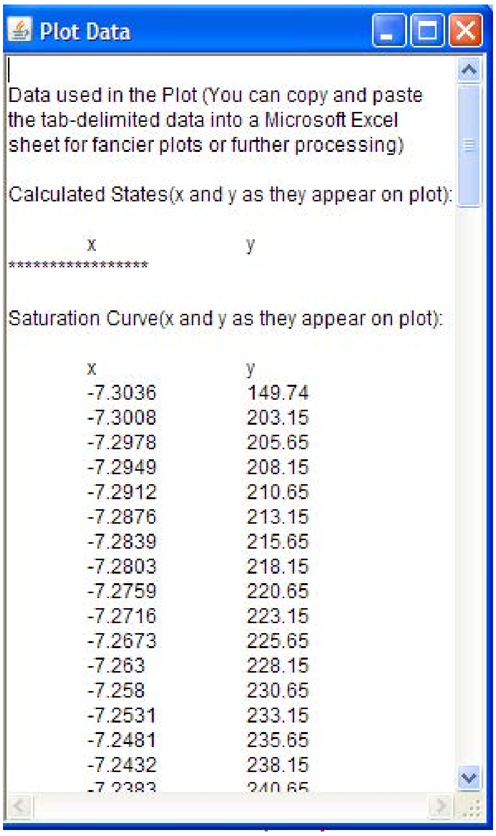
lines for: All States

xMin: 3.2E-4 xMax: 9.1 yMin: 134.77 yMax: 411.78

Note: You can use the zoom buttons (+,-) and drag the plot around to resize. To scribble on the plot by mouse drag, click the pen button first.

Fig. 3.17b. Drawing T-v plot for R134a with TEST

Then, to plot a presentation quality plot, click on 'Data Table' tab, and x-y data table appears and copy this table to EXCEL and plot a graph:



```
Data used in the Plot (You can copy and paste
the tab-delimited data into a Microsoft Excel
sheet for fancier plots or further processing)

Calculated States(x and y as they appear on plot):

           x                y
*****************

Saturation Curve(x and y as they appear on plot):

           x                y
           -7.3036          149.74
           -7.3008          203.15
           -7.2978          205.65
           -7.2949          208.15
           -7.2912          210.65
           -7.2876          213.15
           -7.2839          215.65
           -7.2803          218.15
           -7.2759          220.65
           -7.2716          223.15
           -7.2673          225.65
           -7.263           228.15
           -7.258           230.65
           -7.2531          233.15
           -7.2481          235.65
           -7.2432          238.15
           -7.2383          240.65
```

Fig. 3.17c. Plot data for T-v plot for R134a with TEST

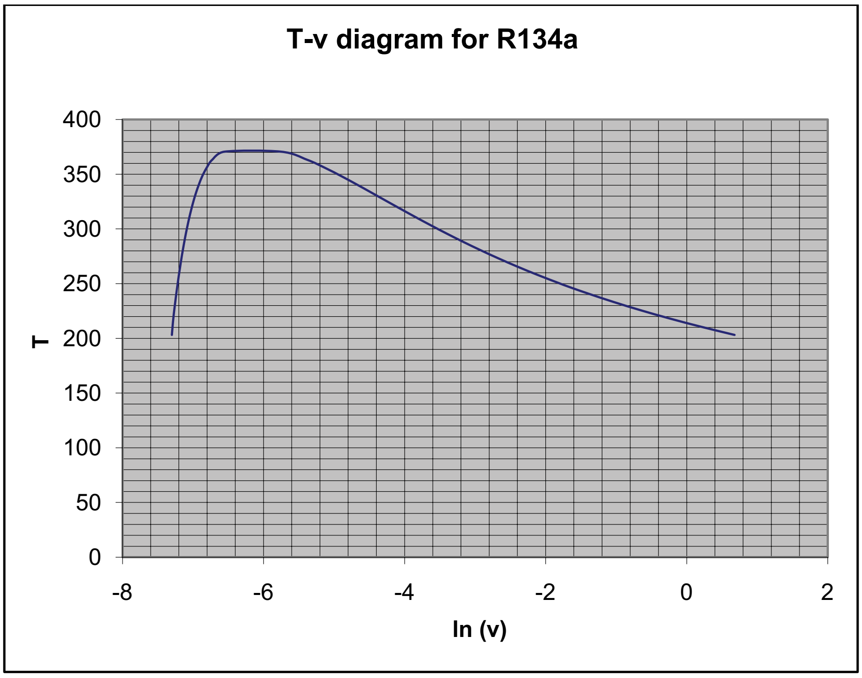


Fig. 3.17d. T-v plot for R134a with EXCEL

3.4 Property values and Tables:

Many times, it is difficult to read accurately from the Property plots, particularly if the scale is logarithmic. We may need property values at a given state; or, we may need a table of property values at a set of points. P, v and T are measurable properties and other properties tabulated are internal energy (u), enthalpy (h) and entropy (s). Generally these properties are calculated from the measured properties by means of complicated state equations. For example, for steam, different formulae are applicable depending upon the region in which the state lies. (see figure 3.18 below).

International Association for Properties of Water and Steam (IAPWS_97) defines the properties of Steam in 5 regions:

- region 1 for the liquid state from low to high pressures,
- region 2 for the vapor and ideal gas state,
- region 3 for the thermodynamic state around the critical point,
- region 4 for the saturation curve (vapor-liquid equilibrium),
- region 5 for high temperatures above 1073.15 K (800 °C) and pressures up to 10 MPa (100 bar).

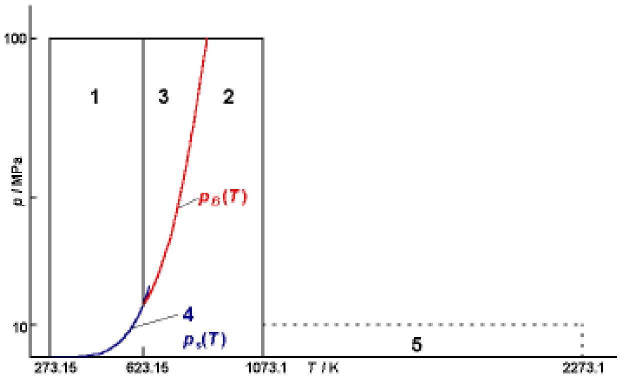


Fig. 3.18a. Five regions for Steam Properties (IAPWS-97)

At this stage, we shall define two quantities:

1. ***Enthalpy:*** The quantity (U + P.v) occurs very often in thermodynamic analysis, particularly in the analysis of steam cycles. It is denoted by H, and is termed as 'Enthalpy' (kJ). On unit mass basis, 'specific enthalpy' is:

$h = u + P \cdot v$ kJ/kg.............. (3.1)

2. ***Quality:*** One small note on the properties in the two phase region, i.e. wet steam.

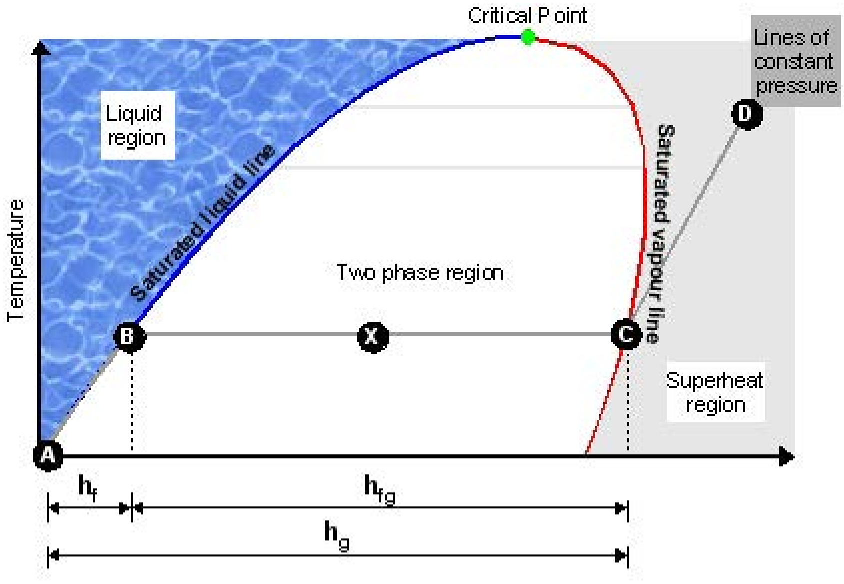


Fig. 3.18b. Five regions for Steam Properties (Ref: www.Steamline.com)

'Wet steam' or two-phase region is the region bounded by the 'Sat. liquid line' and the 'Sat. vapor line'. To fix the state within the two phase region, we need either pressure or temperature and one more *independent* property like 'quality' or 'specific volume' etc. Properties at the sat. liquid state are denoted with a subscript 'f' (ex: v_f, u_f, h_f, s_f etc.) and the properties at the sat. vapor state are denoted with a subscript 'g' (ex: v_g, u_g, h_g, s_g etc.).

Quality in two phase region is defined as the ratio of mass of vapor to the total mass (mass of liquid plus vapor). i.e.

$$x = \frac{m_g}{m_f + m_g} \qquad \text{...(3.2)}$$

And, quality varies from zero to 1.

Further, specific volume of mixture 'v' is given by:

$$v = v_f + x \cdot v_{fg} \quad \text{.......(3.3) where} \quad v_{fg} = v_g - v_f$$

Similarly, internal energy, enthalpy and entropy of the mixture are given by:

$$u = u_f + x \cdot u_{fg} \qquad \text{...(3.4)}$$

$$h = h_f + x \cdot h_{fg} \qquad \text{.....(3.5) and,}$$

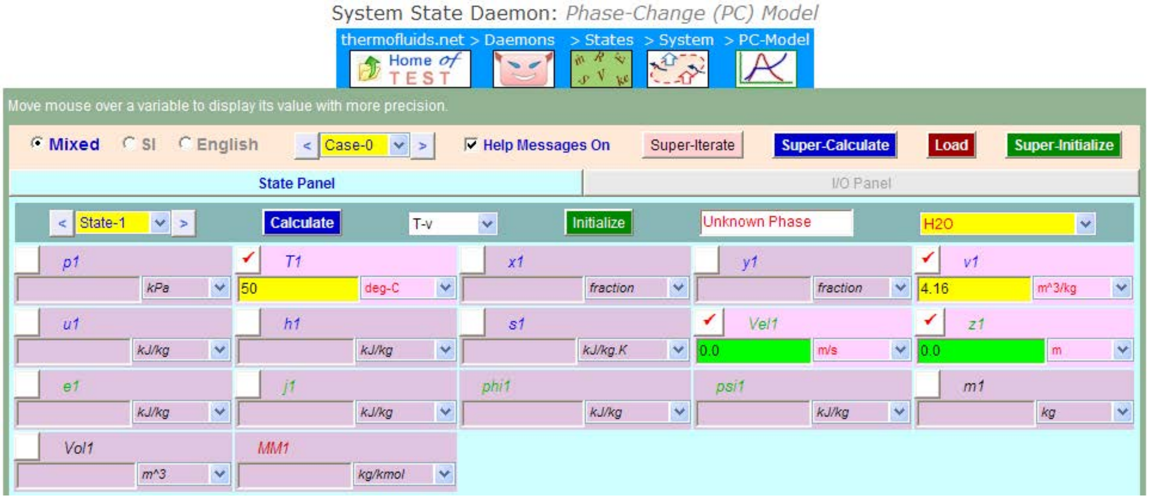
$$s = s_f + x \cdot s_{fg} \qquad \text{.....(3.6)}$$

3.4.1 Property values from TEST:

TEST is perhaps best suited to get property values of steam and many substances by plugging in values of two independent properties. Advantage of TEST is that properties are presented visually immediately, without the need to do any calculations or refer to any tables. Further, the TEST codes generated can be copied, stored and used to regenerate the solutions at a later time if required.

As an example, let us find the properties of water at a temperature of 50 deg. C and specific vol. of 4.16 m3/kg:

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). Following screen appears. H2O is automatically selected as the substance. State required is called as State 1. Select T1 and v1 and plug in the values given, as shown below:


System State Daemon: *Phase-Change (PC) Model*

thermofluids.net > Daemons > States > System > PC-Model

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

State-1

T-v

Unknown Phase

H2O

☑ T1: 50 deg-C

☑ v1: 4.16 m^3/kg

☑ Vel1: 0.0 m/s

☑ z1: 0.0 m

Fig. 3.19a. Finding property values for H2O with TEST

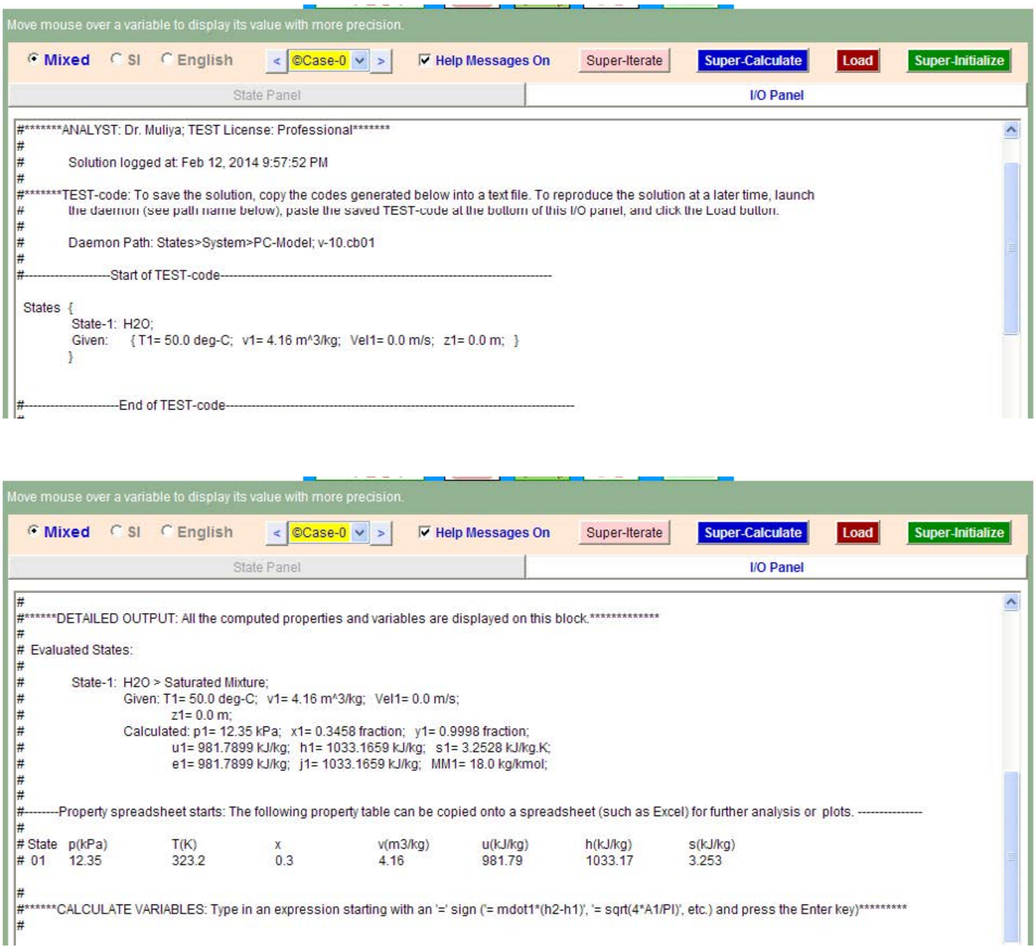
After entering the values of T1 and v1, click on 'Calculate' (or, press Enter), and the following screen appears showing all the properties of H2O:

☐ p1: 12.35001 kPa
✓ T1: 50.0 deg-C
☐ x1: 0.34575 fraction
☐ y1: 0.99984 fraction
✓ v1: 4.16 m^3/kg
☐ u1: 981.78986 kJ/kg
☐ h1: 1033.1659 kJ/kg
☐ s1: 3.25282 kJ/kg.K
✓ Vel1: 0.0 m/s
✓ z1: 0.0 m
☐ e1: 981.78986 kJ/kg
☐ j1: 1033.1659 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: kg
☐ Vol1: m^3
MM1: 18.0 kg/kmol

Fig. 3.19b. Finding property values for H2O with TEST

Note that the state is indicated as: (sat. liquid + vapor mixture), with a **'quality' x1 = 0.34575 and enthalpy h1 = 1033.1659 kJ/kg.** Other properties such as pressure (p1), internal energy (u1), entropy (s1) etc. can also be read from the above fig.

By clicking on the 'Supercalculate' button, TEST codes as well as the detailed output are generated, as shown below:



```
#*******ANALYST: Dr. Muliya; TEST License: Professional*******
#
#         Solution logged at: Feb 12, 2014 9:57:52 PM
#
#*******TEST-code: To save the solution, copy the codes generated below into a text file. To reproduce the solution at a later time, launch
#         the daemon (see path name below), paste the saved TEST-code at the bottom of this I/O panel, and click the Load button.
#
#         Daemon Path: States>System>PC-Model; v-10.cb01
#
#------------------Start of TEST-code--------------------------------------------------------------------------

 States  {
          State-1:  H2O;
          Given:     { T1= 50.0 deg-C;   v1= 4.16 m^3/kg;   Vel1= 0.0 m/s;   z1= 0.0 m;   }
         }


#--------------------End of TEST-code---------------------------------------------------------------------------
```

```
#
#******DETAILED OUTPUT: All the computed properties and variables are displayed on this block.*************
#
#  Evaluated States:
#
#          State-1:  H2O > Saturated Mixture;
#                    Given: T1= 50.0 deg-C;   v1= 4.16 m^3/kg;   Vel1= 0.0 m/s;
#                              z1= 0.0 m;
#                    Calculated: p1= 12.35 kPa;   x1= 0.3458 fraction;   y1= 0.9998 fraction;
#                              u1= 981.7899 kJ/kg;   h1= 1033.1659 kJ/kg;   s1= 3.2528 kJ/kg.K;
#                              e1= 981.7899 kJ/kg;   j1= 1033.1659 kJ/kg;   MM1= 18.0 kg/kmol;
#
#
#--------Property spreadsheet starts: The following property table can be copied onto a spreadsheet (such as Excel) for further analysis or  plots. ---------------
#
# State   p(kPa)        T(K)          x             v(m3/kg)      u(kJ/kg)      h(kJ/kg)      s(kJ/kg)
#  01     12.35         323.2         0.3           4.16          981.79        1033.17       3.253

#
#******CALCULATE VARIABLES: Type in an expression starting with an '=' sign ('= mdot1*(h2-h1)', '= sqrt(4*A1/PI)', etc.) and press the Enter key)*********
#
```

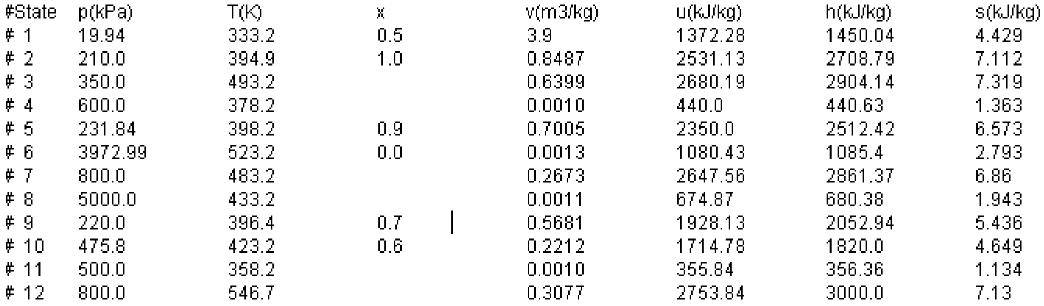
Fig. 3.19c. Finding property values for H2O with TEST

In a similar manner, let us solve the following problem:

Problem 3.1.a: Complete the following Table for H2O using TEST:

State	P (kPa)	T (deg.C)	v (m3/kg)	u (kJ/kg)	h (kJ/kg)	x	Phase
1		60	3.95				
2	210						Sat. vapor
3	350	220					
4	600	105					
5		125		2350			
6		250					Sat. liquid
7	800	210					
8	5000	160					
9	220					0.7	
10		150			1820		
11	500	85					
12	800				3000		

Solution: Open TEST, Click Map – Uniform system – Phase Change model. (See Figs. 3.18a and 3.18b.). H2O is automatically selected as the working substance. Start with State 1. Proceed as described earlier. Next, select State 2. New window appears and plug in the values of properties given, click 'Calculate'. Calculated results appear immediately. In a similar manner, get properties for all the State points, and click 'Supercalculate' to generate the TEST code and compiled output. Results from TEST report are shown below:



```
#State  p(kPa)    T(K)     x         v(m3/kg)   u(kJ/kg)   h(kJ/kg)   s(kJ/kg)
# 1     19.94     333.2    0.5       3.9        1372.28    1450.04    4.429
# 2     210.0     394.9    1.0       0.8487     2531.13    2708.79    7.112
# 3     350.0     493.2              0.6399     2680.19    2904.14    7.319
# 4     600.0     378.2              0.0010     440.0      440.63     1.363
# 5     231.84    398.2    0.9       0.7005     2350.0     2512.42    6.573
# 6     3972.99   523.2    0.0       0.0013     1080.43    1085.4     2.793
# 7     800.0     483.2              0.2673     2647.56    2861.37    6.86
# 8     5000.0    433.2              0.0011     674.87     680.38     1.943
# 9     220.0     396.4    0.7    |  0.5681     1928.13    2052.94    5.436
# 10    475.8     423.2    0.6       0.2212     1714.78    1820.0     4.649
# 11    500.0     358.2              0.0010     355.84     356.36     1.134
# 12    800.0     546.7              0.3077     2753.84    3000.0     7.13
```

Now, complete the Table. Calculated values are given in italics.

State	P (kPa)	T (deg.C)	v (m3/kg)	u (kJ/kg)	h (kJ/kg)	x	Phase
1	19.940	60	3.95	1372.276	1450.042	0.50	Sat. mixture
2	210	121.736	0.849	2531.126	2708.787	1.0	Sat. vapor
3	350	220	0.6399	2680.186	2904.143	--	Sup. vap.
4	600	105	0.0010	440.0	440.63	--	Subcooled liq.
5	231.84	125	0.7005	2350	2512.42	0.9	Sat. mixture
6	3972.99	250	0.0013	1080.43	1085.4	0.0	Sat. liquid
7	800	210	0.2673	2647.56	2861.37	--	Sup.vapor
8	5000	160	0.0011	674.87	680.38	--	Subcooled liq.
9	220	123.2	0.5681	1928.13	2052.94	0.7	Sat. mixture
10	475.8	150	0.2212	1714.78	1820	0.6	Sat. mixture
11	500	85	0.0010	355.84	356.35	--	Subcooled liq.
12	800	273.5	0.3077	2753.84	3000	--	Sup.vapor

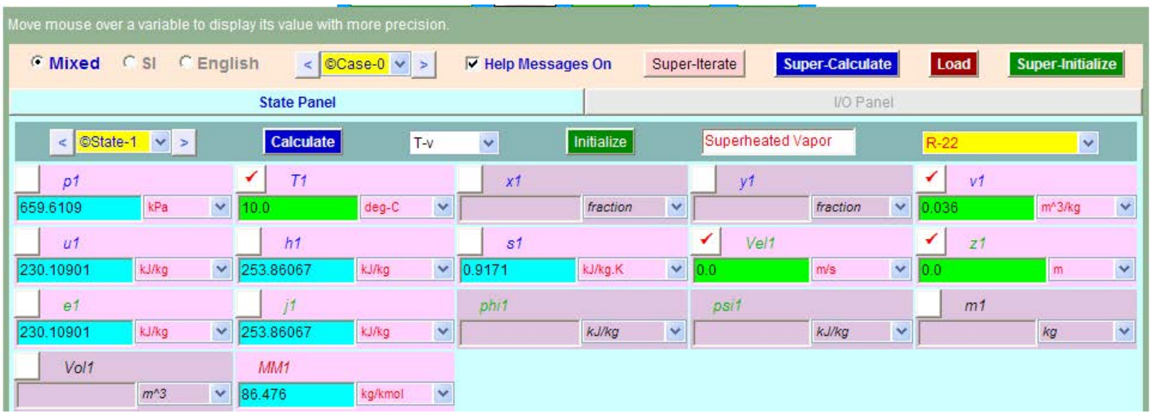
Table 3.3b. Properties of H2O

Problem 3.1.b: Complete the following Table:

Fluid	P(kPa)	T(deg.C)	v(m3/kg)	x	Phase
R-22		10	0.036		
H2O			0.2	0.5	
H2O	50	60			
NH3	60	30			
R-134a			0.005	0.5	

Table 3.3c. Properties of Fluids

Solution: As in the previous case, open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). Following screen appears. Choose R-22 as the substance. State required is called as State 1. Select T1 and v1 and plug in the values given, click 'Calculate':


Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English

©Case-0

☑ Help Messages On

©State-1 T-v Superheated Vapor R-22

☐ p1: 659.6109 kPa
☑ T1: 10.0 deg-C
☐ x1: fraction
☐ y1: fraction
☑ v1: 0.036 m^3/kg
☐ u1: 230.10901 kJ/kg
☐ h1: 253.86067 kJ/kg
☐ s1: 0.9171 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 230.10901 kJ/kg
☐ j1: 253.86067 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: kg
☐ Vol1: m^3
MM1: 86.476 kg/kmol

Fig. 3.19d. Finding property values with TEST

Next, select state 2, choose H2O for substance, plug in the values of v and x, and click 'Calculate'. Then, immediately properties for water are presented. Proceeding similarly, get properties for all states and complete the table as follows:

Fluid	P(kPa)	T(deg.C)	v(m3/kg)	x	Phase
R-22	***659.61***	10	0.036	-	***Sup. vapor***
H2O	***467.99***	***149.38***	0.2	0.5	***Sat. mix.***
H2O	50	60	***0.00102***	-	***Sub. Liq.***
NH3	60	30	***2.452***	-	***Sup. vapor***
R-134a	***2049.62***	***68.59***	0.005	0.5	***Sat. mix.***

Table 3.3d. Properties of Fluids

3.4.2 Property values from EES:

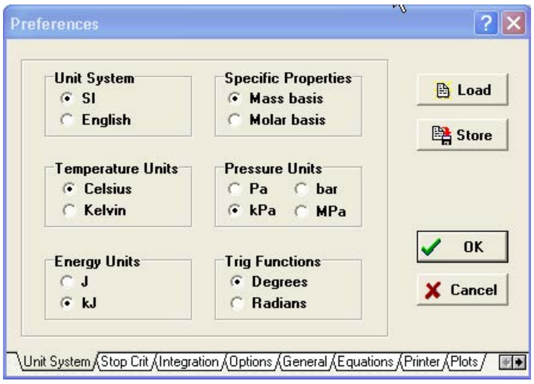
In EES, we have the functions to determine the properties when any two independent properties are given. As an example, let us solve the following problem:

Problem 3.2: Complete the following Table for R-134a:

State	P (kPa)	T (deg.C)	v (m3/kg)	u (kJ/kg)	h (kJ/kg)	x	Phase
1	520	-9					
2		30	0.022				
3	550	90					
4		20		95			
5	400			300			
6	1200				300		

Table 3.4a. Properties of R-134a

Solution: Open EES and first set the 'Unit system' by clicking Options-Unit system as shown below:



Preferences

Unit System
● SI
○ English

Specific Properties
● Mass basis
○ Molar basis

Temperature Units
● Celsius
○ Kelvin

Pressure Units
○ Pa ○ bar
● kPa ○ MPa

Energy Units
○ J
● kJ

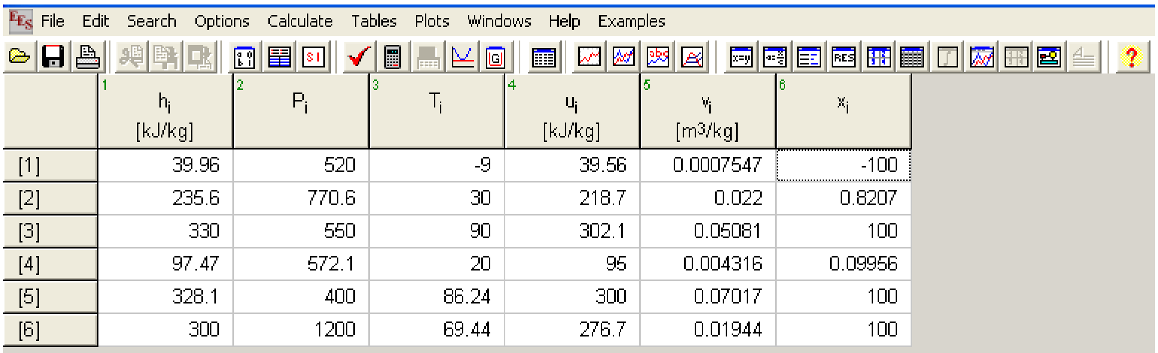
Trig Functions
● Degrees
○ Radians

Fig. 3.20a. Properties of R-134a with EES

Next, in the Equations window, write the EES code as shown below. Note how the built in property functions are used to calculate various properties. Also, note that we have used array notation for various properties so that they are collected neatly in the Array table. Results in Array table are also shown.

```
“Properties of R-134a:”
“Data:”
P[1]=520”kPa”; T[1]=-9”deg.C”
T[2]=30”deg.C”; v[2]=0.022”m3/kg”
```

```
P[3]=550”kPa”; T[3]=90”deg.C”
T[4]=20”deg.C”; u[4]=95”kJ/kg”
P[5]=400”kPa”;u[5]=300”kJ/kg”
P[6]=1200”kPa”; h[6]=300”kJ/kg”

“Calculate properties for State 1:”
v[1]=VOLUME(R134a,T=T[1],P=P[1]) “calculates sp. volume”
u[1]=INTENERGY(R134a,T=T[1],P=P[1]) “calclulates int. energy”
h[1]=ENTHALPY(R134a,T=T[1],P=P[1]) “calculates sp. enthalpy”
x[1]=QUALITY(R134a,h=h[1],P=P[1]) “calculates quality (dryness fraction)”

“Calculate properties for State 2:”
P[2]=PRESSURE(R134a,T=T[2],v=v[2]) “calculates pressure”
u[2]=INTENERGY(R134a,T=T[2],v=v[2]) “calculates int. energy”
h[2]=ENTHALPY(R134a,T=T[2],v=v[2]) “calculates sp. enthalpy”
x[2]=QUALITY(R134a,h=h[2],P=P[2]) “calculates quality (dryness fraction)”

“Calculate properties for State 3:”
v[3]=VOLUME(R134a,T=T[3],P=P[3]) “calculates sp. volume”
u[3]=INTENERGY(R134a,T=T[3],v=v[3]) “calculates int. energy”
h[3]=ENTHALPY(R134a,T=T[3],v=v[3]) “calculates sp. enthalpy”
x[3]=QUALITY(R134a,h=h[3],P=P[3]) “calculates quality (dryness fraction)”

«Calculate properties for State 4:»
P[4]=PRESSURE(R134a,T=T[4],u=u[4]) «calculates pressure»
v[4]=VOLUME(R134a,T=T[4],u=u[4]) «calculates sp. volume»
h[4]=ENTHALPY(R134a,T=T[4],v=v[4]) “calculates sp. enthalpy”
x[4]=QUALITY(R134a,h=h[4],P=P[4]) “calculates quality (dryness fraction)”

“Calculate properties for State 5:”
v[5]=VOLUME(R134a,P=P[5],u=u[5]) “calculates sp. volume”
T[5]=TEMPERATURE(R134a,u=u[5],P=P[5]) “calculates temperature”
h[5]=ENTHALPY(R134a,T=T[5],v=v[5]) “calculates enthalpy”
x[5]=QUALITY(R134a,h=h[5],P=P[5]) “calculates quality (dryness fraction)”

“Calculate properties for State 6:”
v[6]=VOLUME(R134a,P=P[6],h=h[6]) “calculates sp. volume”
T[6]=TEMPERATURE(R134a,h=h[6],P=P[6]) “calculates temperature”
u[6]=INTENERGY(R134a,T=T[6],v=v[6]) “calculates int. energy”
x[6]=QUALITY(R134a,h=h[6],P=P[6]) “calculates quality (dryness fraction)”
```



	1 h_i [kJ/kg]	2 P_i	3 T_i	4 u_i [kJ/kg]	5 v_i [m3/kg]	6 x_i
[1]	39.96	520	-9	39.56	0.0007547	-100
[2]	235.6	770.6	30	218.7	0.022	0.8207
[3]	330	550	90	302.1	0.05081	100
[4]	97.47	572.1	20	95	0.004316	0.09956
[5]	328.1	400	86.24	300	0.07017	100
[6]	300	1200	69.44	276.7	0.01944	100

Fig. 3.20b. Array Table

Now, we can complete the Table for Prob. 3.2:

State	**P (kPa)**	**T (deg.C)**	**v (m3/kg)**	**u (kJ/kg)**	**h (kJ/kg)**	**x**	**Phase**
1	520	-9	*0.0007547*	*39.56*	*39.96*	--	*Subcooled liq.*
2	*770.6*	30	0.022	*218.7*	*235.6*	*0.8207*	*Sat.mix.*
3	550	90	*0.05081*	*302.1*	*330*	--	*Sup. vap.*
4	*572.1*	20	*0.004316*	95	*97.47*	*0.09956*	*Sat. mix.*
5	400	*86.24*	*0.07017*	300	*328.1*	--	*Sup. vap.*
6	1200	*69.44*	*0.01944*	*276.7*	300	--	*Sup. vap.*

Table 3.4b. Properties of R-134a

It may be observed that EES does not specifically indicate the phase of the fluid; it has to be inferred by looking at the quality (x) or by locating the state in one of the property diagrams.

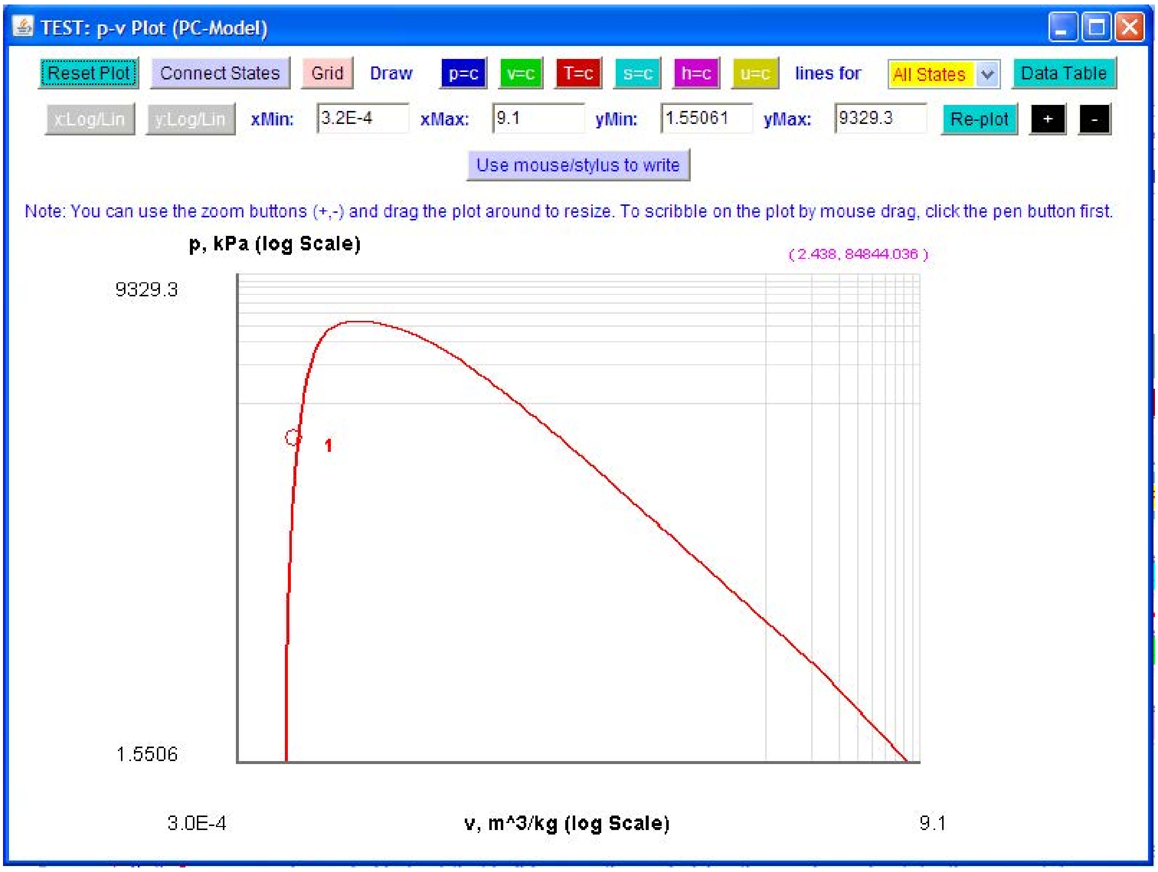
In this connection, it may be stated that while using TEST, after calculating the state, the phase of the substance is indicated explicitly. For example, *if we work out the state 1 in the above problem using TEST*, following is the result:


Move mouse over a variable to display its value with more precision.
● Mixed ○ SI ○ English
Case-0
☑ Help Messages On
@State-1
p-v
Subcooled Liquid
R-134a
☑ p1: 520.0 kPa
☑ T1: -9.0 deg-C
☐ x1: fraction
☐ y1: fraction
☐ v1: 7.6E-4 m^3/kg
☐ u1: 38.90112 kJ/kg
☐ h1: 39.29465 kJ/kg
☐ s1: 0.15656 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 38.90112 kJ/kg
☐ j1: 39.29465 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: kg
☐ Vol1: m^3
MM1: kg/kmol

Fig. 3.21(a) Properties of R-134a with TEST

Note that State 1 is in the sub-cooled liquid region.

If we get the p-v plot, State 1 is also shown in that plot immediately:



Note: You can use the zoom buttons (+,-) and drag the plot around to resize. To scribble on the plot by mouse drag, click the pen button first.

Fig. 3.21(b) State point 1 on the p-v plot for R-134a with TEST

After calculating all the six states, if we click 'Supercalculate', the TEST code and the output results are generated. The property table obtained is shown below:

#State	p(kPa)	T(K)	x	v(m3/kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg)
# 1	520.0	264.2	8.0E-4		38.9	39.29	0.157
# 2	771.0	303.2	0.8	0.022	217.58	234.55	0.812
# 3	550.0	363.2		0.0508	301.22	329.16	1.131
# 4	572.8	293.2	0.1	0.0045	95.0	97.58	0.362
# 5	400.0	360.5		0.0704	300.0	328.17	1.153
# 6	1200.0	343.0		0.0195	276.59	300.0	0.991

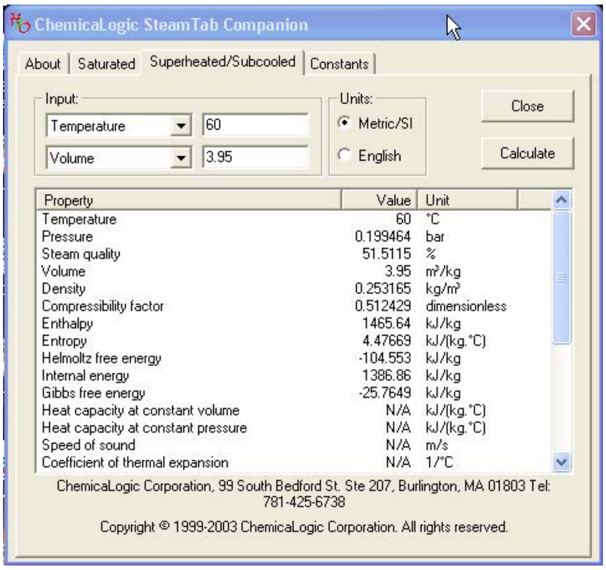
Compare these values with those obtained using EES.

3.4.3 Property values from 'free' software:

Here, main disadvantage is that these free software are available only for Water/Steam. If we have to calculate properties for any other fluid, then we have to use either EES or TEST.

Method of using 'SteamTab companion' has already been explained in Chapter 1. So, now, we shall just show the results for State 1 and State 5 of Prob. 3.1:

Using 'SteamTab companion', for State 1 of Prob. 3.1:



Input:
Temperature 60
Volume 3.95

Units:
● Metric/SI
○ English

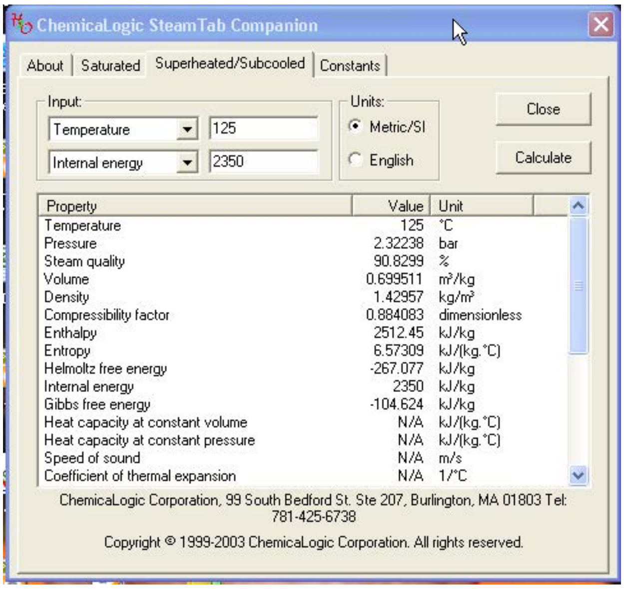
Property	Value	Unit
Temperature	60	°C
Pressure	0.199464	bar
Steam quality	51.5115	%
Volume	3.95	m³/kg
Density	0.253165	kg/m³
Compressibility factor	0.512429	dimensionless
Enthalpy	1465.64	kJ/kg
Entropy	4.47669	kJ/(kg.°C)
Helmoltz free energy	-104.553	kJ/kg
Internal energy	1386.86	kJ/kg
Gibbs free energy	-25.7649	kJ/kg
Heat capacity at constant volume	N/A	kJ/(kg.°C)
Heat capacity at constant pressure	N/A	kJ/(kg.°C)
Speed of sound	N/A	m/s
Coefficient of thermal expansion	N/A	1/°C

ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

Fig. 3.22a. Properties of Steam with 'SteamTab companion'

Using 'SteamTab companion', for State 5 of Prob. 3.1:



Input:
Temperature 125
Internal energy 2350

Units:
● Metric/SI
○ English

Property	Value	Unit
Temperature	125	°C
Pressure	2.32238	bar
Steam quality	90.8299	%
Volume	0.699511	m³/kg
Density	1.42957	kg/m³
Compressibility factor	0.884083	dimensionless
Enthalpy	2512.45	kJ/kg
Entropy	6.57309	kJ/(kg.°C)
Helmoltz free energy	-267.077	kJ/kg
Internal energy	2350	kJ/kg
Gibbs free energy	-104.624	kJ/kg
Heat capacity at constant volume	N/A	kJ/(kg.°C)
Heat capacity at constant pressure	N/A	kJ/(kg.°C)
Speed of sound	N/A	m/s
Coefficient of thermal expansion	N/A	1/°C

ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

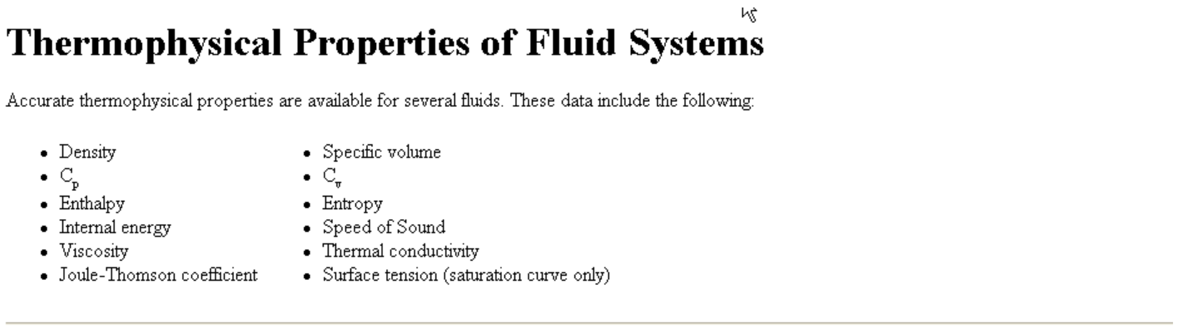
Fig. 3.22b. Properties of Steam from 'SteamTab companion'

Compare these values with the values in Table 3.3 b.

3.4.4 Property values from 'online software':

3.4.4.1 From NIST Website:

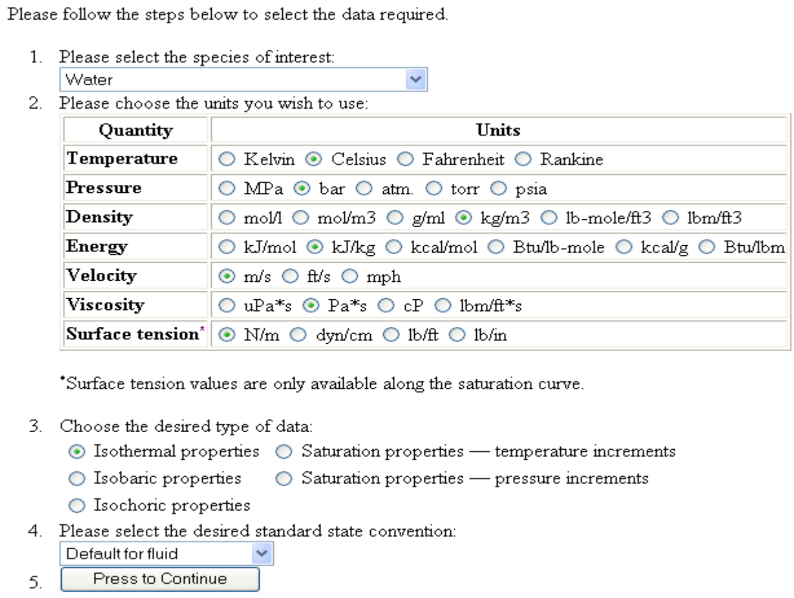
Property values can be calculated online for many fluids. Most popular and versatile online software is from NIST, which can give all types of data and graphs for a huge number of fluids. Go to: http://webbook.nist.gov/chemistry/fluid/. Following window appears:



Thermophysical Properties of Fluid Systems

Accurate thermophysical properties are available for several fluids. These data include the following:

- Density
- C_p
- Enthalpy
- Internal energy
- Viscosity
- Joule-Thomson coefficient
- Specific volume
- C_v
- Entropy
- Speed of Sound
- Thermal conductivity
- Surface tension (saturation curve only)



Please follow the steps below to select the data required.

1. Please select the species of interest:
   Water
2. Please choose the units you wish to use:

Quantity	Units
Temperature	○ Kelvin ● Celsius ○ Fahrenheit ○ Rankine
Pressure	○ MPa ● bar ○ atm. ○ torr ○ psia
Density	○ mol/l ○ mol/m3 ○ g/ml ● kg/m3 ○ lb-mole/ft3 ○ lbm/ft3
Energy	○ kJ/mol ● kJ/kg ○ kcal/mol ○ Btu/lb-mole ○ kcal/g ○ Btu/lbm
Velocity	● m/s ○ ft/s ○ mph
Viscosity	○ uPa*s ● Pa*s ○ cP ○ lbm/ft*s
Surface tension*	● N/m ○ dyn/cm ○ lb/ft ○ lb/in

*Surface tension values are only available along the saturation curve.

3. Choose the desired type of data:
   ● Isothermal properties ○ Saturation properties — temperature increments
   ○ Isobaric properties ○ Saturation properties — pressure increments
   ○ Isochoric properties
4. Please select the desired standard state convention:
   Default for fluid
5.

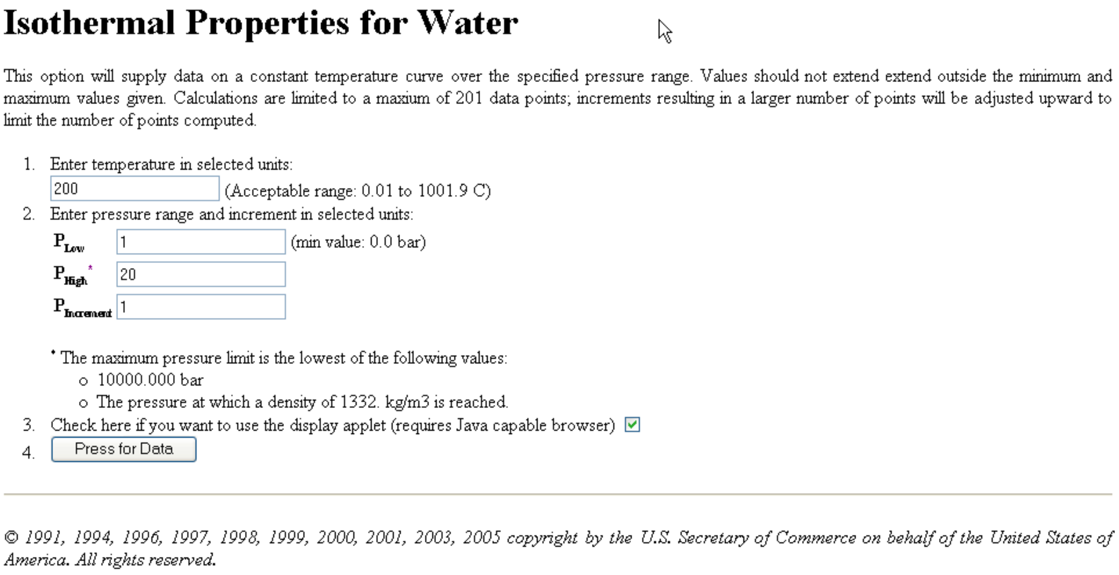
Fig. 3.23a. Properties of Water from NIST

In the above window, choose the species; there are a host of substances you can choose, including refrigerants, cryogenic fluids etc. Water is selected.

Next choose the units in which we wish the properties to be presented.

Next, choose the type of data you need, i.e. isothermal, isobaric, isochoric or saturation properties. We have chosen 'Isothermal'. Properties in tabular form can be obtained in these formats.

Next, press the 'continue' button. We get:



Isothermal Properties for Water

This option will supply data on a constant temperature curve over the specified pressure range. Values should not extend extend outside the minimum and maximum values given. Calculations are limited to a maxium of 201 data points; increments resulting in a larger number of points will be adjusted upward to limit the number of points computed.

1. Enter temperature in selected units:
   200 (Acceptable range: 0.01 to 1001.9 C)
2. Enter pressure range and increment in selected units:
   P_{Low} 1 (min value: 0.0 bar)
   P_{High}* 20
   $P_{Increment}$ 1

   * The maximum pressure limit is the lowest of the following values:
     - 10000.000 bar
     - The pressure at which a density of 1332. kg/m3 is reached.
3. Check here if you want to use the display applet (requires Java capable browser) ☑
4.

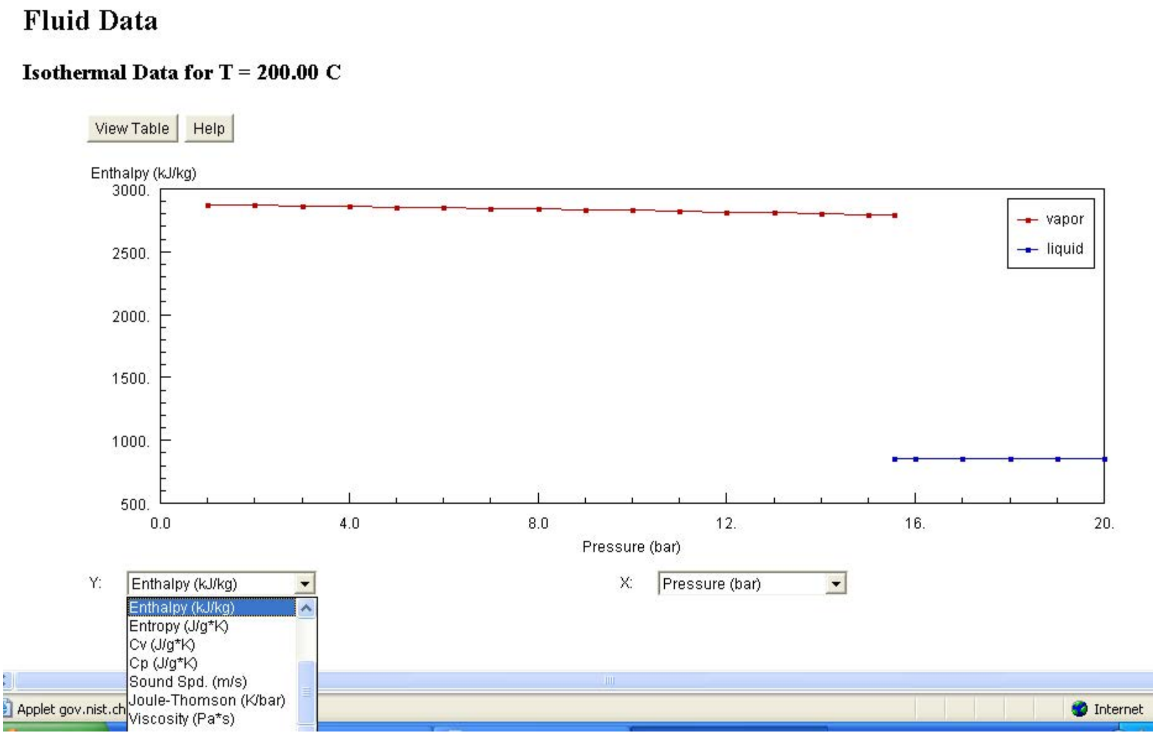
© 1991, 1994, 1996, 1997, 1998, 1999, 2000, 2001, 2003, 2005 copyright by the U.S. Secretary of Commerce on behalf of the United States of America. All rights reserved.

Fig. 3.23b. Properties of Water from NIST

Enter the temperature as, say, 200 deg.C, and pressure range as 1 to 20 bar, with an increment of 1 bar. Press the button 'Press for data'. We get following window:

Isothermal Properties for Water

- Fluid Data
- Auxiliary Data
- References
- Additional Information
- Important Information About This Data
- Notes
- **Other Data Available:**
    - View data in HTML table.
    - Download data as a tab-delimited text file.
    - Main NIST Chemistry WebBook page for this species.
    - Recommended citation for data from this page.
    - Fluid data for other species



Fluid Data

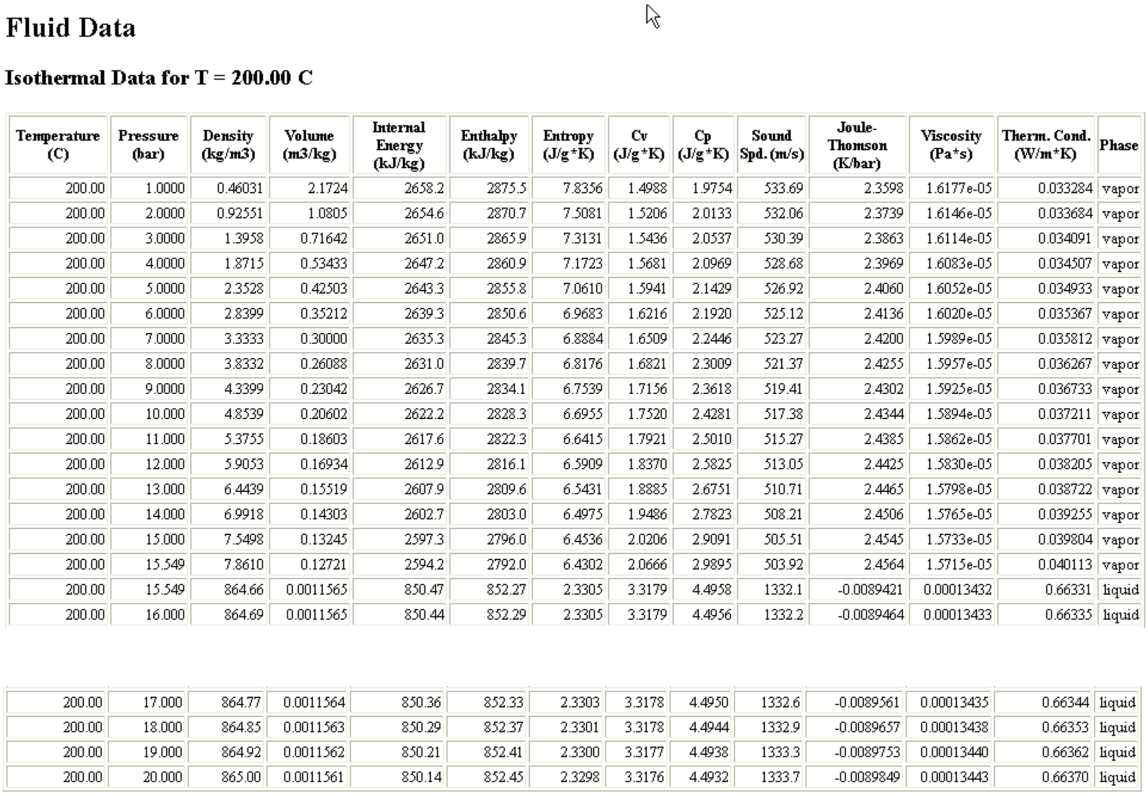
Isothermal Data for T = 200.00 C

Y: Enthalpy (kJ/kg)

X: Pressure (bar)

Fig. 3.23c. Properties of Water from NIST

In the above, first graphical representation is presented. Several graphs can be drawn instantly by choosing the x and y coordinates. As an example, we have drawn the P-h graph. All the data can be obtained in tabular form too. Press 'View data in HTML table'. We get:



Fluid Data

Isothermal Data for T = 200.00 C

Temperature (C)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)	Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase
200.00	1.0000	0.46031	2.1724	2658.2	2875.5	7.8356	1.4988	1.9754	533.69	2.3598	1.6177e-05	0.033284	vapor
200.00	2.0000	0.92551	1.0805	2654.6	2870.7	7.5081	1.5206	2.0133	532.06	2.3739	1.6146e-05	0.033684	vapor
200.00	3.0000	1.3958	0.71642	2651.0	2865.9	7.3131	1.5436	2.0537	530.39	2.3863	1.6114e-05	0.034091	vapor
200.00	4.0000	1.8715	0.53433	2647.2	2860.9	7.1723	1.5681	2.0969	528.68	2.3969	1.6083e-05	0.034507	vapor
200.00	5.0000	2.3528	0.42503	2643.3	2855.8	7.0610	1.5941	2.1429	526.92	2.4060	1.6052e-05	0.034933	vapor
200.00	6.0000	2.8399	0.35212	2639.3	2850.6	6.9683	1.6216	2.1920	525.12	2.4136	1.6020e-05	0.035367	vapor
200.00	7.0000	3.3333	0.30000	2635.3	2845.3	6.8884	1.6509	2.2446	523.27	2.4200	1.5989e-05	0.035812	vapor
200.00	8.0000	3.8332	0.26088	2631.0	2839.7	6.8176	1.6821	2.3009	521.37	2.4255	1.5957e-05	0.036267	vapor
200.00	9.0000	4.3399	0.23042	2626.7	2834.1	6.7539	1.7156	2.3618	519.41	2.4302	1.5925e-05	0.036733	vapor
200.00	10.000	4.8539	0.20602	2622.2	2828.3	6.6955	1.7520	2.4281	517.38	2.4344	1.5894e-05	0.037211	vapor
200.00	11.000	5.3755	0.18603	2617.6	2822.3	6.6415	1.7921	2.5010	515.27	2.4385	1.5862e-05	0.037701	vapor
200.00	12.000	5.9053	0.16934	2612.9	2816.1	6.5909	1.8370	2.5825	513.05	2.4425	1.5830e-05	0.038205	vapor
200.00	13.000	6.4439	0.15519	2607.9	2809.6	6.5431	1.8885	2.6751	510.71	2.4465	1.5798e-05	0.038722	vapor
200.00	14.000	6.9918	0.14303	2602.7	2803.0	6.4975	1.9486	2.7823	508.21	2.4506	1.5765e-05	0.039255	vapor
200.00	15.000	7.5498	0.13245	2597.3	2796.0	6.4536	2.0206	2.9091	505.51	2.4545	1.5733e-05	0.039804	vapor
200.00	15.549	7.8610	0.12721	2594.2	2792.0	6.4302	2.0666	2.9895	503.92	2.4564	1.5715e-05	0.040113	vapor
200.00	15.549	864.66	0.0011565	850.47	852.27	2.3305	3.3179	4.4958	1332.1	-0.0089421	0.00013432	0.66331	liquid
200.00	16.000	864.69	0.0011565	850.44	852.29	2.3305	3.3179	4.4956	1332.2	-0.0089464	0.00013433	0.66335	liquid
200.00	17.000	864.77	0.0011564	850.36	852.33	2.3303	3.3178	4.4950	1332.6	-0.0089561	0.00013435	0.66344	liquid
200.00	18.000	864.85	0.0011563	850.29	852.37	2.3301	3.3178	4.4944	1332.9	-0.0089657	0.00013438	0.66353	liquid
200.00	19.000	864.92	0.0011562	850.21	852.41	2.3300	3.3177	4.4938	1333.3	-0.0089753	0.00013440	0.66362	liquid
200.00	20.000	865.00	0.0011561	850.14	852.45	2.3298	3.3176	4.4932	1333.7	-0.0089849	0.00013443	0.66370	liquid

Fig. 3.23d. Properties of Water from NIST

In the same window, **auxiliary data** for water is also given:

Reference States

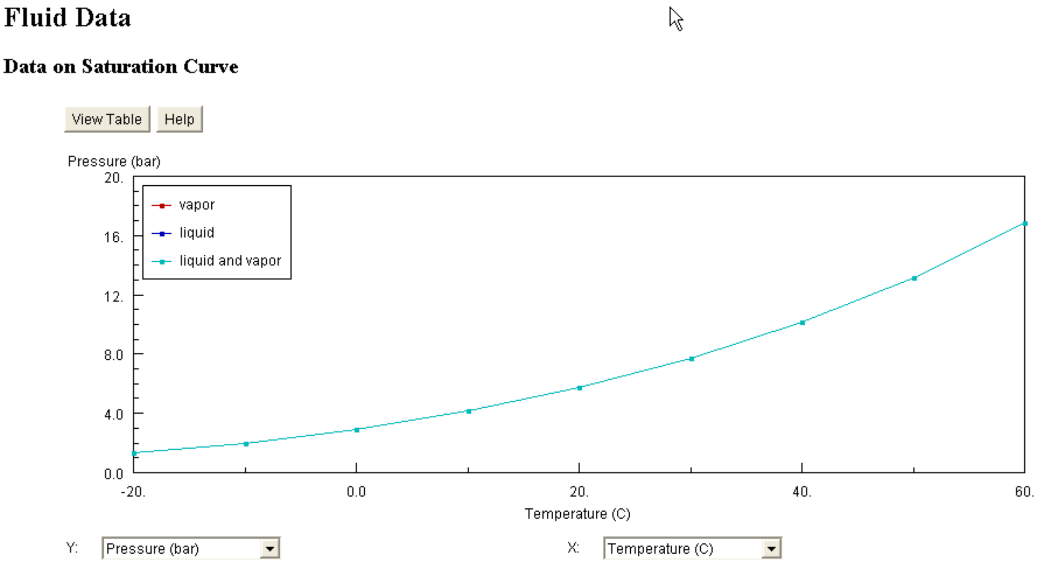
Internal energy	U = 0 at 273.16 K for saturated liquid.
Entropy	S = 0 at 273.16 K for saturated liquid.

Additional fluid data

Critical temperature (T_c)	373.946 C
Critical pressure (P_c)	220.640 bar
Critical density (D_c)	322.000000 kg/m3
Acentric factor	0.3443
Normal boiling point	99.9743 C
Dipole moment	1.855 Debye

Finally, the references are also shown in the same window.

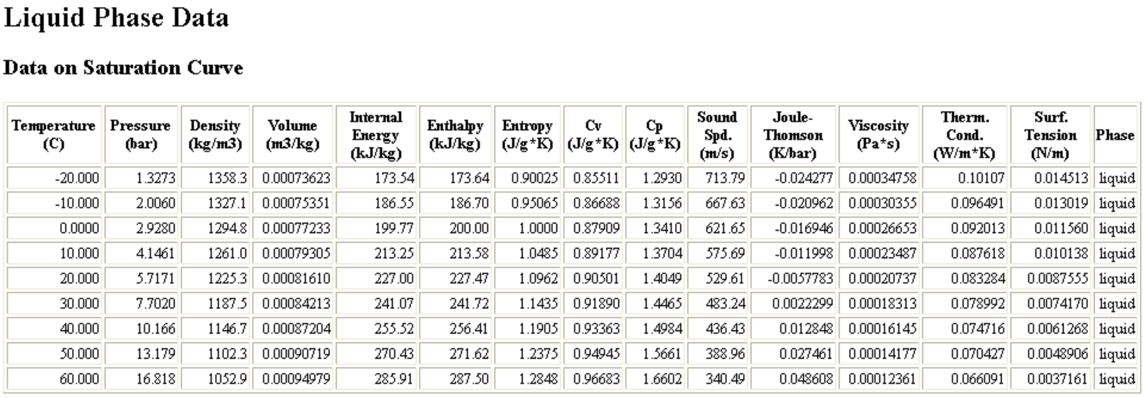
As another example, proceeding in a similar manner, following P-T graph and Table of data is obtained for Saturation properties for **R134a:**



Fluid Data

Data on Saturation Curve

Fig. 3.24a. Properties of R134a from NIST

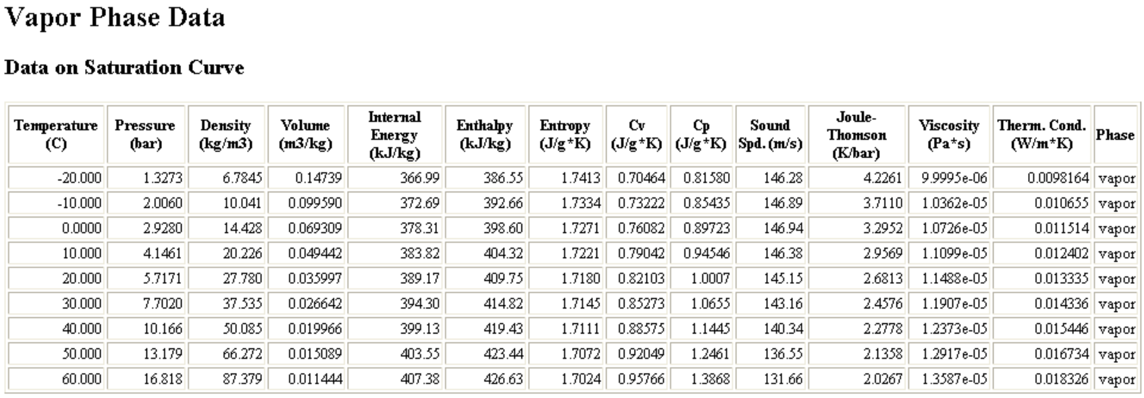


Liquid Phase Data

Data on Saturation Curve

Temperature (C)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)	Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Surf. Tension (N/m)	Phase
-20.000	1.3273	1358.3	0.00073623	173.54	173.64	0.90025	0.85511	1.2930	713.79	-0.024277	0.00034758	0.10107	0.014513	liquid
-10.000	2.0060	1327.1	0.00075351	186.55	186.70	0.95065	0.86688	1.3156	667.63	-0.020962	0.00030355	0.096491	0.013019	liquid
0.0000	2.9280	1294.8	0.00077233	199.77	200.00	1.0000	0.87909	1.3410	621.65	-0.016946	0.00026653	0.092013	0.011560	liquid
10.000	4.1461	1261.0	0.00079305	213.25	213.58	1.0485	0.89177	1.3704	575.69	-0.011998	0.00023487	0.087618	0.010138	liquid
20.000	5.7171	1225.3	0.00081610	227.00	227.47	1.0962	0.90501	1.4049	529.61	-0.0057783	0.00020737	0.083284	0.0087555	liquid
30.000	7.7020	1187.5	0.00084213	241.07	241.72	1.1435	0.91890	1.4465	483.24	0.0022299	0.00018313	0.078992	0.0074170	liquid
40.000	10.166	1146.7	0.00087204	255.52	256.41	1.1905	0.93363	1.4984	436.43	0.012848	0.00016145	0.074716	0.0061268	liquid
50.000	13.179	1102.3	0.00090719	270.43	271.62	1.2375	0.94945	1.5661	388.96	0.027461	0.00014177	0.070427	0.0048906	liquid
60.000	16.818	1052.9	0.00094979	285.91	287.50	1.2848	0.96683	1.6602	340.49	0.048608	0.00012361	0.066091	0.0037161	liquid

Fig. 3.24b. Properties of R134a from NIST



Vapor Phase Data

Data on Saturation Curve

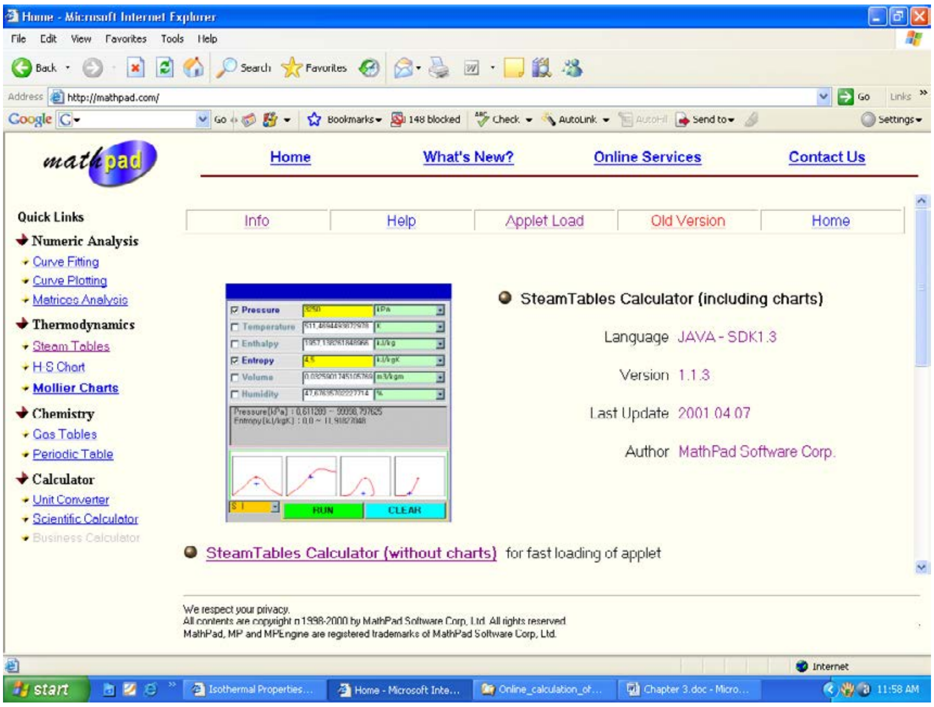
Temperature (C)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)	Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase
-20.000	1.3273	6.7845	0.14739	366.99	386.55	1.7413	0.70464	0.81580	146.28	4.2261	9.9995e-06	0.0098164	vapor
-10.000	2.0060	10.041	0.099590	372.69	392.66	1.7334	0.73222	0.85435	146.89	3.7110	1.0362e-05	0.010655	vapor
0.0000	2.9280	14.428	0.069309	378.31	398.60	1.7271	0.76082	0.89723	146.94	3.2952	1.0726e-05	0.011514	vapor
10.000	4.1461	20.226	0.049442	383.82	404.32	1.7221	0.79042	0.94546	146.38	2.9569	1.1099e-05	0.012402	vapor
20.000	5.7171	27.780	0.035997	389.17	409.75	1.7180	0.82103	1.0007	145.15	2.6813	1.1488e-05	0.013335	vapor
30.000	7.7020	37.535	0.026642	394.30	414.82	1.7145	0.85273	1.0655	143.16	2.4576	1.1907e-05	0.014336	vapor
40.000	10.166	50.085	0.019966	399.13	419.43	1.7111	0.88575	1.1445	140.34	2.2778	1.2373e-05	0.015446	vapor
50.000	13.179	66.272	0.015089	403.55	423.44	1.7072	0.92049	1.2461	136.55	2.1358	1.2917e-05	0.016734	vapor
60.000	16.818	87.379	0.011444	407.38	426.63	1.7024	0.95766	1.3868	131.66	2.0267	1.3587e-05	0.018326	vapor

Fig. 3.24c. Properties of R134a from NIST

3.4.4.2 From Mathpad Website:[Ref:8]

This gives data and plots for properties of Water/Steam only.

Go to www.mathpad.com. Press ‘Steam Tables’. We get:



Address: http://mathpad.com/

Quick Links
- Numeric Analysis
  - Curve Fitting
  - Curve Plotting
  - Matrices Analysis
- Thermodynamics
  - Steam Tables
  - H S Chart
  - Mollier Charts
- Chemistry
  - Gas Tables
  - Periodic Table
- Calculator
  - Unit Converter
  - Scientific Calculator
  - Business Calculator

● SteamTables Calculator (including charts)

Language JAVA - SDK1.3

Version 1.1.3

Last Update 2001.04.07

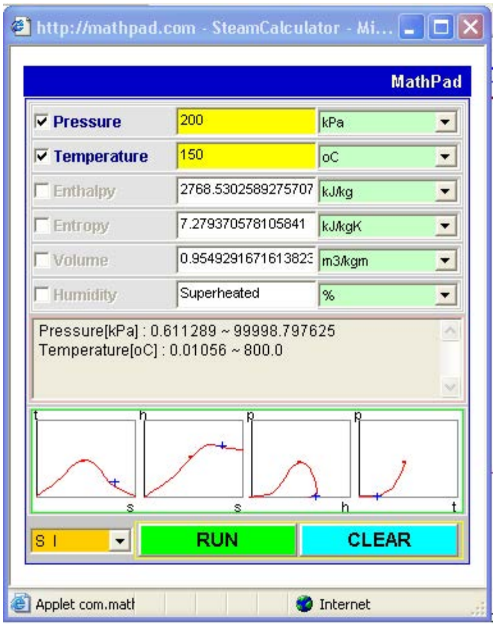
Author MathPad Software Corp.

● SteamTables Calculator (without charts) for fast loading of applet

We respect your privacy.
All contents are copyright n 1998-2000 by MathPad Software Corp, Ltd. All rights reserved.
MathPad, MP and MPEngine are registered trademarks of MathPad Software Corp, Ltd.

Fig. 3.25a. Properties of H2O from Mathpad

Note that there are two versions of this calculator: one, including charts and the other without charts. Click on the RUN. We get the following screen. Chose SI units. Select Pressure and Temperature; Available range for these properties is immediately indicated, and enter the values of P and T as 200 kPa and 150 deg.C and press ‘RUN’. We get the following. Note that location of the state is indicated by cross hairs on the plots.



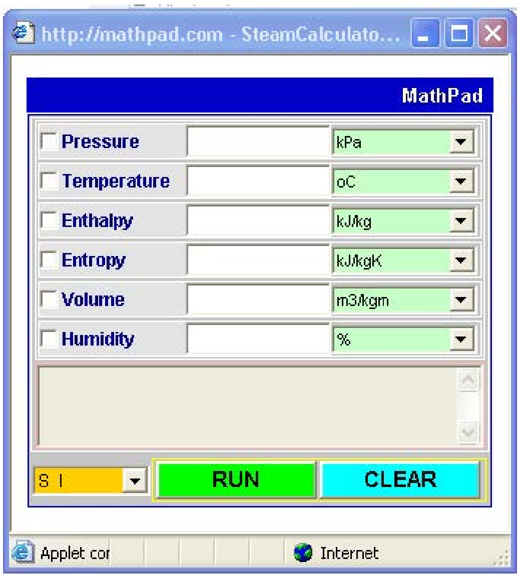
☑ Pressure	200	kPa
☑ Temperature	150	oC
☐ Enthalpy	2768.5302589275707	kJ/kg
☐ Entropy	7.279370578105841	kJ/kgK
☐ Volume	0.9549291671613823	m3/kgm
☐ Humidity	Superheated	%

Pressure[kPa] : 0.611289 ~ 99998.797625
Temperature[oC] : 0.01056 ~ 800.0

S I

Fig. 3.25b. Properties of H2O from Mathpad

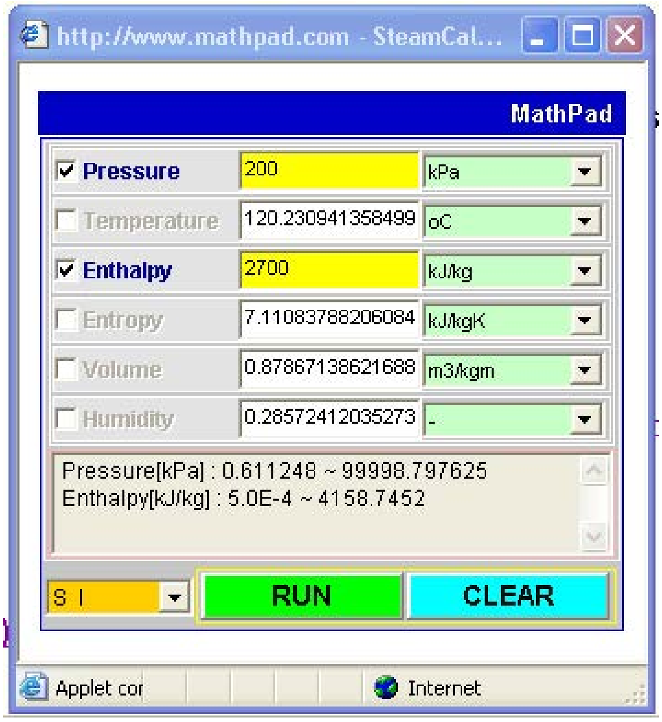
If you click on the 'Steam Tables calculator (without charts)', you get the following screen:



☐ Pressure kPa
☐ Temperature oC
☐ Enthalpy kJ/kg
☐ Entropy kJ/kgK
☐ Volume m3/kgm
☐ Humidity %
S I

Fig. 3.25c. Properties of H2O from Mathpad

Chose SI units. Select Pressure and Enthalpy. Available range for these properties is immediately indicated, and enter the values of P and h as 200 kPa and 2700 kJ/kg and press ‘RUN’. We get the following:



☑ Pressure 200 kPa
☐ Temperature 120.230941358499 oC
☑ Enthalpy 2700 kJ/kg
☐ Entropy 7.11083788206084 kJ/kgK
☐ Volume 0.87867138621688 m3/kgm
☐ Humidity 0.28572412035273 -

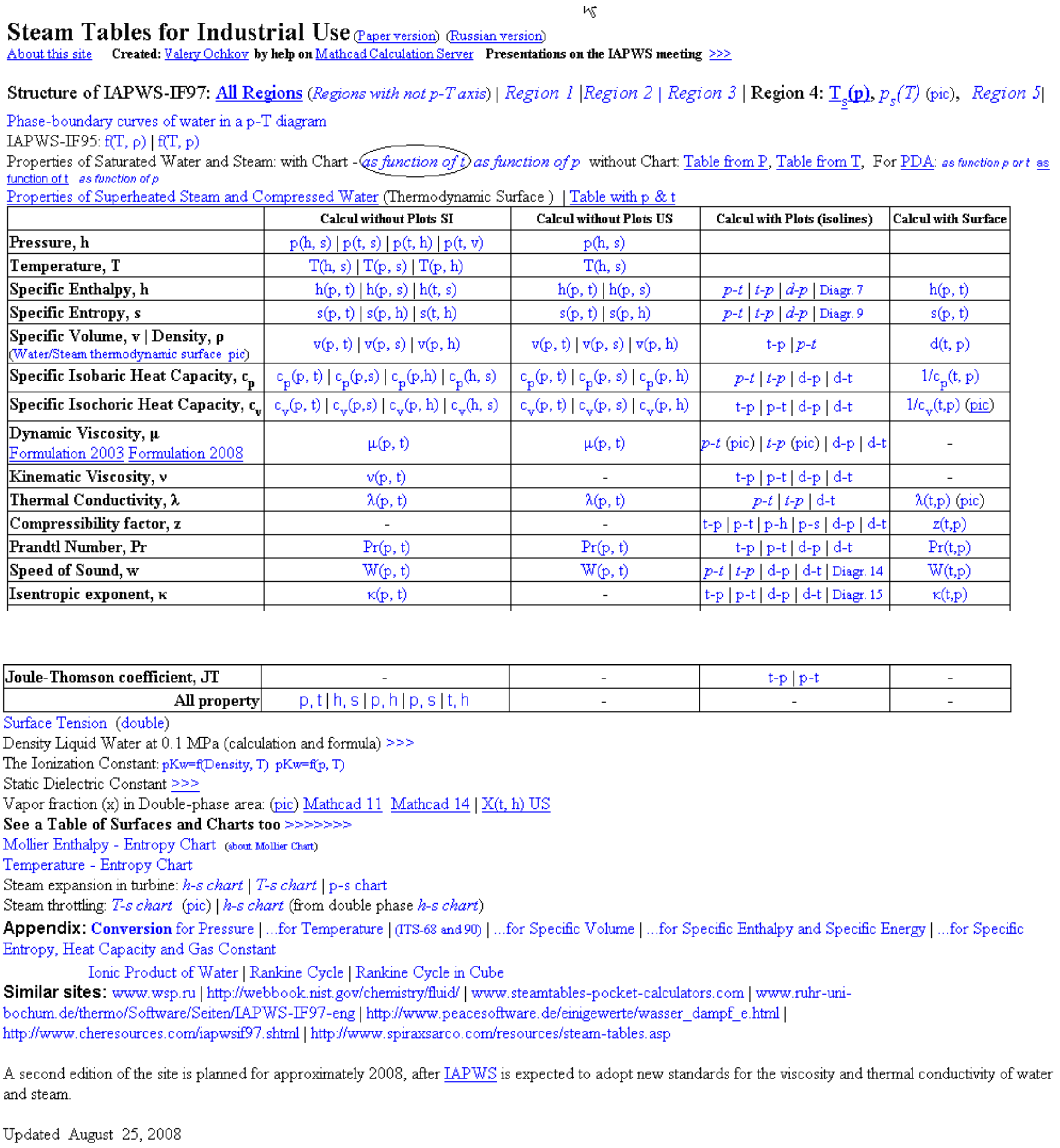
Pressure[kPa] : 0.611248 ~ 99998.797625
Enthalpy[kJ/kg] : 5.0E-4 ~ 4158.7452

S I

Fig. 3.25d. Properties of H2O from Mathpad

3.4.4.3 From Moscow Power Engg. Institute (MPEI) Website [Ref: 13]:

Properties of Water/Steam are presented in a comprehensive manner in this Website. Data are calculated in a Mathcad calculation server. As you open the website, following screen is presented, with several possible choices.



Steam Tables for Industrial Use (Paper version) (Russian version)
About this site **Created:** Valery Ochkov **by help on** Mathcad Calculation Server **Presentations on the IAPWS meeting** >>>

Structure of IAPWS-IF97: **All Regions** (*Regions with not p-T axis*) | *Region 1* |*Region 2* | *Region 3* | **Region 4:** T_s(p), $p_s(T)$ (pic), *Region 5*|
Phase-boundary curves of water in a p-T diagram
IAPWS-IF95: f(T, ρ) | f(T, p)
Properties of Saturated Water and Steam: with Chart - *as function of t* *as function of p* without Chart: Table from P, Table from T, For PDA: *as function p or t* as function of t *as function of p*
Properties of Superheated Steam and Compressed Water (Thermodynamic Surface) | Table with p & t

	Calcul without Plots SI	Calcul without Plots US	Calcul with Plots (isolines)	Calcul with Surface
Pressure, h	p(h, s) | p(t, s) | p(t, h) | p(t, v)	p(h, s)		
Temperature, T	T(h, s) | T(p, s) | T(p, h)	T(h, s)		
Specific Enthalpy, h	h(p, t) | h(p, s) | h(t, s)	h(p, t) | h(p, s)	*p-t* | *t-p* | *d-p* | Diagr. 7	h(p, t)
Specific Entropy, s	s(p, t) | s(p, h) | s(t, h)	s(p, t) | s(p, h)	*p-t* | *t-p* | *d-p* | Diagr. 9	s(p, t)
Specific Volume, v | Density, ρ (Water/Steam thermodynamic surface pic)	v(p, t) | v(p, s) | v(p, h)	v(p, t) | v(p, s) | v(p, h)	t-p | *p-t*	d(t, p)
Specific Isobaric Heat Capacity, c_p	c_p(p, t) | c_p(p,s) | c_p(p,h) | c_p(h, s)	c_p(p, t) | c_p(p, s) | c_p(p, h)	*p-t* | *t-p* | d-p | d-t	1/c_p(t, p)
Specific Isochoric Heat Capacity, c_v	c_v(p, t) | c_v(p,s) | c_v(p, h) | c_v(h, s)	c_v(p, t) | c_v(p, s) | c_v(p, h)	t-p | p-t | d-p | d-t	1/c_v(t,p) (pic)
Dynamic Viscosity, μ Formulation 2003 Formulation 2008	μ(p, t)	μ(p, t)	*p-t* (pic) | *t-p* (pic) | d-p | d-t	-
Kinematic Viscosity, ν	ν(p, t)	-	t-p | p-t | d-p | d-t	-
Thermal Conductivity, λ	λ(p, t)	λ(p, t)	*p-t* | *t-p* | d-t	λ(t,p) (pic)
Compressibility factor, z	-	-	t-p | p-t | p-h | p-s | d-p | d-t	z(t,p)
Prandtl Number, Pr	Pr(p, t)	Pr(p, t)	t-p | p-t | d-p | d-t	Pr(t,p)
Speed of Sound, w	W(p, t)	W(p, t)	*p-t* | *t-p* | d-p | d-t | Diagr. 14	W(t,p)
Isentropic exponent, κ	κ(p, t)	-	t-p | p-t | d-p | d-t | Diagr. 15	κ(t,p)
Joule-Thomson coefficient, JT	-	-	t-p | p-t	-
All property	p, t | h, s | p, h | p, s | t, h	-	-	-

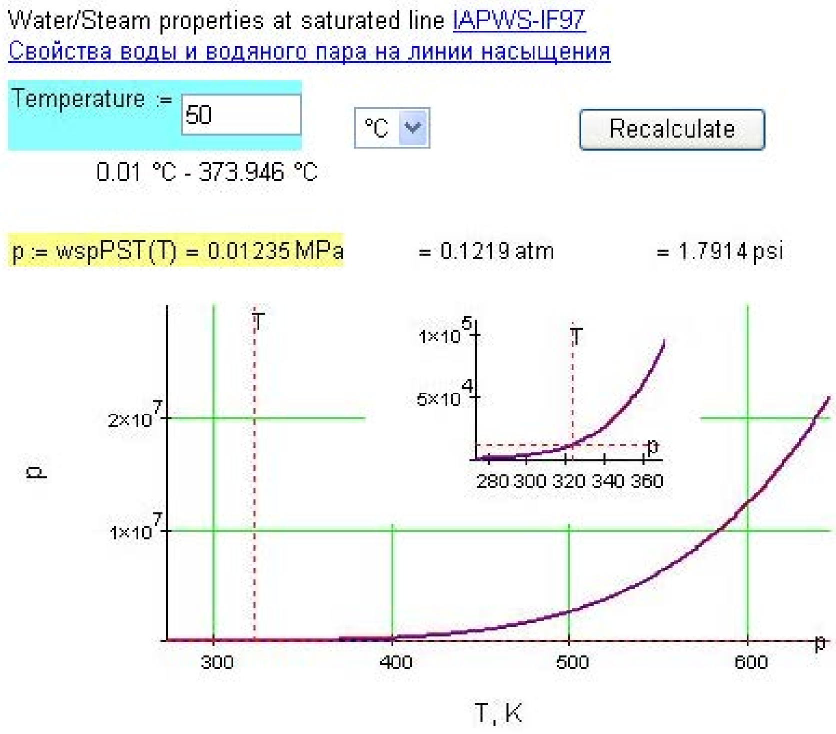
Surface Tension (double)
Density Liquid Water at 0.1 MPa (calculation and formula) >>>
The Ionization Constant: pKw=f(Density, T) pKw=f(p, T)
Static Dielectric Constant >>>
Vapor fraction (x) in Double-phase area: (pic) Mathcad 11 Mathcad 14 | X(t, h) US
See a Table of Surfaces and Charts too >>>>>>>
Mollier Enthalpy - Entropy Chart (about Mollier Chart)
Temperature - Entropy Chart
Steam expansion in turbine: *h-s chart* | *T-s chart* | p-s chart
Steam throttling: *T-s chart* (pic) | *h-s chart* (from double phase *h-s chart*)
Appendix: **Conversion** for Pressure | ...for Temperature | (ITS-68 and 90) | ...for Specific Volume | ...for Specific Enthalpy and Specific Energy | ...for Specific Entropy, Heat Capacity and Gas Constant
Ionic Product of Water | Rankine Cycle | Rankine Cycle in Cube
Similar sites: www.wsp.ru | http://webbook.nist.gov/chemistry/fluid/ | www.steamtables-pocket-calculators.com | www.ruhr-uni-bochum.de/thermo/Software/Seiten/IAPWS-IF97-eng | http://www.peacesoftware.de/einigewerte/wasser_dampf_e.html | http://www.cheresources.com/iapwsif97.shtml | http://www.spiraxsarco.com/resources/steam-tables.asp

A second edition of the site is planned for approximately 2008, after IAPWS is expected to adopt new standards for the viscosity and thermal conductivity of water and steam.

Updated August 25, 2008

Fig. 3.26. Properties of H2O from MPEI

As an example of its use, let us calculate the properties of sat. water and steam with chart as a function of temperature (t). Click on the appropriate button on the page as shown and enter 50 deg.C for t; following results and plots appear:



Water/Steam properties at saturated line IAPWS-IF97
Свойства воды и водяного пара на линии насыщения

Temperature := 50 °C
0.01 °C - 373.946 °C

p := wspPST(T) = 0.01235 MPa = 0.1219 atm = 1.7914 psi

Энтальпия Enthalpy--

h' := wspHSWT(T) = 209.336 kJ/kg   h' = 49.999 kcal/kg   h' = 89.998 Btu/lb

h" := wspHSST(T) = 2591.31 kJ/kg   h" = 618.924 kcal/kg   h" = 1114.063 Btu/lb

r := wspRST(T) = 2381.974 kJ/kg   r = 568.925 kcal/kg   r = 1024.065 Btu/lb

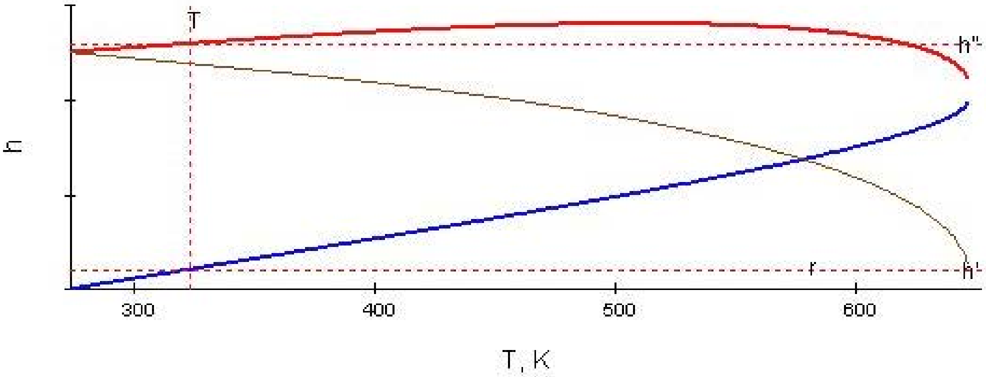
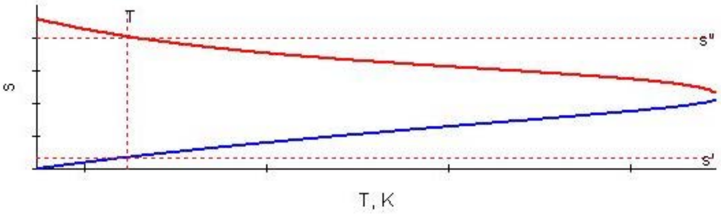


Fig. 3.27 a,b. Properties of H2O from MPEI

Энтропия Entropy---

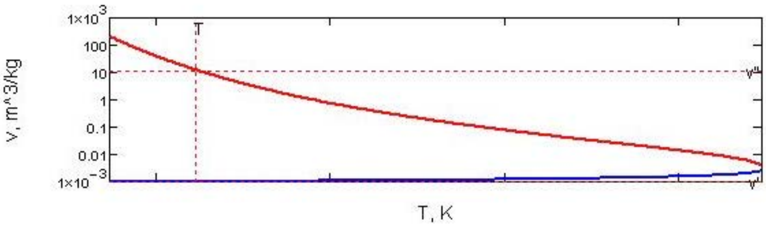
s' := wspSSWT(T) = 0.70379 kJ/(kg K)   s' = 0.1681 Btu/(lb °R) or kcal/(kg °C)

s" := wspSSST(T) = 8.07491 kJ/(kg K)   s" = 1.92866 Btu/(lb °R) or kcal/(kg °C)



v' := wspVSWT(T) = $1.01214 \times 10^{-3}\ m^3/kg$ v' = $0.016213\ ft^3/lb$

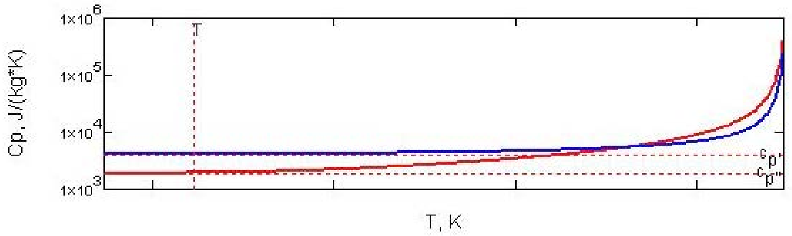
v" := wspVSST(T) = $12.02786\ m^3/kg$ v" = $192.667901\ ft^3/lb$



Удельная изобарная теплоемкость Specific isobaric heat capacity--

$c_{p'}$:= wspCPSWT(T) = 4.17976 kJ/(kg K) $c_{p'}$ = 0.99832 Btu/(lb °R) or kcal/(kg °C)

$c_{p''}$:= wspCPSST(T) = 1.94825 kJ/(kg K) $c_{p''}$ = 0.46533 Btu/(lb °R) or kcal/(kg °C)



Удельная изохорная теплоемкость Specific isochoric heat capacity--

$c_{v'}$:= wspCVSWT(T) = 4.0243 kJ/(kg K) $c_{v'}$ = 0.9612 Btu/(lb °R) or kcal/(kg °C)

$c_{v''}$:= wspCVSST(T) = 1.4675 kJ/(kg K) $c_{v''}$ = 0.3505 Btu/(lb °R) or kcal/(kg °C)

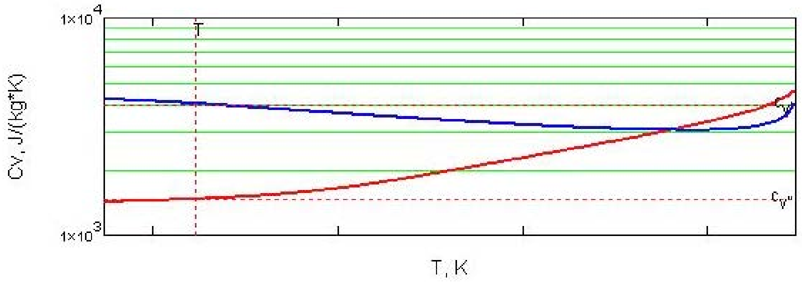
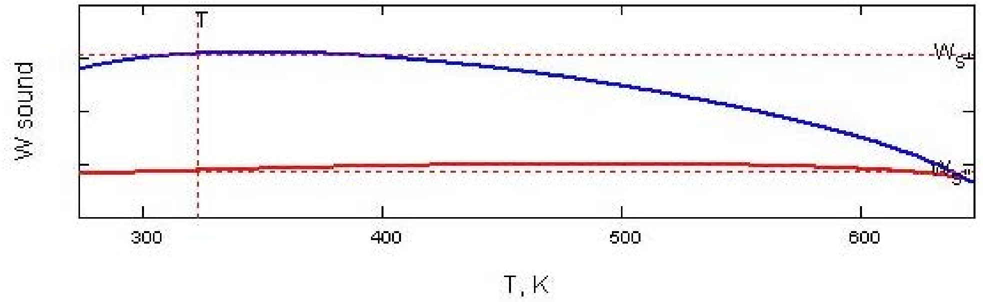


Fig. 3.27 c,d,e,f. Properties of H2O from MPEI

Скорость звука Sound speed--

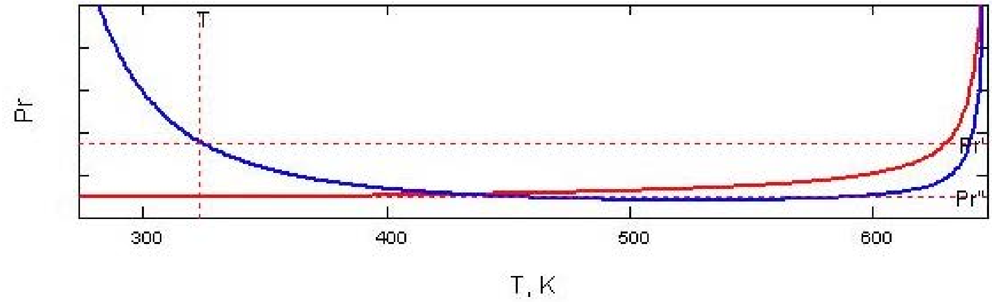
$W_{s'}$:= wspWSWT(T) = 1545.176 m/s $W_{s'}$ = 5562.632 km/h

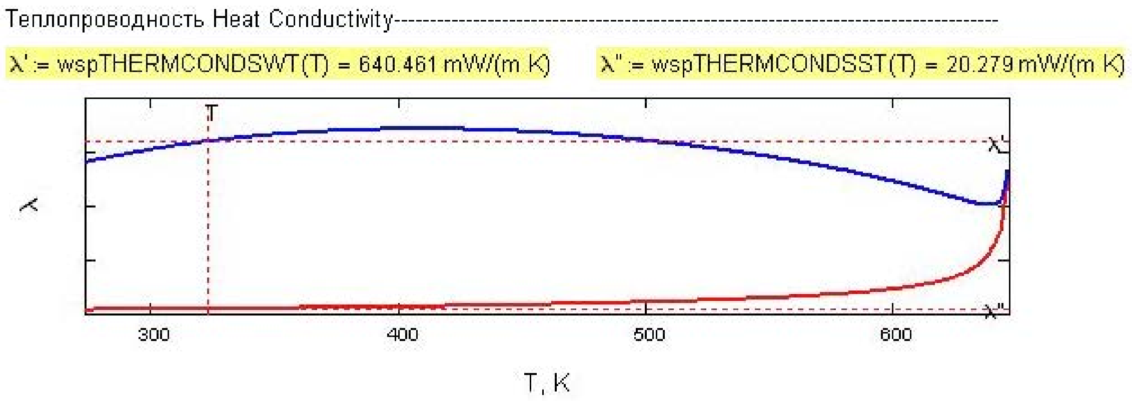
$W_{s''}$:= wspWSST(T) = 443.203 m/s $W_{s''}$ = 1595.532 km/h



Число Прандтля Prandtl number---

Pr' := wspPRANDTLESWT(T) = 3.56658   Pr" := wspPRANDTLESST(T) = 1.01036

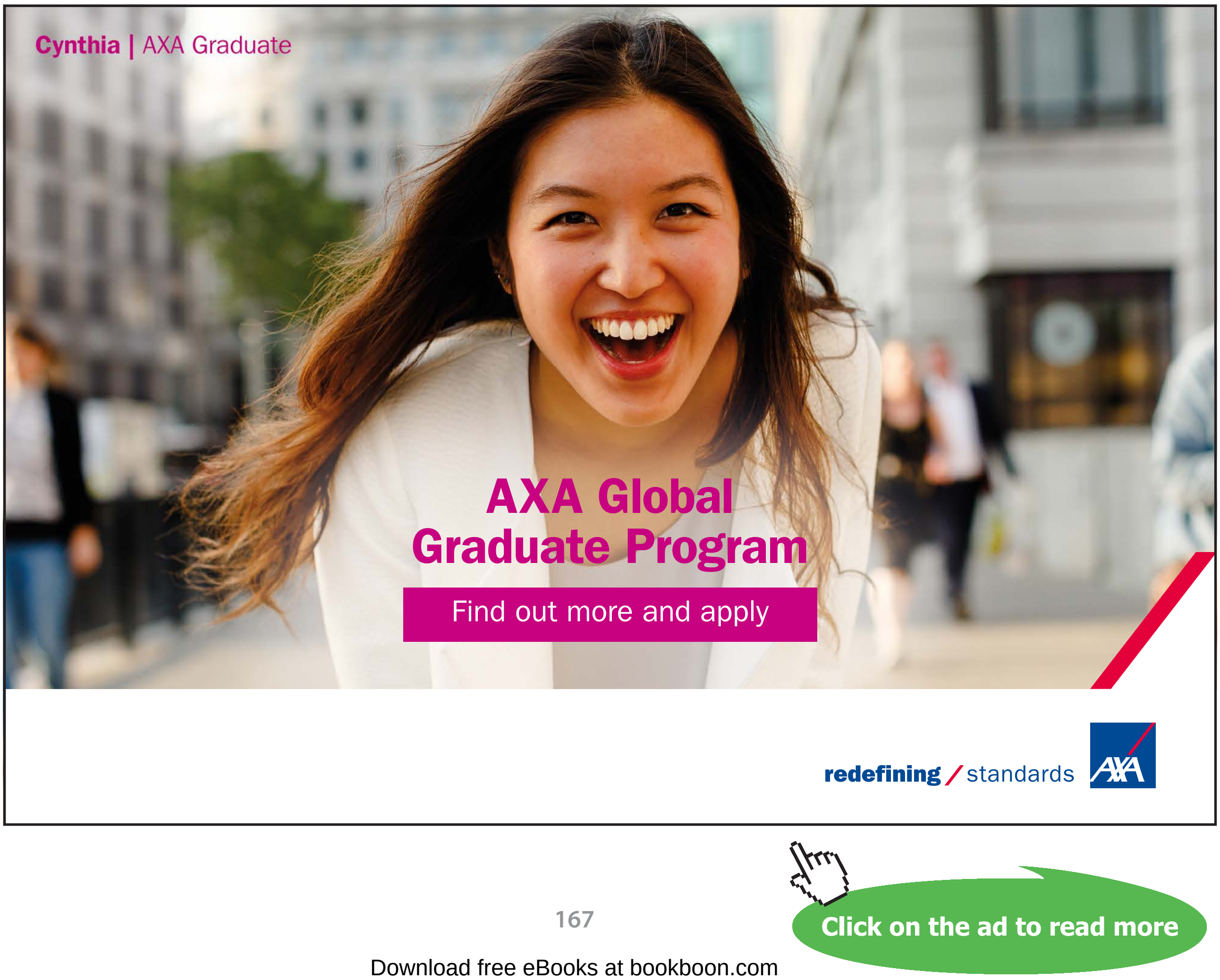




Теплопроводность Heat Conductivity---

λ' := wspTHERMCONDSWT(T) = 640.461 mW/(m K)   λ'' := wspTHERMCONDSST(T) = 20.279 mW/(m K)

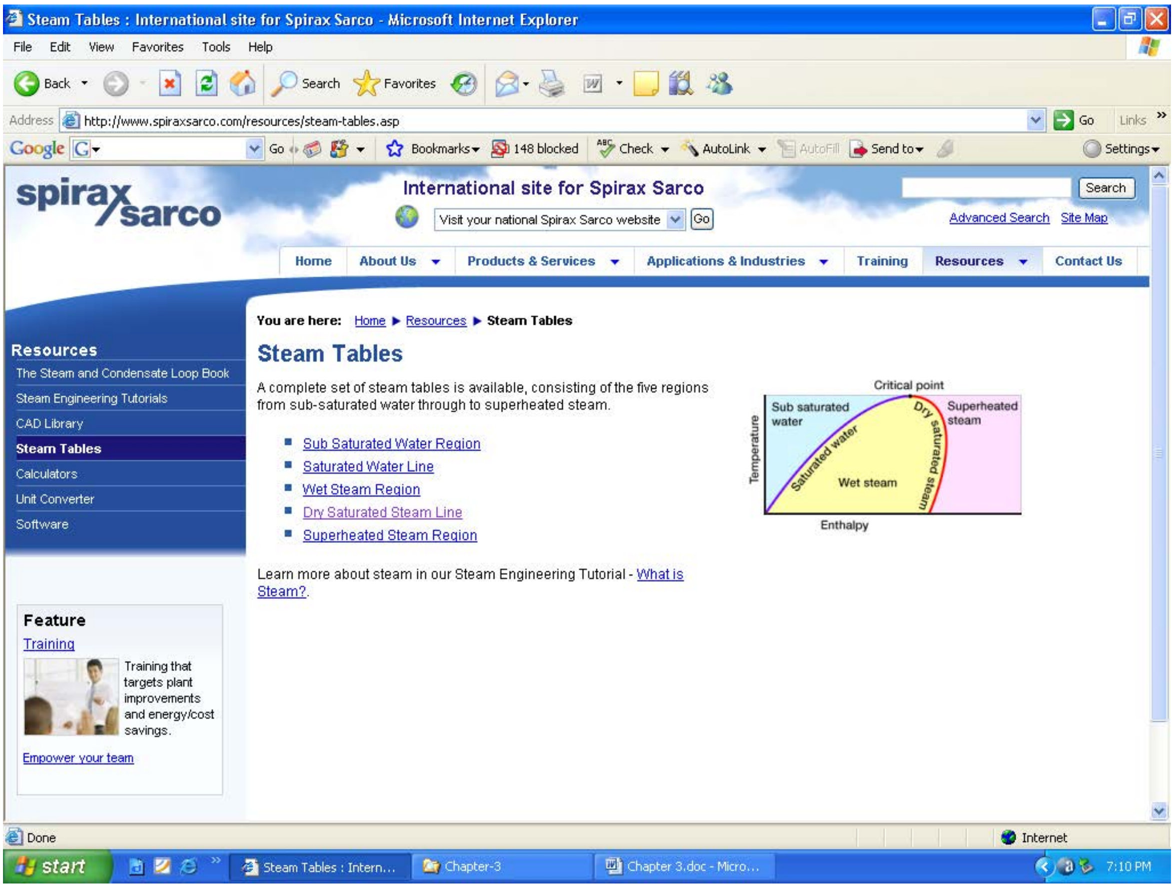
Fig. 3.27 g,h,i. Properties of H2O from MPEI



3.4.4.4 From Spirax Sarco Website:[Ref:14]

(Ref: http://www.spiraxsarco.com/resources/steam-tables.asp)

This is a very informative website for steam; it contains lot of information and useful tutorials, in addition to steam table calculation software. When you click on the above link, following window appears:



You are here: Home ▶ Resources ▶ Steam Tables

Steam Tables

A complete set of steam tables is available, consisting of the five regions from sub-saturated water through to superheated steam.

- Sub Saturated Water Region
- Saturated Water Line
- Wet Steam Region
- Dry Saturated Steam Line
- Superheated Steam Region

Learn more about steam in our Steam Engineering Tutorial - What is Steam?.

Feature

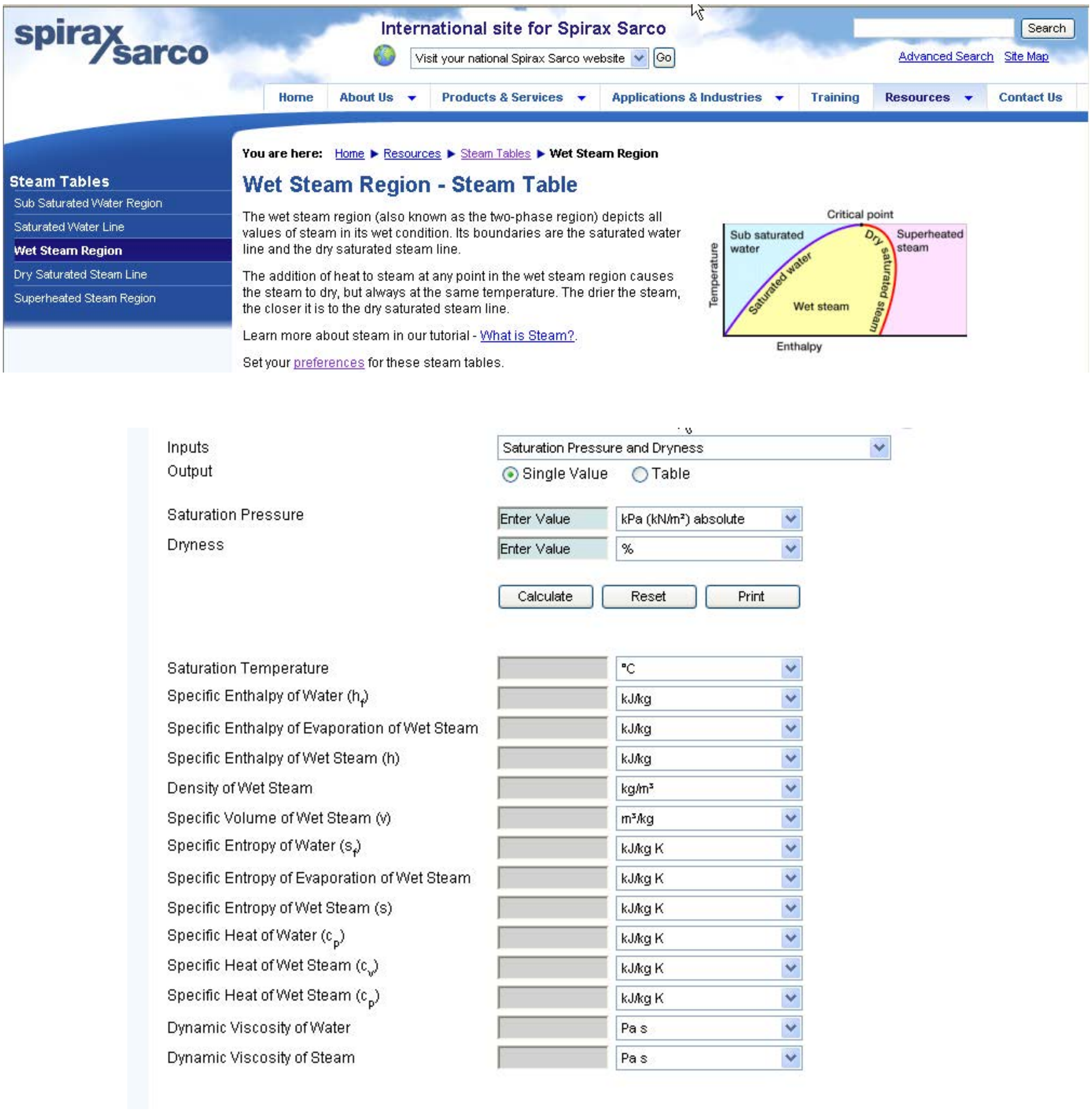
Training

Training that targets plant improvements and energy/cost savings.

Empower your team

Fig. 3.28a. Properties of H2O from Spirax Sarco

We can get steam tables in any of the five regions by clicking on the appropriate link. Let us click on the wet steam region:



You are here: Home ▶ Resources ▶ Steam Tables ▶ Wet Steam Region

Wet Steam Region - Steam Table

The wet steam region (also known as the two-phase region) depicts all values of steam in its wet condition. Its boundaries are the saturated water line and the dry saturated steam line.

The addition of heat to steam at any point in the wet steam region causes the steam to dry, but always at the same temperature. The drier the steam, the closer it is to the dry saturated steam line.

Learn more about steam in our tutorial - What is Steam?.

Set your preferences for these steam tables.

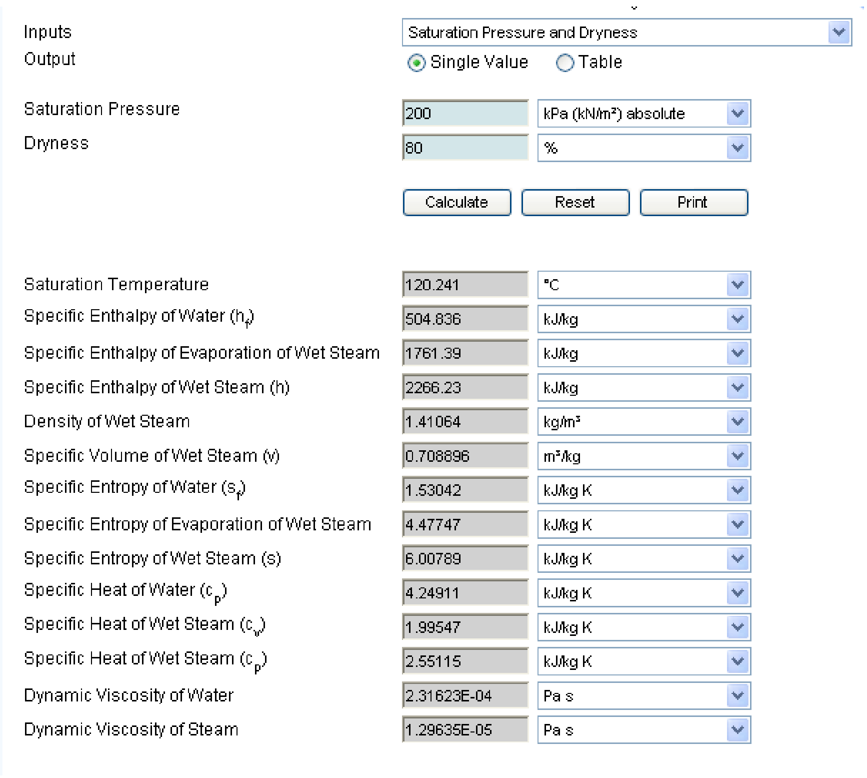
Inputs: Saturation Pressure and Dryness
Output: ● Single Value ○ Table

Saturation Pressure: Enter Value kPa (kN/m²) absolute
Dryness: Enter Value %

Saturation Temperature: °C
Specific Enthalpy of Water (h_f): kJ/kg
Specific Enthalpy of Evaporation of Wet Steam: kJ/kg
Specific Enthalpy of Wet Steam (h): kJ/kg
Density of Wet Steam: kg/m³
Specific Volume of Wet Steam (v): m³/kg
Specific Entropy of Water (s_f): kJ/kg K
Specific Entropy of Evaporation of Wet Steam: kJ/kg K
Specific Entropy of Wet Steam (s): kJ/kg K
Specific Heat of Water (c_p): kJ/kg K
Specific Heat of Wet Steam (c_v): kJ/kg K
Specific Heat of Wet Steam (c_p): kJ/kg K
Dynamic Viscosity of Water: Pa s
Dynamic Viscosity of Steam: Pa s

Fig. 3.28b. Properties of H2O from Spirax Sarco

Note that you can get output for a single point (state) or you can generate a table for a set of states. Let us get property at a single point. Input can be pressure and quality (dryness) or other combinations which can be chosen from the widget. For now, enter Psat = 200 kPa and dryness = 80%. Press 'Calculate'. You get:



Inputs	Saturation Pressure and Dryness	
Output	● Single Value ○ Table	
Saturation Pressure	200	kPa (kN/m^2) absolute
Dryness	80	%
Saturation Temperature	120.241	°C
Specific Enthalpy of Water (h$_f$)	504.836	kJ/kg
Specific Enthalpy of Evaporation of Wet Steam	1761.39	kJ/kg
Specific Enthalpy of Wet Steam (h)	2266.23	kJ/kg
Density of Wet Steam	1.41064	kg/m^3
Specific Volume of Wet Steam (v)	0.708896	m^3/kg
Specific Entropy of Water (s$_f$)	1.53042	kJ/kg K
Specific Entropy of Evaporation of Wet Steam	4.47747	kJ/kg K
Specific Entropy of Wet Steam (s)	6.00789	kJ/kg K
Specific Heat of Water (c$_p$)	4.24911	kJ/kg K
Specific Heat of Wet Steam (c$_v$)	1.99547	kJ/kg K
Specific Heat of Wet Steam (c$_p$)	2.55115	kJ/kg K
Dynamic Viscosity of Water	2.31623E-04	Pa s
Dynamic Viscosity of Steam	1.29635E-05	Pa s

Fig. 3.28c. Properties of H2O from Spirax Sarco

3.4.5 Property Tables:

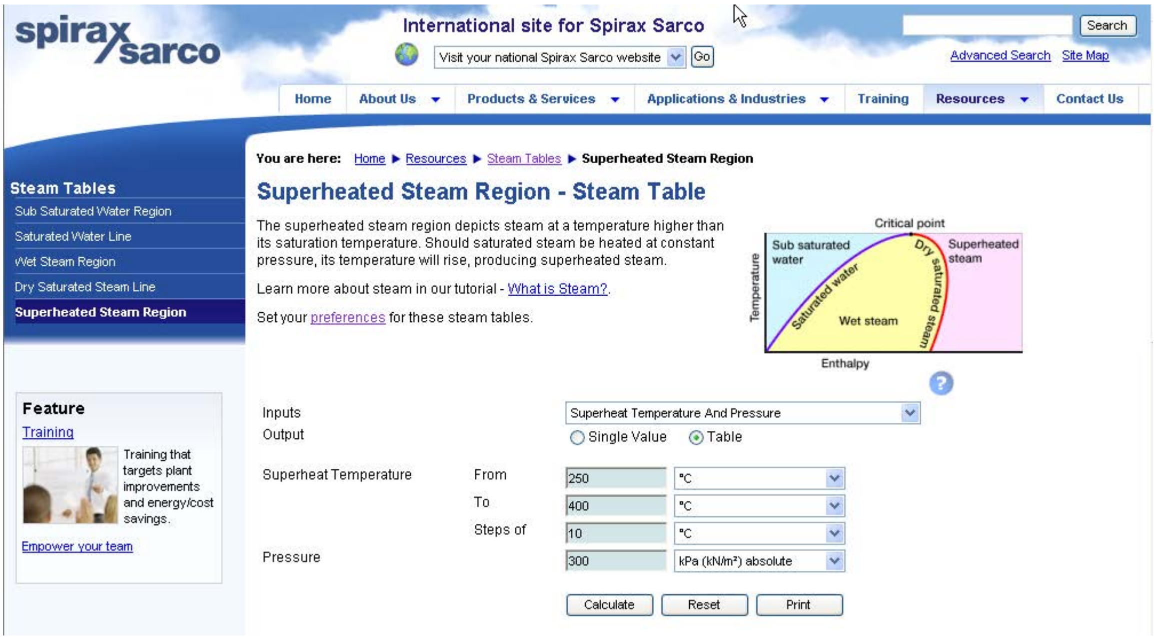
Many times, values of properties are required in a tabular form for reference. Tables can be obtained in the given range immediately from some of these software.

3.4.5.1 Property table from NIST:

This has already been explained under article 3.4.4. Advantage of NIST website is that you can get property table and several types of plots not only for Water but also for a very large number of fluids. So, it is a very useful site and should always be kept in mind while looking for properties of substances.

3.4.5.2 Property table from Spirax Sarco:

Click on http://www.spiraxsarco.com/resources/steam-tables.asp). Then click on Superheated region. Select the Inputs as Superheated temperature and pressure, and Outputs as Table:



You are here: Home ▶ Resources ▶ Steam Tables ▶ Superheated Steam Region

Superheated Steam Region - Steam Table

The superheated steam region depicts steam at a temperature higher than its saturation temperature. Should saturated steam be heated at constant pressure, its temperature will rise, producing superheated steam.

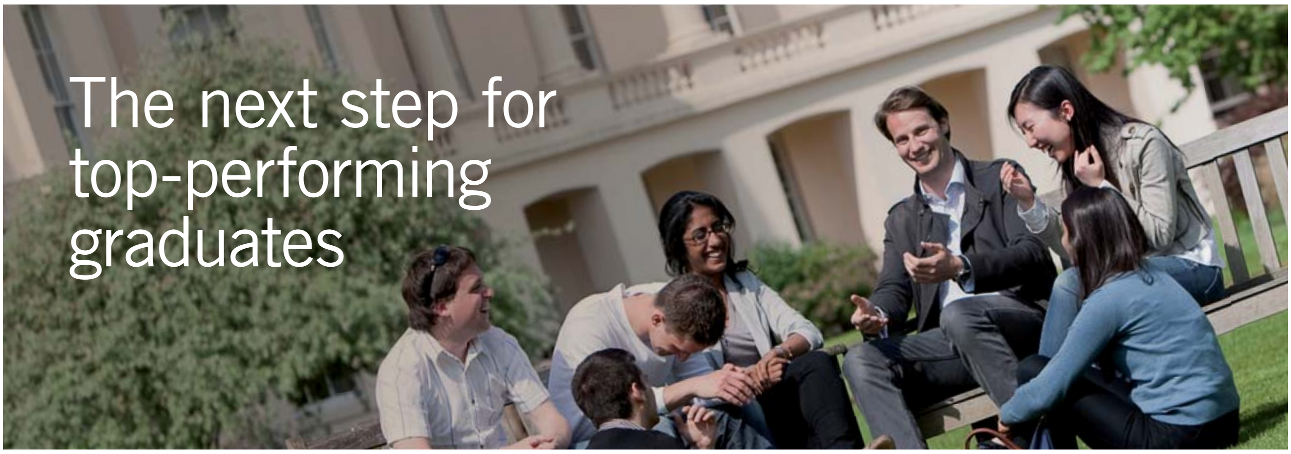
Learn more about steam in our tutorial - What is Steam?.

Set your preferences for these steam tables.

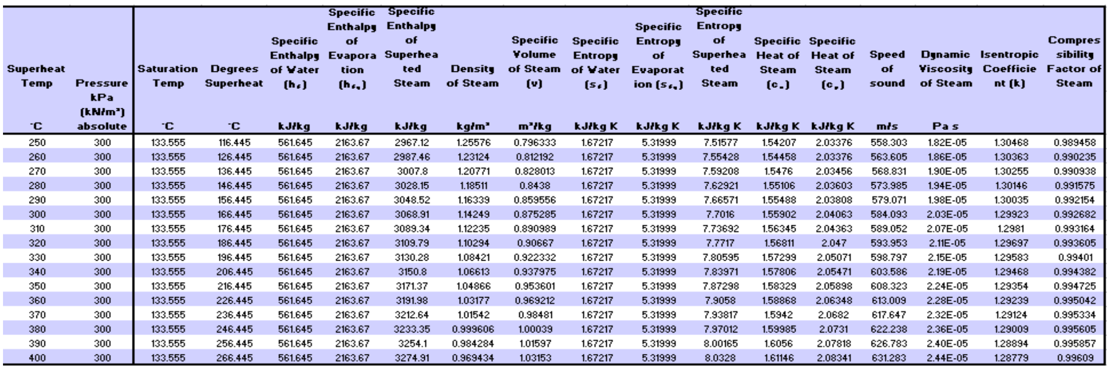
Training that targets plant improvements and energy/cost savings.

Inputs: Superheat Temperature And Pressure
Output: ○ Single Value ● Table
Superheat Temperature From 250 °C
To 400 °C
Steps of 10 °C
Pressure 300 kPa (kN/m²) absolute

Fig. 3.29a. Properties of H2O from Spirax Sarco



Enter the values for temperature range and pressure. Click on 'Calculate'. We get:



Superheat Temp °C	Pressure kPa (kN/m^2) absolute	Saturation Temp °C	Degrees Superheat °C	Specific Enthalpy of Water (h_f) kJ/kg	Specific Enthalpy of Evaporation (h_{fg}) kJ/kg	Specific Enthalpy of Superheated Steam kJ/kg	Density of Steam kg/m^3	Specific Volume of Steam (v) m^3/kg	Specific Entropy of Water (s_f) kJ/kg K	Specific Entropy of Evaporation (s_{fg}) kJ/kg K	Specific Entropy of Superheated Steam kJ/kg K	Specific Heat of Steam (c_v) kJ/kg K	Specific Heat of Steam (c_p) kJ/kg K	Speed of sound m/s	Dynamic Viscosity of Steam Pa s	Isentropic Coefficient (k)	Compressibility Factor of Steam
250	300	133.555	116.445	561.645	2163.67	2967.12	1.25576	0.796333	1.67217	5.31999	7.51577	1.54207	2.03376	558.303	1.82E-05	1.30468	0.989458
260	300	133.555	126.445	561.645	2163.67	2987.46	1.23124	0.812192	1.67217	5.31999	7.55428	1.54458	2.03376	563.605	1.86E-05	1.30363	0.990235
270	300	133.555	136.445	561.645	2163.67	3007.8	1.20771	0.828013	1.67217	5.31999	7.59208	1.5476	2.03456	568.831	1.90E-05	1.30255	0.990938
280	300	133.555	146.445	561.645	2163.67	3028.15	1.18511	0.8438	1.67217	5.31999	7.62921	1.55106	2.03603	573.985	1.94E-05	1.30146	0.991575
290	300	133.555	156.445	561.645	2163.67	3048.52	1.16339	0.859556	1.67217	5.31999	7.66571	1.55488	2.03808	579.071	1.98E-05	1.30035	0.992154
300	300	133.555	166.445	561.645	2163.67	3068.91	1.14249	0.875285	1.67217	5.31999	7.7016	1.55902	2.04063	584.093	2.03E-05	1.29923	0.992682
310	300	133.555	176.445	561.645	2163.67	3089.34	1.12235	0.890989	1.67217	5.31999	7.73692	1.56345	2.04363	589.052	2.07E-05	1.2981	0.993164
320	300	133.555	186.445	561.645	2163.67	3109.79	1.10294	0.90667	1.67217	5.31999	7.7717	1.56811	2.047	593.953	2.11E-05	1.29697	0.993605
330	300	133.555	196.445	561.645	2163.67	3130.28	1.08421	0.922332	1.67217	5.31999	7.80595	1.57299	2.05071	598.797	2.15E-05	1.29583	0.99401
340	300	133.555	206.445	561.645	2163.67	3150.8	1.06613	0.937975	1.67217	5.31999	7.83971	1.57806	2.05471	603.586	2.19E-05	1.29468	0.994382
350	300	133.555	216.445	561.645	2163.67	3171.37	1.04866	0.953601	1.67217	5.31999	7.87298	1.58329	2.05898	608.323	2.24E-05	1.29354	0.994725
360	300	133.555	226.445	561.645	2163.67	3191.98	1.03177	0.969212	1.67217	5.31999	7.9058	1.58868	2.06348	613.009	2.28E-05	1.29239	0.995042
370	300	133.555	236.445	561.645	2163.67	3212.64	1.01542	0.98481	1.67217	5.31999	7.93817	1.5942	2.0682	617.647	2.32E-05	1.29124	0.995334
380	300	133.555	246.445	561.645	2163.67	3233.35	0.999606	1.00039	1.67217	5.31999	7.97012	1.59985	2.0731	622.238	2.36E-05	1.29009	0.995605
390	300	133.555	256.445	561.645	2163.67	3254.1	0.984284	1.01597	1.67217	5.31999	8.00165	1.6056	2.07818	626.783	2.40E-05	1.28894	0.995857
400	300	133.555	266.445	561.645	2163.67	3274.91	0.969434	1.03153	1.67217	5.31999	8.0328	1.61146	2.08341	631.283	2.44E-05	1.28779	0.99609

Fig. 3.29b. Properties of H2O from Spirax Sarco

3.4.5.3 Property table from TEST:

Go to TEST – Map and click on 'Tables & Charts':

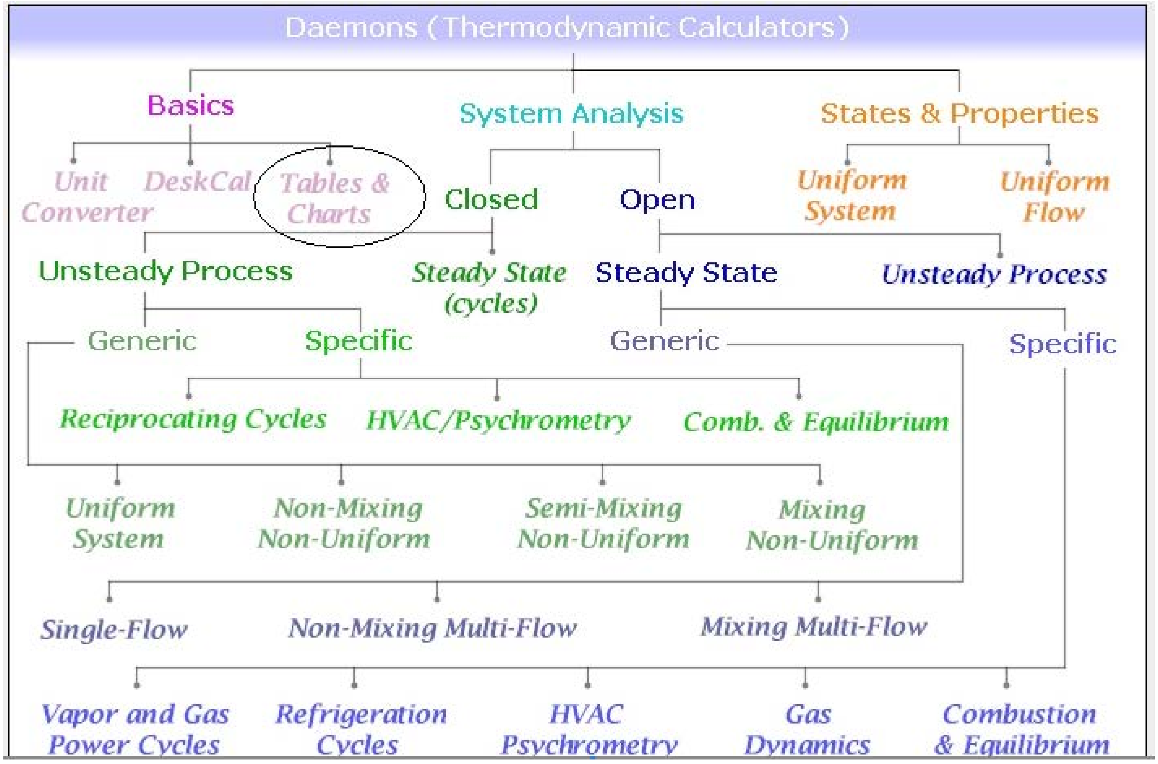
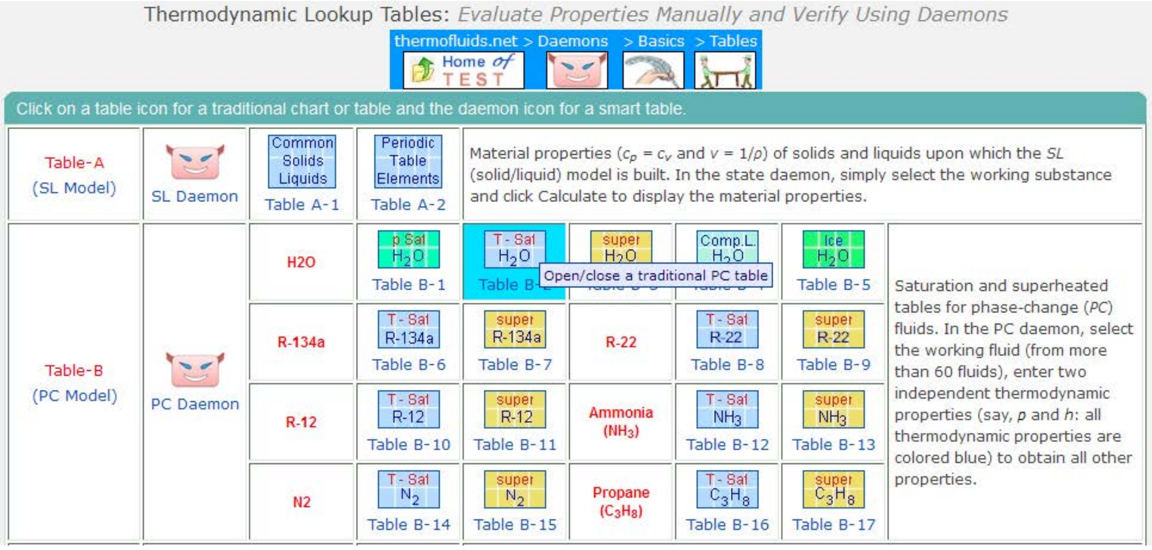


Fig. 3.30a. Property Table of H2O from TEST

We get:



Thermodynamic Lookup Tables: *Evaluate Properties Manually and Verify Using Daemons*

Click on a table icon for a traditional chart or table and the daemon icon for a smart table.

Table-A (SL Model)	SL Daemon	Common Solids Liquids Table A-1	Periodic Table Elements Table A-2	Material properties ($c_p = c_v$ and $v = 1/\rho$) of solids and liquids upon which the *SL* (solid/liquid) model is built. In the state daemon, simply select the working substance and click Calculate to display the material properties.				
Table-B (PC Model)	PC Daemon	H2O	p Sat H_2O Table B-1	T - Sat H_2O Table B Open/close a traditional PC table	super H_2O	Comp.L. H_2O	Ice H_2O Table B-5	Saturation and superheated tables for phase-change (*PC*) fluids. In the PC daemon, select the working fluid (from more than 60 fluids), enter two independent thermodynamic properties (say, *p* and *h*: all thermodynamic properties are colored blue) to obtain all other properties.
		R-134a	T - Sat R-134a Table B-6	super R-134a Table B-7	R-22	T - Sat R-22 Table B-8	super R-22 Table B-9	
		R-12	T - Sat R-12 Table B-10	super R-12 Table B-11	Ammonia (NH_3)	T - Sat NH_3 Table B-12	super NH_3 Table B-13	
		N2	T - Sat N_2 Table B-14	super N_2 Table B-15	Propane (C_3H_8)	T - Sat C_3H_8 Table B-16	super C_3H_8 Table B-17	

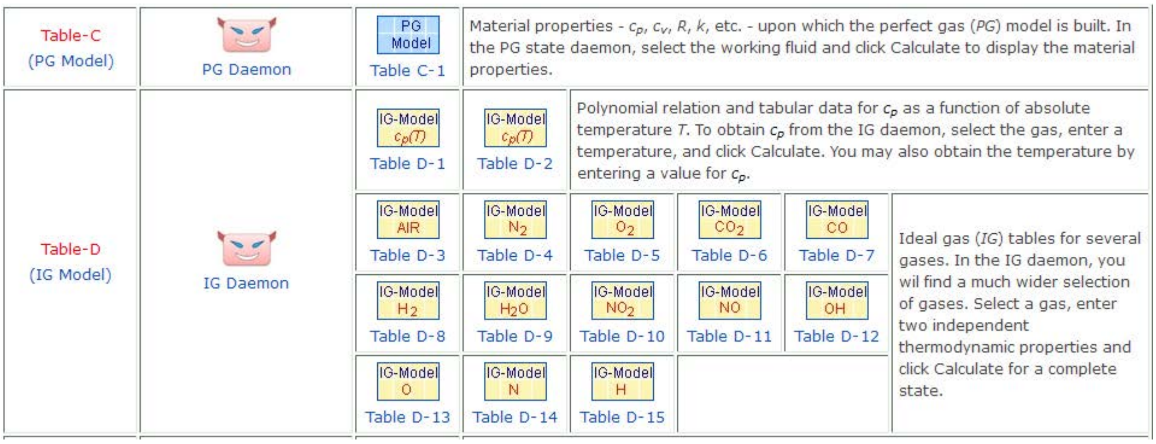


Table-C (PG Model)	PG Daemon	PG Model Table C-1	Material properties - c_p, c_v, R, k, etc. - upon which the perfect gas (*PG*) model is built. In the PG state daemon, select the working fluid and click Calculate to display the material properties.				
Table-D (IG Model)	IG Daemon	IG-Model $c_p(T)$ Table D-1	IG-Model $c_p(T)$ Table D-2	Polynomial relation and tabular data for c_p as a function of absolute temperature *T*. To obtain c_p from the IG daemon, select the gas, enter a temperature, and click Calculate. You may also obtain the temperature by entering a value for c_p.			
		IG-Model AIR Table D-3	IG-Model N_2 Table D-4	IG-Model O_2 Table D-5	IG-Model CO_2 Table D-6	IG-Model CO Table D-7	Ideal gas (*IG*) tables for several gases. In the IG daemon, you wil find a much wider selection of gases. Select a gas, enter two independent thermodynamic properties and click Calculate for a complete state.
		IG-Model H_2 Table D-8	IG-Model H_2O Table D-9	IG-Model NO_2 Table D-10	IG-Model NO Table D-11	IG-Model OH Table D-12	
		IG-Model O Table D-13	IG-Model N Table D-14	IG-Model H Table D-15			

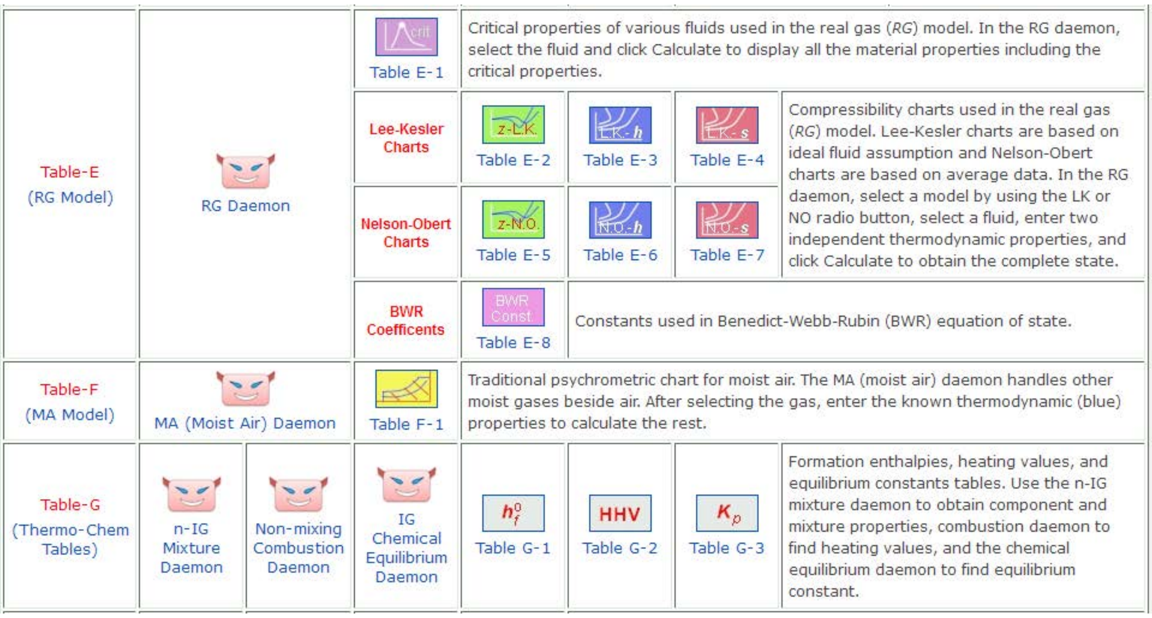


Table-E (RG Model)	RG Daemon	crit Table E-1	Critical properties of various fluids used in the real gas (*RG*) model. In the RG daemon, select the fluid and click Calculate to display all the material properties including the critical properties.				
		Lee-Kesler Charts	z-LK Table E-2	LK-h Table E-3	LK-s Table E-4	Compressibility charts used in the real gas (*RG*) model. Lee-Kesler charts are based on ideal fluid assumption and Nelson-Obert charts are based on average data. In the RG daemon, select a model by using the LK or NO radio button, select a fluid, enter two independent thermodynamic properties, and click Calculate to obtain the complete state.	
		Nelson-Obert Charts	z-N.O. Table E-5	N.O.-h Table E-6	N.O.-s Table E-7		
		BWR Coefficents	BWR Const Table E-8	Constants used in Benedict-Webb-Rubin (BWR) equation of state.			
Table-F (MA Model)	MA (Moist Air) Daemon	Table F-1	Traditional psychrometric chart for moist air. The MA (moist air) daemon handles other moist gases beside air. After selecting the gas, enter the known thermodynamic (blue) properties to calculate the rest.				
Table-G (Thermo-Chem Tables)	n-IG Mixture Daemon	Non-mixing Combustion Daemon	IG Chemical Equilibrium Daemon	h_f^0 Table G-1	HHV Table G-2	K_p Table G-3	Formation enthalpies, heating values, and equilibrium constants tables. Use the n-IG mixture daemon to obtain component and mixture properties, combustion daemon to find heating values, and the chemical equilibrium daemon to find equilibrium constant.

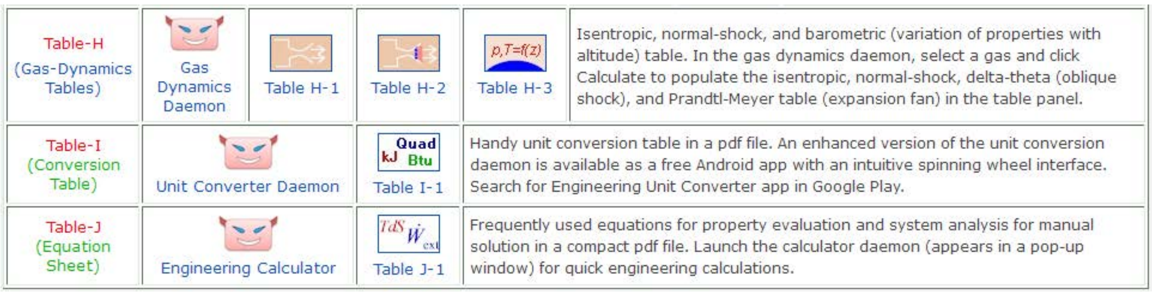


Table-H (Gas-Dynamics Tables)	Gas Dynamics Daemon	Table H-1	Table H-2	p,T=f(z) Table H-3	Isentropic, normal-shock, and barometric (variation of properties with altitude) table. In the gas dynamics daemon, select a gas and click Calculate to populate the isentropic, normal-shock, delta-theta (oblique shock), and Prandtl-Meyer table (expansion fan) in the table panel.
Table-I (Conversion Table)	Unit Converter Daemon		Quad kJ Btu Table I-1	Handy unit conversion table in a pdf file. An enhanced version of the unit conversion daemon is available as a free Android app with an intuitive spinning wheel interface. Search for Engineering Unit Converter app in Google Play.	
Table-J (Equation Sheet)	Engineering Calculator		TdS W exit Table J-1	Frequently used equations for property evaluation and system analysis for manual solution in a compact pdf file. Launch the calculator daemon (appears in a pop-up window) for quick engineering calculations.	

Fig. 3.30b. Property Table of H2O from TEST

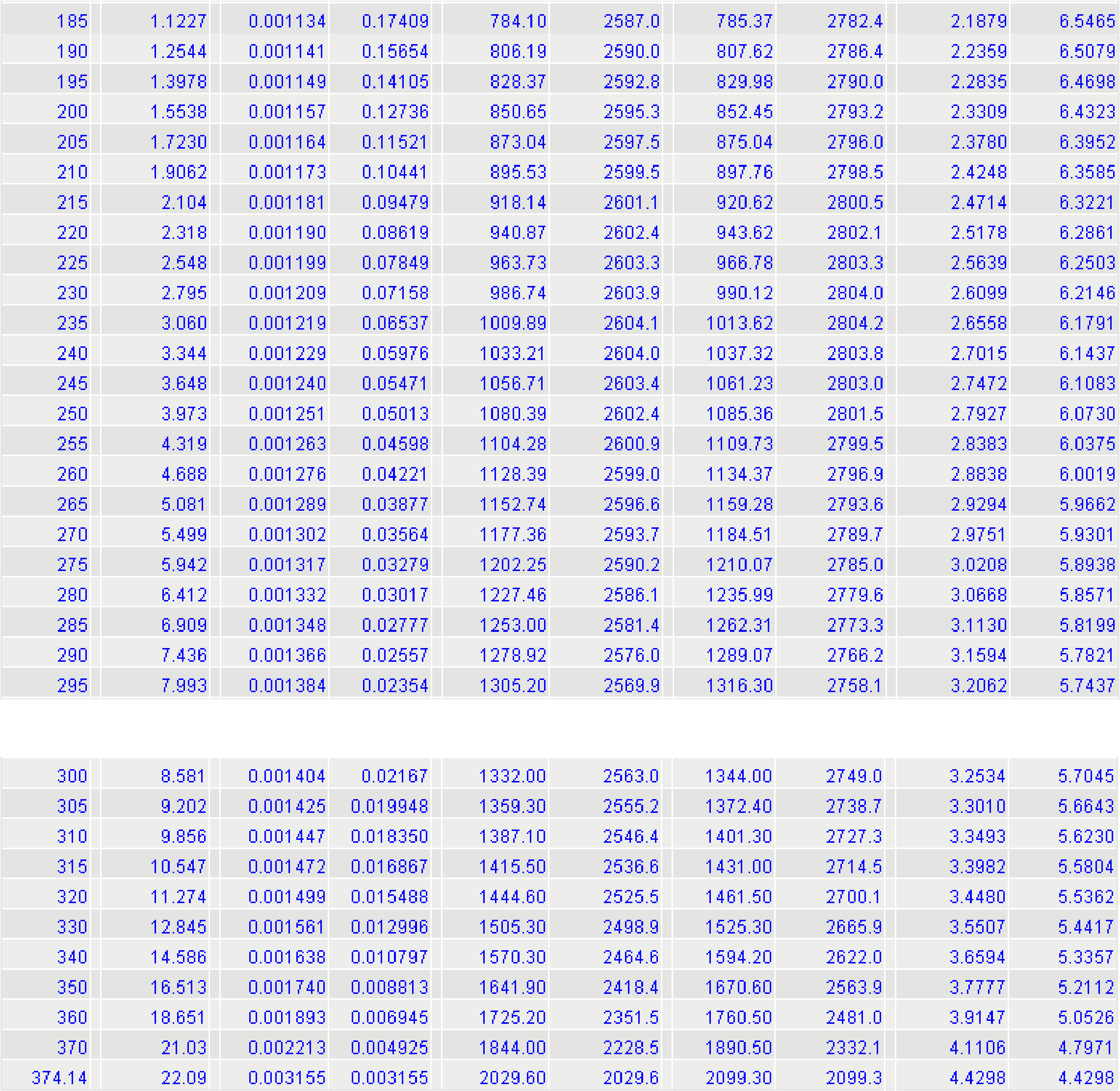
Click on desired Table. For example, click on Tsat-H2O. We get Sat. water-Temp-Table:

Table-B.2, PC Model, H_2O: *Saturation Temperature Table*

☑ SI Units ☐ English Units

Saturated Water (H2O)--Temperature Table

		Spec. Volume		*Internal Energy*		*Enthalpy*		*Entropy*	
deg-C	**kPa**	m^3/kg		kJ/kg		kJ/kg		kJ/kg*K	
Temp.	Sat. press.	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor
T °C	p_sat@T	v_f	v_g	u_f	u_g	h_f	h_g	s_f	s_g
0.01	0.6113	0.001000	206.14	0.00	2375.3	0.01	2501.4	0.0000	9.1562
5	0.8721	0.001000	147.12	20.97	2382.3	20.98	2510.6	0.0761	9.0257
10	1.2276	0.001000	106.38	42.00	2389.2	42.01	2519.8	0.1510	8.9008
15	1.7051	0.001001	77.93	62.99	2396.1	62.99	2528.9	0.2245	8.7814
20	2.339	0.001002	57.79	83.95	2402.9	83.96	2538.1	0.2966	8.6672
25	3.169	0.001003	43.36	104.88	2409.8	104.89	2547.2	0.3674	8.5580
30	4.246	0.001004	32.89	125.78	2416.6	125.79	2556.3	0.4369	8.4533
35	5.628	0.001006	25.22	146.67	2423.4	146.68	2565.3	0.5053	8.3531
40	7.384	0.001008	19.52	167.56	2430.1	167.57	2574.3	0.5725	8.2570
45	9.593	0.001010	15.26	188.44	2436.8	188.45	2583.2	0.6387	8.1648
50	12.349	0.001012	12.03	209.32	2443.5	209.33	2592.1	0.7038	8.0763
55	15.758	0.001015	9.568	230.21	2450.1	230.23	2600.9	0.7679	7.9913
60	19.940	0.001017	7.671	251.11	2456.6	251.13	2609.6	0.8312	7.9096
65	25.03	0.001020	6.197	272.02	2463.1	272.06	2618.3	0.8935	7.8310
70	31.19	0.001023	5.042	292.95	2469.6	292.98	2626.8	0.9549	7.7553
75	38.58	0.001026	4.131	313.90	2475.9	313.93	2643.7	1.0155	7.6824
80	47.39	0.001029	3.407	334.86	2482.2	334.91	2635.3	1.0753	7.6122
85	57.83	0.001033	2.828	355.84	2488.4	355.90	2651.9	1.1343	7.5445
90	70.14	0.001036	2.361	376.85	2494.5	376.92	2660.1	1.1925	7.4791
95	84.55	0.001040	1.982	397.88	2500.6	397.96	2668.1	1.2500	7.4159
T °C	p_sat@T **MPa**	v_f	v_g	u_f	u_g	h_f	h_g	s_f	s_g
100	0.10135	0.001044	1.6729	418.94	2506.5	419.04	2676.1	1.3069	7.3549
105	0.12082	0.001048	1.4194	440.02	2512.4	440.15	2683.8	1.3630	7.2958
110	0.14327	0.001052	1.2102	461.14	2518.1	461.30	2691.5	1.4185	7.2387
115	0.16906	0.001056	1.0366	482.30	2523.7	482.48	2699.0	1.4734	7.1833
120	0.19853	0.001060	0.8919	503.50	2529.3	503.71	2706.3	1.5276	7.1296
125	0.2321	0.001065	0.7706	524.74	2534.6	524.99	2713.5	1.5813	7.0775
130	0.2701	0.001070	0.6685	546.02	2539.9	546.31	2720.5	1.6344	7.0269
135	0.3130	0.001075	0.5822	567.35	2545.0	567.69	2727.3	1.6870	6.9777
140	0.3613	0.001080	0.5089	588.74	2550.0	589.13	2733.9	1.7391	6.9299
145	0.4154	0.001085	0.4463	610.18	2554.9	610.63	2740.3	1.7907	6.8833
150	0.4758	0.001091	0.3928	631.68	2559.5	632.20	2746.5	1.8418	6.8379
155	0.5431	0.001096	0.3468	653.24	2564.1	653.84	2752.4	1.8925	6.7935
160	0.6178	0.001102	0.3071	674.87	2568.4	675.55	2758.1	1.9427	6.7502
165	0.7005	0.001108	0.2727	696.56	2572.5	697.34	2763.5	1.9925	6.7078
170	0.7917	0.001114	0.2428	718.33	2576.5	719.21	2768.7	2.0419	6.6663
175	0.8920	0.001121	0.2168	740.17	2580.2	741.17	2773.6	2.0909	6.6256
180	1.0021	0.001127	0.19405	762.09	2583.7	763.22	2778.2	2.1396	6.5857



185	1.1227	0.001134	0.17409	784.10	2587.0	785.37	2782.4	2.1879	6.5465
190	1.2544	0.001141	0.15654	806.19	2590.0	807.62	2786.4	2.2359	6.5079
195	1.3978	0.001149	0.14105	828.37	2592.8	829.98	2790.0	2.2835	6.4698
200	1.5538	0.001157	0.12736	850.65	2595.3	852.45	2793.2	2.3309	6.4323
205	1.7230	0.001164	0.11521	873.04	2597.5	875.04	2796.0	2.3780	6.3952
210	1.9062	0.001173	0.10441	895.53	2599.5	897.76	2798.5	2.4248	6.3585
215	2.104	0.001181	0.09479	918.14	2601.1	920.62	2800.5	2.4714	6.3221
220	2.318	0.001190	0.08619	940.87	2602.4	943.62	2802.1	2.5178	6.2861
225	2.548	0.001199	0.07849	963.73	2603.3	966.78	2803.3	2.5639	6.2503
230	2.795	0.001209	0.07158	986.74	2603.9	990.12	2804.0	2.6099	6.2146
235	3.060	0.001219	0.06537	1009.89	2604.1	1013.62	2804.2	2.6558	6.1791
240	3.344	0.001229	0.05976	1033.21	2604.0	1037.32	2803.8	2.7015	6.1437
245	3.648	0.001240	0.05471	1056.71	2603.4	1061.23	2803.0	2.7472	6.1083
250	3.973	0.001251	0.05013	1080.39	2602.4	1085.36	2801.5	2.7927	6.0730
255	4.319	0.001263	0.04598	1104.28	2600.9	1109.73	2799.5	2.8383	6.0375
260	4.688	0.001276	0.04221	1128.39	2599.0	1134.37	2796.9	2.8838	6.0019
265	5.081	0.001289	0.03877	1152.74	2596.6	1159.28	2793.6	2.9294	5.9662
270	5.499	0.001302	0.03564	1177.36	2593.7	1184.51	2789.7	2.9751	5.9301
275	5.942	0.001317	0.03279	1202.25	2590.2	1210.07	2785.0	3.0208	5.8938
280	6.412	0.001332	0.03017	1227.46	2586.1	1235.99	2779.6	3.0668	5.8571
285	6.909	0.001348	0.02777	1253.00	2581.4	1262.31	2773.3	3.1130	5.8199
290	7.436	0.001366	0.02557	1278.92	2576.0	1289.07	2766.2	3.1594	5.7821
295	7.993	0.001384	0.02354	1305.20	2569.9	1316.30	2758.1	3.2062	5.7437
300	8.581	0.001404	0.02167	1332.00	2563.0	1344.00	2749.0	3.2534	5.7045
305	9.202	0.001425	0.019948	1359.30	2555.2	1372.40	2738.7	3.3010	5.6643
310	9.856	0.001447	0.018350	1387.10	2546.4	1401.30	2727.3	3.3493	5.6230
315	10.547	0.001472	0.016867	1415.50	2536.6	1431.00	2714.5	3.3982	5.5804
320	11.274	0.001499	0.015488	1444.60	2525.5	1461.50	2700.1	3.4480	5.5362
330	12.845	0.001561	0.012996	1505.30	2498.9	1525.30	2665.9	3.5507	5.4417
340	14.586	0.001638	0.010797	1570.30	2464.6	1594.20	2622.0	3.6594	5.3357
350	16.513	0.001740	0.008813	1641.90	2418.4	1670.60	2563.9	3.7777	5.2112
360	18.651	0.001893	0.006945	1725.20	2351.5	1760.50	2481.0	3.9147	5.0526
370	21.03	0.002213	0.004925	1844.00	2228.5	1890.50	2332.1	4.1106	4.7971
374.14	22.09	0.003155	0.003155	2029.60	2029.6	2099.30	2099.3	4.4298	4.4298

Fig. 3.30c. Property Table of H2O from TEST

Similarly, we can get compressed water tables and Tables for R134a.

3.4.5.4 Property table from free software WSProps:

This software is from www.Sourceforge.net. As you start WSProps, go to File-New and following window appears:

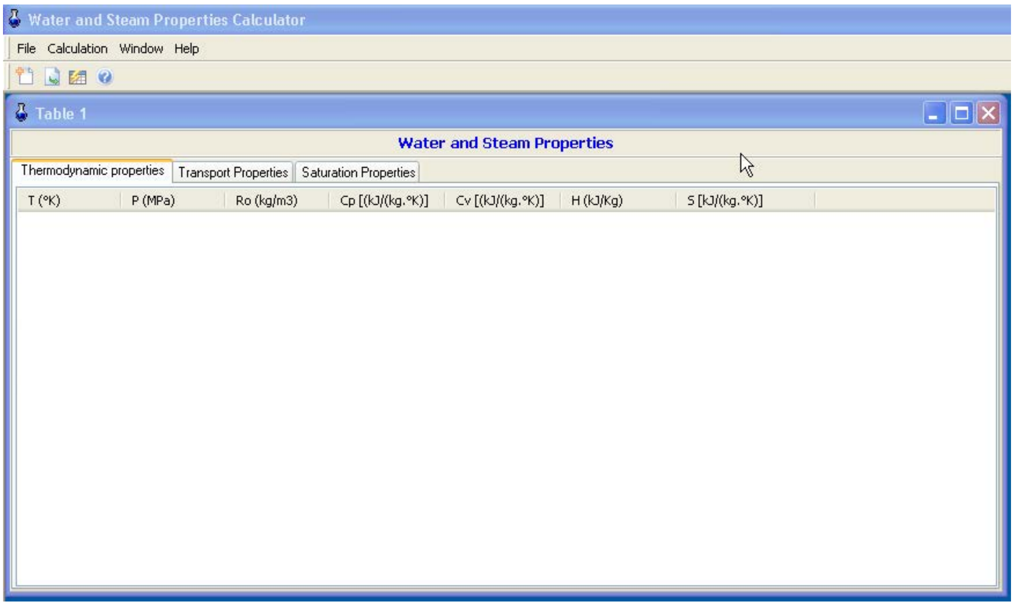
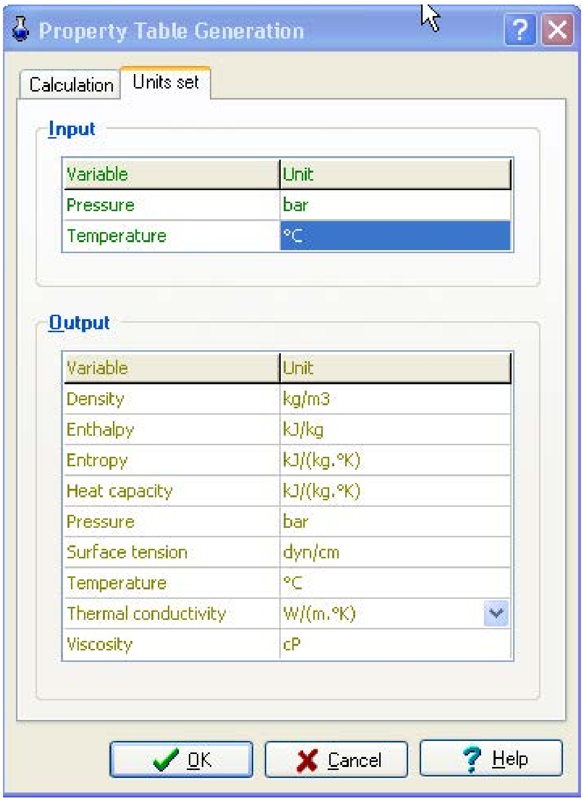


Fig. 3.31a. Property Table of H2O from WSProps

First set the Units by going to Calculation-Run. Set the Units as shown below:

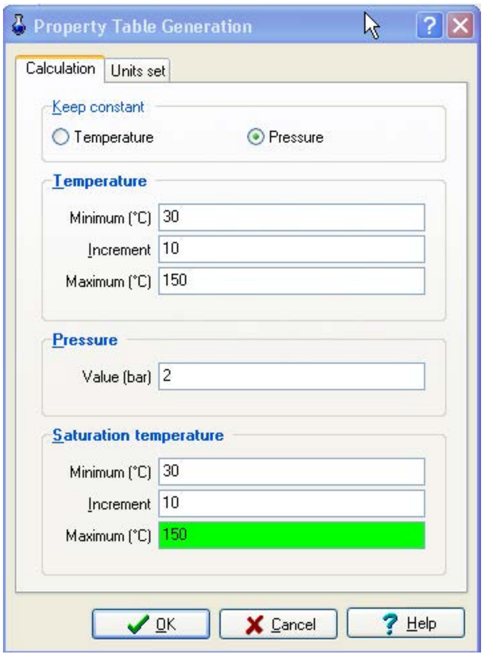


Variable	Unit
Pressure	bar
Temperature	°C

Variable	Unit
Density	kg/m3
Enthalpy	kJ/kg
Entropy	kJ/(kg.°K)
Heat capacity	kJ/(kg.°K)
Pressure	bar
Surface tension	dyn/cm
Temperature	°C
Thermal conductivity	W/(m.°K)
Viscosity	cP

Fig. 3.31b. Property Table of H2O from WSProps

Next, press the calculation tab.



Keep constant
○ Temperature ● Pressure

Temperature
Minimum (°C) 30
Increment 10
Maximum (°C) 150

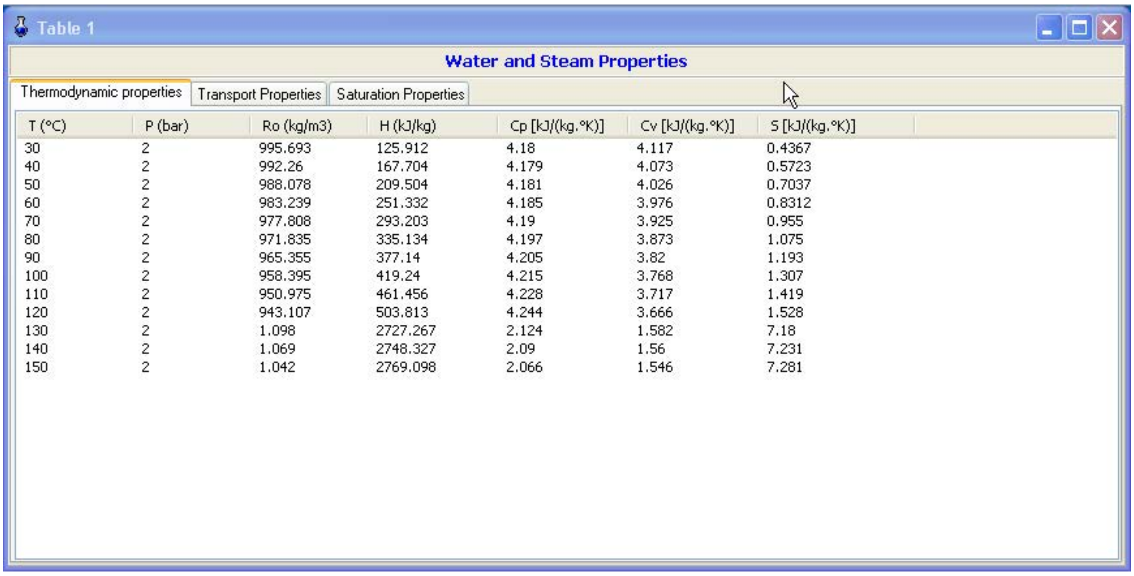
Pressure
Value (bar) 2

Saturation temperature
Minimum (°C) 30
Increment 10
Maximum (°C) 150

Fig. 3.31c. Property Table of H2O from WSProps

Enter the Temperature range and pressure values as shown above and click OK.

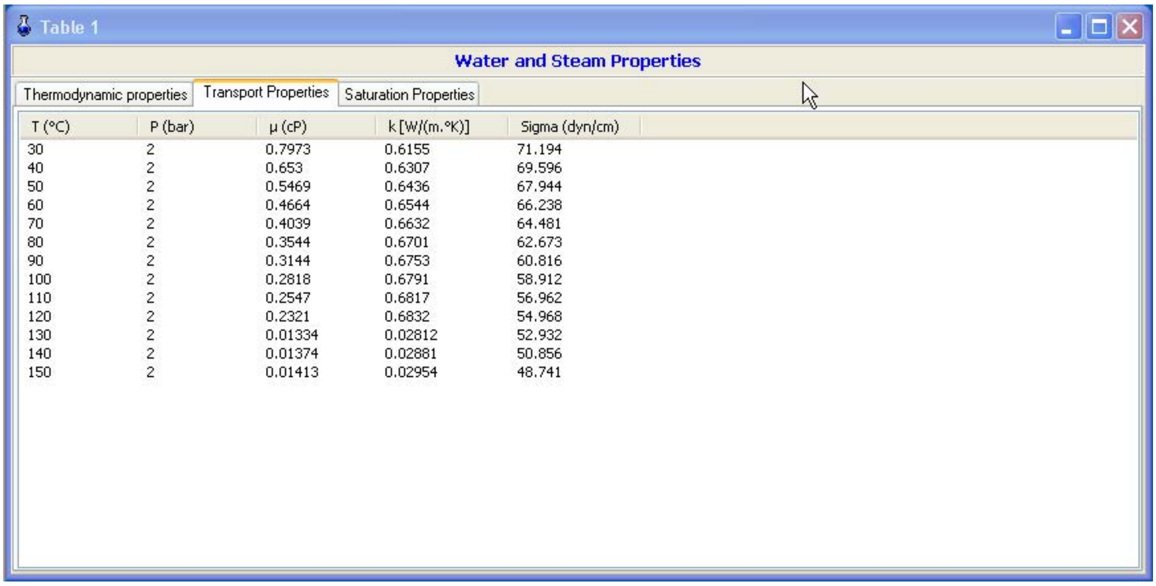
We get:



T (°C)	P (bar)	Ro (kg/m3)	H (kJ/kg)	Cp [kJ/(kg.°K)]	Cv [kJ/(kg.°K)]	S [kJ/(kg.°K)]
30	2	995.693	125.912	4.18	4.117	0.4367
40	2	992.26	167.704	4.179	4.073	0.5723
50	2	988.078	209.504	4.181	4.026	0.7037
60	2	983.239	251.332	4.185	3.976	0.8312
70	2	977.808	293.203	4.19	3.925	0.955
80	2	971.835	335.134	4.197	3.873	1.075
90	2	965.355	377.14	4.205	3.82	1.193
100	2	958.395	419.24	4.215	3.768	1.307
110	2	950.975	461.456	4.228	3.717	1.419
120	2	943.107	503.813	4.244	3.666	1.528
130	2	1.098	2727.267	2.124	1.582	7.18
140	2	1.069	2748.327	2.09	1.56	7.231
150	2	1.042	2769.098	2.066	1.546	7.281

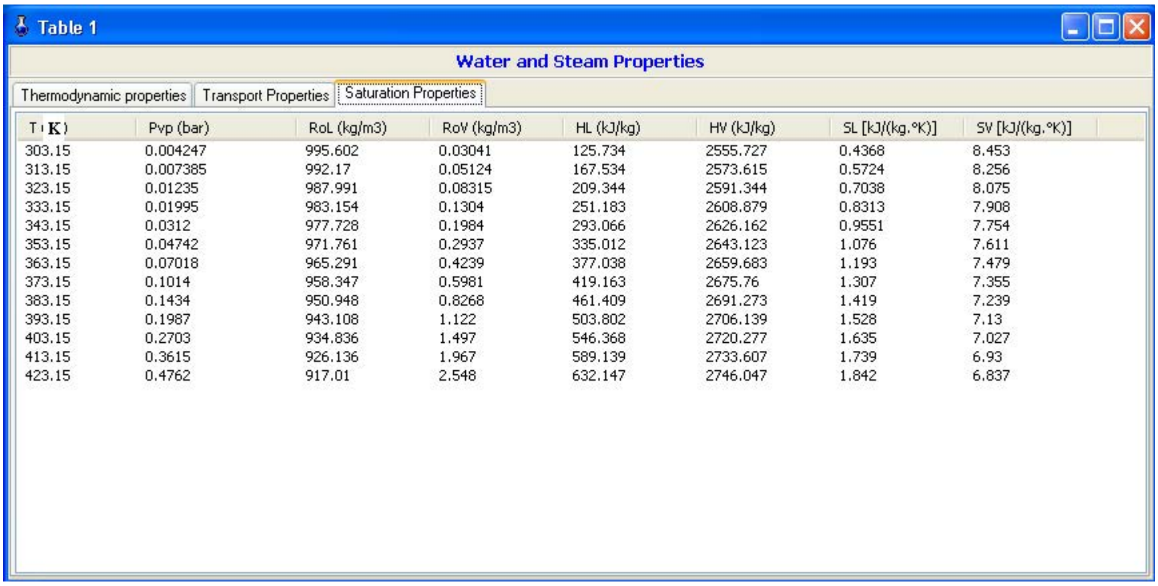
Fig. 3.31d. Property Table of H2O from WSProps

Thermodynamic properties, Transport properties and saturation properties are obtained by clicking on the respective tabs:



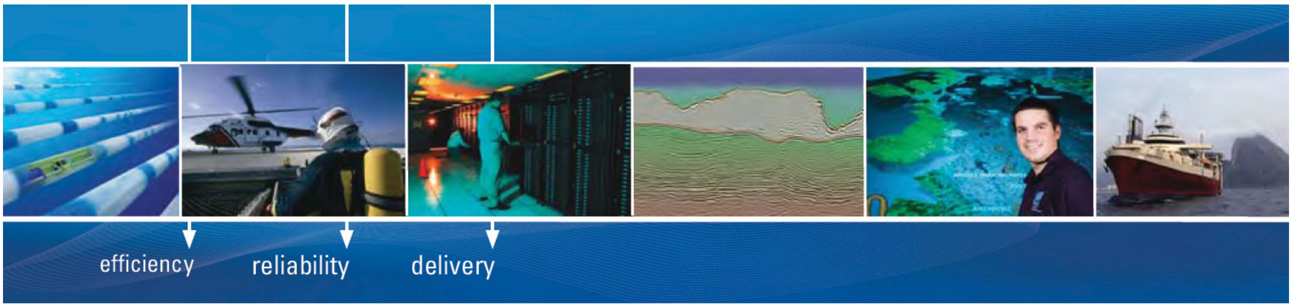
T (°C)	P (bar)	μ (cP)	k [W/(m.°K)]	Sigma (dyn/cm)
30	2	0.7973	0.6155	71.194
40	2	0.653	0.6307	69.596
50	2	0.5469	0.6436	67.944
60	2	0.4664	0.6544	66.238
70	2	0.4039	0.6632	64.481
80	2	0.3544	0.6701	62.673
90	2	0.3144	0.6753	60.816
100	2	0.2818	0.6791	58.912
110	2	0.2547	0.6817	56.962
120	2	0.2321	0.6832	54.968
130	2	0.01334	0.02812	52.932
140	2	0.01374	0.02881	50.856
150	2	0.01413	0.02954	48.741

Fig. 3.31e. Property Table of H2O from WSProps



T (K)	Pvp (bar)	RoL (kg/m3)	RoV (kg/m3)	HL (kJ/kg)	HV (kJ/kg)	SL [kJ/(kg.°K)]	SV [kJ/(kg.°K)]
303.15	0.004247	995.602	0.03041	125.734	2555.727	0.4368	8.453
313.15	0.007385	992.17	0.05124	167.534	2573.615	0.5724	8.256
323.15	0.01235	987.991	0.08315	209.344	2591.344	0.7038	8.075
333.15	0.01995	983.154	0.1304	251.183	2608.879	0.8313	7.908
343.15	0.0312	977.728	0.1984	293.066	2626.162	0.9551	7.754
353.15	0.04742	971.761	0.2937	335.012	2643.123	1.076	7.611
363.15	0.07018	965.291	0.4239	377.038	2659.683	1.193	7.479
373.15	0.1014	958.347	0.5981	419.163	2675.76	1.307	7.355
383.15	0.1434	950.948	0.8268	461.409	2691.273	1.419	7.239
393.15	0.1987	943.108	1.122	503.802	2706.139	1.528	7.13
403.15	0.2703	934.836	1.497	546.368	2720.277	1.635	7.027
413.15	0.3615	926.136	1.967	589.139	2733.607	1.739	6.93
423.15	0.4762	917.01	2.548	632.147	2746.047	1.842	6.837

Fig. 3.31f. Property Table of H2O from WSProps



3.5 Example Problems:

Let us work out a few problems to illustrate the use of these software.

Problem 3.3. Find the enthalpy and entropy of steam when the pressure is 2 MPa and specific volume is 0.09 m3/kg. [VTU, 2005]

Solution: If this problem has to be solved using conventional steam tables, tedious interpolation will be required. But, the problem is solved very easily with TEST:

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). Substance 'H2O' is automatically selected. Select P1 and v1 and enter the values given. Take care to select proper units. See Fig. 3.34a below:

x1 = _____ fraction [Quality of saturated mixture]

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

State-1

No-Plots

Unknown Phase

H2O

☑ p1: 2 MPa

☑ v1: 0.09 m^3/kg

☑ Vel1: 0.0 m/s

☑ z1: 0.0 m

Fig. 3.32a. Properties of H2O from TEST

Now, click 'Calculate' and immediately all the results are displayed, as shown below:

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

©State-1

No-Plots

Sat.Mixture: Liq.+Vap.

H2O

☑ p1: 2.0 MPa

T1: 212.42111 deg-C

x1: 0.90235 fraction

y1: 0.99872 fraction

☑ v1: 0.09 m^3/kg

u1: 2434.8665 kJ/kg

h1: 2614.8535 kJ/kg

s1: 5.96068 kJ/kg.K

☑ Vel1: 0.0 m/s

☑ z1: 0.0 m

e1: 2434.8665 kJ/kg

j1: 2614.8535 kJ/kg

MM1: 18.0 kg/kmol

Fig. 3.32b. Properties of H2O from TEST

Read the result as: **h1 = 2614.85 kJ/kg, and s1 = 5.96 kJ/kg.K,** and the state is: sat. mixture with quality (i.e. dryness fraction) = 0.902.

By clicking on the T-s plot widget, you can locate the state on the T-s diagram too, as shown Fig. 3.34c and 3.34d below:


Move mouse over a variable to display its value with more precision.

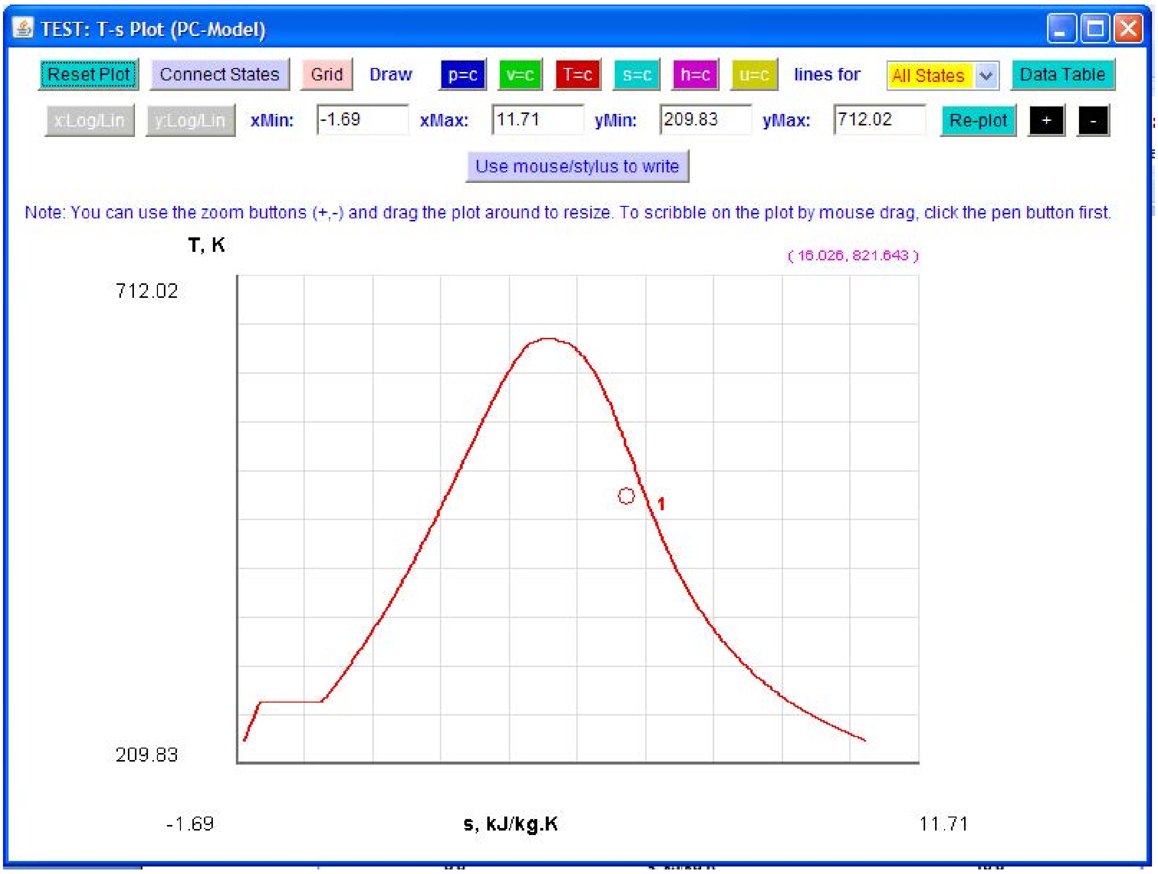
● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

State Panel | I/O Panel

State-1 | T-s | Sat.Mixture: Liq.+Vap. | H2O

☑ p1: 2.0 MPa
☐ T1: 212.42111 deg-C
x1: 235 fraction
☐ y1: 0.99872 fraction
☑ v1: 0.09 m^3/kg
☐ u1: 2434.8665 kJ/kg
☐ h1: 2614.8535 kJ/kg
s1: 068 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 2434.8665 kJ/kg
☐ j1: 2614.8535 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: kg
☐ Vol1: m^3
MM1: 18.0 kg/kmol

Fig. 3.32c. Properties of H2O from TEST


TEST: T-s Plot (PC-Model)

xMin: -1.69 xMax: 11.71 yMin: 209.83 yMax: 712.02

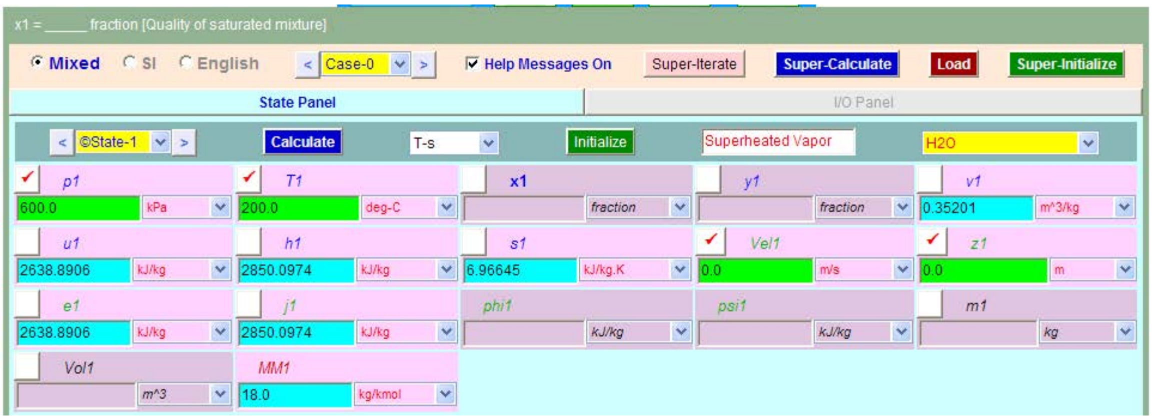
Note: You can use the zoom buttons (+,-) and drag the plot around to resize. To scribble on the plot by mouse drag, click the pen button first.

Fig. 3.32d. Properties of H2O from TEST – (T-s) plot

Problem 3.4. A rigid container is filled with steam at 600 kPa and 200 deg.C. At what temperature the steam begins to condense when it is cooled? Determine the corresponding pressure. [VTU, 2004]

Solution: Container is 'rigid' – means that the volume remains constant. Let us solve this problem in TEST. Let state 1 be at 600 kPa and 200 deg.C.

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). Substance 'H2O' is automatically selected. Select P1 and 1 and enter the values given. Take care to select proper units. Click 'Calculate' and all properties at state 1 are presented. See Fig. 3.35a below:



☑ p1: 600.0 kPa
☑ T1: 200.0 deg-C
☐ x1: fraction
☐ y1: fraction
☐ v1: 0.35201 m^3/kg
☐ u1: 2638.8906 kJ/kg
☐ h1: 2850.0974 kJ/kg
☐ s1: 6.96645 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 2638.8906 kJ/kg
☐ j1: 2850.0974 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: kg
☐ Vol1: m^3
MM1: 18.0 kg/kmol

Fig. 3.33a. Properties of H2O from TEST – State 1

Next, select State 2. Since State 2 is saturated vapor (when condensation just begins), 'quality' x2 =1. Also, since volume remains constant, v2 = v1. Enter these values of x2 and v2 as shown, and click 'Calculate'. You get the following result:


Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English — Case-0 — ☑ Help Messages On

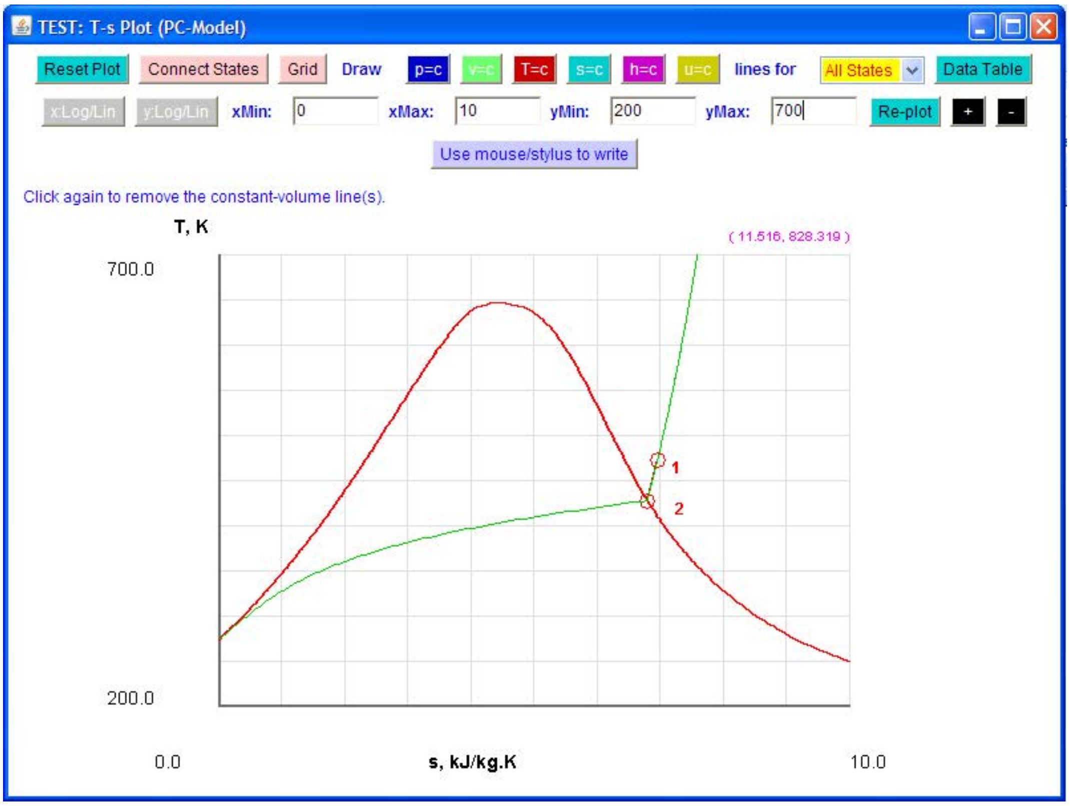
State-2 — T-s — Saturated Vapor — H2O

☐ p2: 534.4379 kPa
☐ T2: 154.39099 deg-C
☑ x2: 1.0 fraction
☐ y2: 1.0 fraction
☑ v2: =v1 m^3/kg
☐ u2: 2563.4646 kJ/kg
☐ h2: 2751.6104 kJ/kg
☐ s2: 6.79925 kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: 2563.4646 kJ/kg
☐ j2: 2751.6104 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☐ m2: kg
☐ Vol2: m^3
MM2: 18.0 kg/kmol

Fig. 3.33b. Properties of H2O from TEST – State 2

Note that condensation occurs at T2 = 154.39 deg.C and the corresponding pressure P2 = 534.49 kPa. And if we need the amount of heat rejected, it is equal to (u2 – u1), since volume is constant; and (u2-u1) = (2563.46 – 2638.89) = -75.43 kJ/kg. (-ve sign indicates that heat is rejected.).

Next, states 1 and 2 can be shown on a T-s diagram. Choose T-s on the Plots widget and the plot appears as shown below. Press 'Connect states', click 'v = c' tab to produce the const. volume line, and adjust xmin, xmax, ymin and ymax as shown:


TEST: T-s Plot (PC-Model)

xMin: 0 xMax: 10 yMin: 200 yMax: 700

Click again to remove the constant-volume line(s).

Fig. 3.33c. Properties of H2O from TEST – (T-s) plot

Note that constant volume line passes through states 1 and 2, as it should.

Problem 3.5. A pressure cooker contains 1.5 kg of steam at 5 bar pressure and 0.8 dry. Find the quantity of heat which must be rejected so that the quality of steam becomes 0.4 dry.… [VTU, 2003]

Solution: Again, TEST is very convenient to solve this problem.

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at P1 = 5 bar, m1 = 1.5 kg, x1 = 0.8. Enter these values and press 'Calculate'. All properties at state 1 are presented immediately:

☑ p1	☐ T1	☑ x1	☐ y1	☐ v1
5.0 bar	151.81055 deg-C	0.8 fraction	0.99927 fraction	0.30101 m^3/kg
☐ u1	☐ h1	☐ s1	☑ Vel1	☑ z1
2176.8577 kJ/kg	2326.895 kJ/kg	5.82959 kJ/kg.K	0.0 m/s	0.0 m
☐ e1	☐ j1	phi1	psi1	☑ m1
2176.8577 kJ/kg	2326.895 kJ/kg	kJ/kg	kJ/kg	1.5 kg
☐ Vol1	MM1			
0.45152 m^3	18.0 kg/kmol			

Fig. 3.34a. Properties of H2O from TEST – State 1

Next, enter parameters for state 2, i.e. m2 = m1, x2 = 0.4, v2 = v1; Press 'Calculate' and we get:

☐ p2	☐ T2	☑ x2	☐ y2	☑ v2
2.37861 bar	125.83346 deg-C	0.4 fraction	0.99788 fraction	=v1 m^3/kg
☐ u2	☐ h2	☐ s2	☑ Vel2	☑ z2
1331.263 kJ/kg	1403.0631 kJ/kg	3.7818 kJ/kg.K	0.0 m/s	0.0 m
☐ e2	☐ j2	phi2	psi2	☑ m2
1331.263 kJ/kg	1403.0631 kJ/kg	kJ/kg	kJ/kg	=m1 kg
☐ Vol2	MM2			
0.45152 m^3	18.0 kg/kmol			

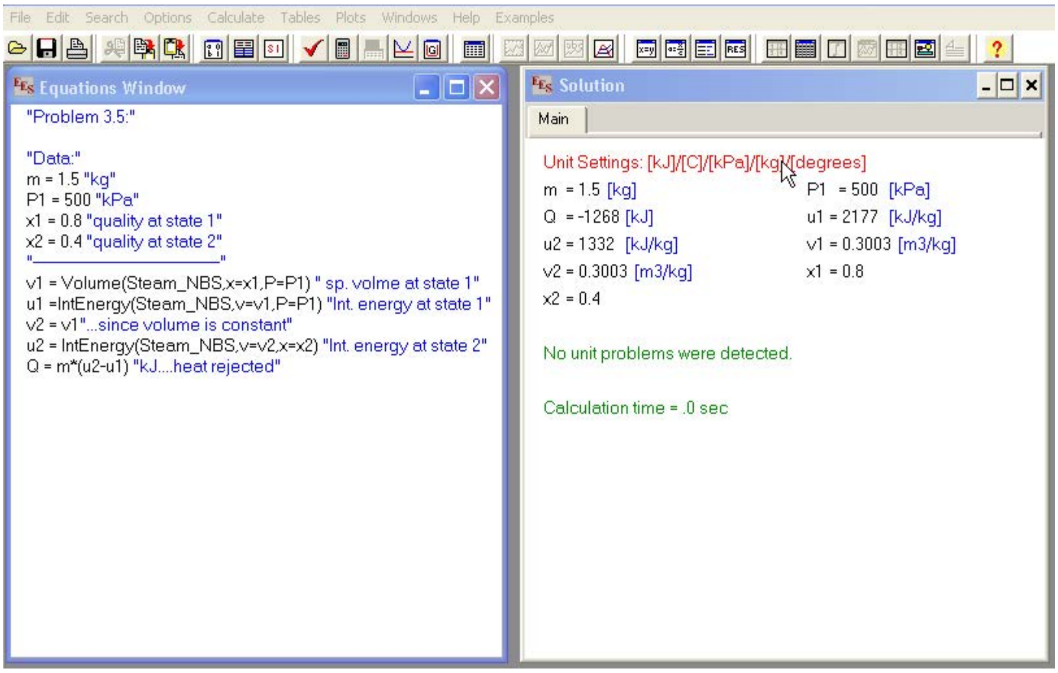
Fig. 3.34b. Properties of H2O from TEST – State 2

Since volume is constant, heat rejected =

(u2 – u1) = (1331.263 – 2176.8577) kJ/kg x 1.5 kg = **– 1268.4 kJ. (-ve sign indicates that heat is rejected.)**

Alternatively:

Let us solve this problem in EES. In the Equation window of EES, enter the equations and press F2 for solution. We get:



```
"Problem 3.5:"

"Data:"
m = 1.5 "kg"
P1 = 500 "kPa"
x1 = 0.8 "quality at state 1"
x2 = 0.4 "quality at state 2"
"______________________"
v1 = Volume(Steam_NBS,x=x1,P=P1) " sp. volme at state 1"
u1 =IntEnergy(Steam_NBS,v=v1,P=P1) "Int. energy at state 1"
v2 = v1"...since volume is constant"
u2 = IntEnergy(Steam_NBS,v=v2,x=x2) "Int. energy at state 2"
Q = m*(u2-u1) "kJ....heat rejected"
```

```
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
m  = 1.5 [kg]                P1  = 500  [kPa]
Q  = -1268 [kJ]              u1 = 2177  [kJ/kg]
u2 = 1332  [kJ/kg]           v1 = 0.3003 [m3/kg]
v2 = 0.3003 [m3/kg]          x1 = 0.8
x2 = 0.4

No unit problems were detected.

Calculation time = .0 sec
```

Fig. 3.34c. Properties of H2O from EES

Problem 3.6: A rigid vessel contains 1 kg of wet steam at a pressure of 0.15 MPa. When the mixture is heated, the state passes through the critical point. Determine:

i. the volume of the vessel
ii. mass of liquid and vapor initially in the vessel
iii. temperature of the mixture when the pressure has risen to 3 MPa, and
iv. the heat transfer required to produce the final state (iii)….[VTU, 2004]

Solution:

Note two points:

i. Since 1 kg of wet steam passes through the critical point in a closed vessel, it is clear that the volume must be equal to critical volume = 0.003155 m3/kg.
ii. Specific volume of wet steam is given by:

$$v = v_f + x \cdot v_{fg}$$

$$\text{i.e.} \quad v = v_f + x \cdot (v_g - v_f)$$

$$\text{i.e.} \quad v = (1 - x) \cdot v_f + x \cdot v_g$$

$$\text{i.e.} \quad v = x \cdot v_g \quad \text{...aprrox...(3.7)} \quad \text{since } v_f << v_g$$

Therefore, for a constant volume process, we can write, approximately:

$$x_1 \cdot v_{g1} = x_2 \cdot v_{g2} \qquad \text{...(3.8)}$$

Where x_1, x_2 are the dryness fraction values at state 1 and state 2 respectively.

First let us solve this problem with TEST:

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at P1 = 0.15 MPa, m1 = 1.0 kg, v1 = 0.003155 m3/kg. Enter these values and press 'Calculate'. All properties at state 1 are presented immediately:

Sat.Mixture: Liq.+Vap.; H2O

☑ p1: 0.15 MPa
☐ T1: 111.34738 deg-C
☐ x1: 0.00181 fraction
☐ y1: 0.66682 fraction
☑ v1: 0.003155 m^3/kg
☐ u1: 470.56345 kJ/kg
☐ h1: 471.03622 kJ/kg
☐ s1: 1.44376 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 470.56345 kJ/kg
☐ j1: 471.03622 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☑ m1: 1.0 kg
☐ Vol1: 0.00316 m^3
MM1: 18.0 kg/kmol

Fig. 3.35a. Properties of H2O from TEST

Note that internal energy u1 = 470.563 kJ/kg and quality x1 = 0.00181.

Next, calculate for state 2, with v2 = v1 and P2 = 3 MPa. We get the following screen, where we note that **u2 = 1052.0969 kJ/kg, and T2 = 233.9 deg.C**

Sat.Mixture: Liq.+Vap.; H2O

☑ p2: 3.0 MPa
☐ T2: 233.89996 deg-C
☐ x2: 0.0296 fraction
☐ y2: 0.62568 fraction
☑ v2: =v1 m^3/kg
☐ u2: 1052.0969 kJ/kg
☐ h2: 1061.5619 kJ/kg
☐ s2: 2.75054 kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: 1052.0969 kJ/kg
☐ j2: 1061.5619 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☐ m2: kg
☐ Vol2: m^3
MM2: 18.0 kg/kmol

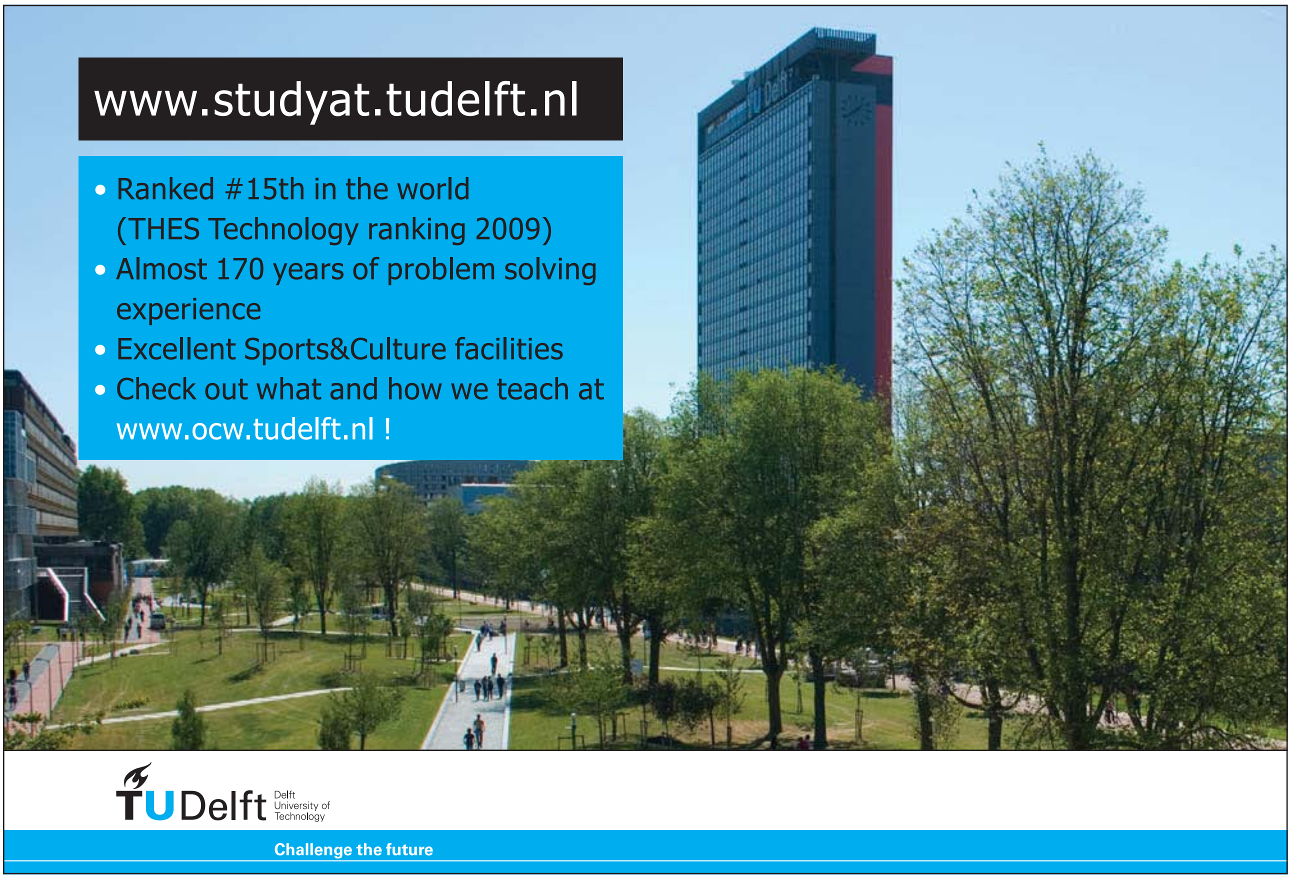
Fig. 3.35b. Properties of H2O from TEST

For completeness, draw the T-v plot too. As explained earlier, select the T-v plot and the plot appears immediately. Draw the v = const. line by clicking v = c tab (see fig. below). Note that constant volume line connecting states 1 and 2 passes through the critical point.

xMin: 5.0E-4 xMax: 20610.3 yMin: 209.83 yMax: 712.02

Click again to remove the constant-volume line(s).

Fig. 3.35c. T-v plot for H2O from TEST



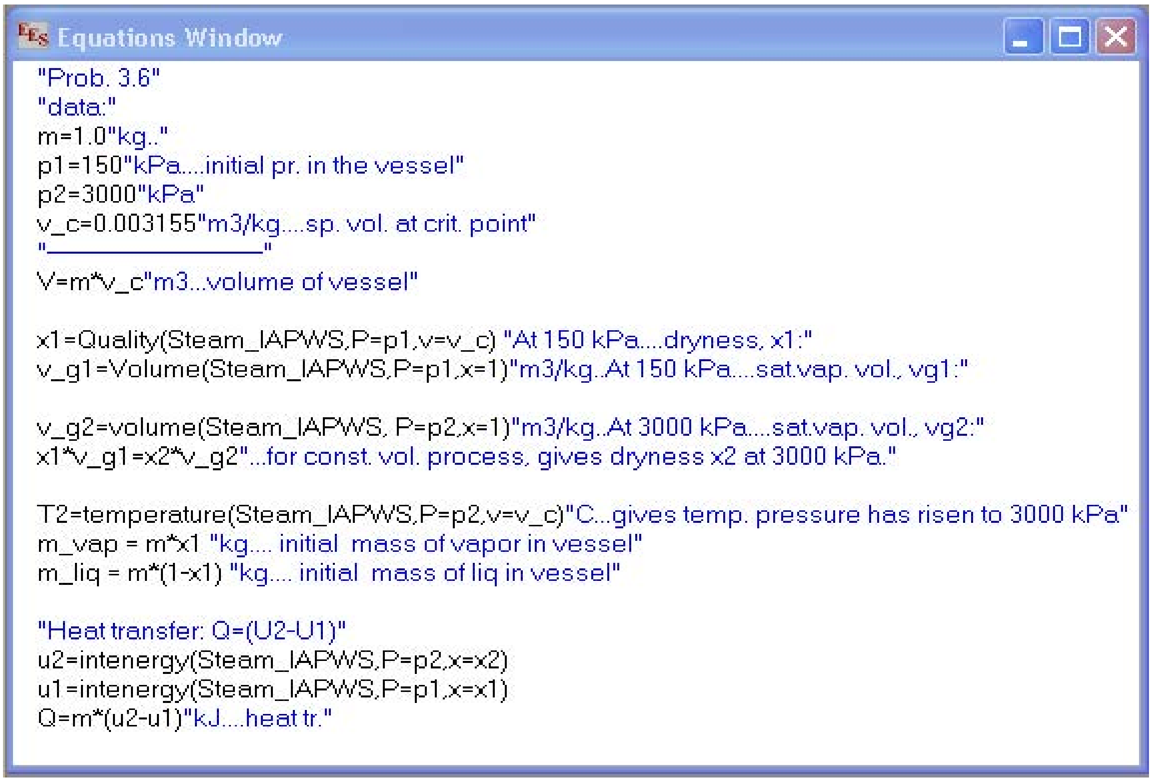
Therefore, the solution is:

a) volume of the vessel = 0.003155 m^3
b) mass of liquid and vapor initially in the vessel: By definition, 'quality' is the mass fraction of vapor present in the mixture. So, since the total mass is 1 kg, we have: mass of vapor = x1 = 0.00181 kg, and mass of liquid = (1 – x1) = 0.9982 kg.
c) temperature of the mixture when the pressure has risen to 3 MPa = T2 = 233.9 deg.C, and
d) the heat transfer required to produce the final state 2: Q = (u2-u1) = 581.53 kJ.

Alternatively:

Let us solve this problem with EES:

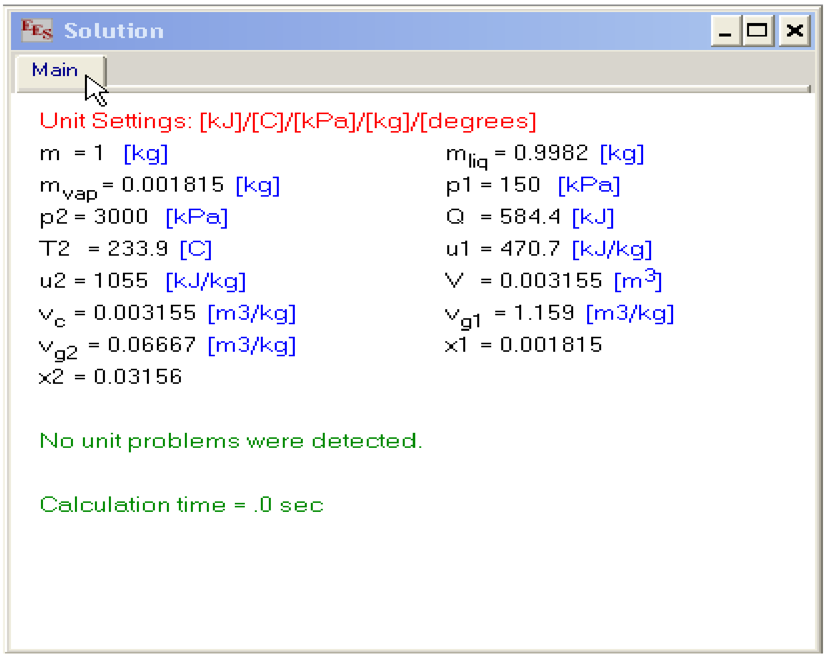
Write down the equations in the Equations window, as shown below. Read the comments against each eqn.



```
"Prob. 3.6"
"data:"
m=1.0"kg.."
p1=150"kPa....initial pr. in the vessel"
p2=3000"kPa"
v_c=0.003155"m3/kg....sp. vol. at crit. point"
"________________________"
V=m*v_c"m3...volume of vessel"

x1=Quality(Steam_IAPWS,P=p1,v=v_c) "At 150 kPa....dryness, x1:"
v_g1=Volume(Steam_IAPWS,P=p1,x=1)"m3/kg..At 150 kPa....sat.vap. vol., vg1:"

v_g2=volume(Steam_IAPWS, P=p2,x=1)"m3/kg..At 3000 kPa....sat.vap. vol., vg2:"
x1*v_g1=x2*v_g2"...for const. vol. process, gives dryness x2 at 3000 kPa."

T2=temperature(Steam_IAPWS,P=p2,v=v_c)"C...gives temp. pressure has risen to 3000 kPa"
m_vap = m*x1 "kg.... initial  mass of vapor in vessel"
m_liq = m*(1-x1) "kg.... initial  mass of liq in vessel"

"Heat transfer: Q=(U2-U1)"
u2=intenergy(Steam_IAPWS,P=p2,x=x2)
u1=intenergy(Steam_IAPWS,P=p1,x=x1)
Q=m*(u2-u1)"kJ....heat tr."
```

Fig. 3.36a. Properties of H2O from EES

Now, press F2 to calculate. Following results appear:



```
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
m  = 1  [kg]                          mliq = 0.9982 [kg]
mvap = 0.001815 [kg]                  p1 = 150  [kPa]
p2 = 3000  [kPa]                      Q  = 584.4 [kJ]
T2  = 233.9 [C]                       u1 = 470.7 [kJ/kg]
u2 = 1055  [kJ/kg]                    V  = 0.003155 [m3]
vc = 0.003155 [m3/kg]                 vg1  = 1.159 [m3/kg]
vg2 = 0.06667 [m3/kg]                 x1  = 0.001815
x2 = 0.03156

No unit problems were detected.

Calculation time = .0 sec
```

Fig. 3.36b. Solution for Prob.3.6 from EES

Very slight difference in u2, x2 and Q obtained from TEST and EES are due to the approximation made in EES code, viz. x1.vg1 = x2.vg2.

Problem 3.7: A vessel having a capacity of 0.85 m^3, contains steam at 12 bar and 0.92 dry. Steam is blown off until the pressure drops to 6 bar. The valve is then closed and the vessel is cooled until the pressure is 4 bar. Assuming that the specific enthalpy of steam is constant during the blowing off period, determine:

i. quantity of steam blown off
ii. quality of steam in the vessel after cooling, and
iii. quantity of steam in the vessel after cooling …. [VTU, 2004]

Solution:

Since the problem involves finding out the states, TEST is most convenient to use.

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at P1 = 12 bar, Vol1 = 0.85 m^3, x1 = 0.92. Enter these values and press 'Calculate'. All properties at state 1 are presented immediately:

Sat.Mixture: Liq.+Vap.
H2O

☑ p1: 12.0 bar
☐ T1: 187.98997 deg-C
☑ x1: 0.92 fraction
☐ y1: 0.99939 fraction
☐ v1: 0.15035 m^3/kg
☐ u1: 2445.4998 kJ/kg
☐ h1: 2625.9255 kJ/kg
☐ s1: 6.17876 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 2445.4998 kJ/kg
☐ j1: 2625.9255 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: 5.65329 kg
☑ Vol1: 0.85 m^3
MM1: 18.0 kg/kmol

Fig. 3.37a. Properties of H2O with TEST – state 1

We get mass, m1 = 5.65329 kg, enthalpy h1 =2625.9255 kJ/kg.

Now, some steam is blown off at constant enthalpy, till the pressure becomes 6 bar. i.e. at state 2, P2 = 6 bar, h2 = h1, and vessel volume remains same as Vol1. Enter these values for state 2. Click on 'Calculate'. We get:

☑ p2: 6.0 bar
☐ T2: 158.85 deg-C
☐ x2: 0.93727 fraction
☐ y2: 0.99977 fraction
☐ v2: 0.29594 m^3/kg
☐ u2: 2448.3635 kJ/kg
☑ h2: =h1 kJ/kg
☐ s2: 6.45708 kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: 2448.3635 kJ/kg
☐ j2: 2625.9255 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☐ m2: 2.87224 kg
☑ Vol2: =Vol1 m^3
MM2: 18.0 kg/kmol

Fig. 3.37b. Properties of H2O with TEST – state 2

Now, we note that the mass m2 in the vessel is m2 = 2.87224 kg.

Now, the vessel is cooled at constant volume Vol1 until the pressure is 4 bar; this is state 3. So, select state 3 and enter P3 = 4 bar, Vol3 = Vol1, m3 = m2; click on 'Calculate'. Properties at state 3 are presented:

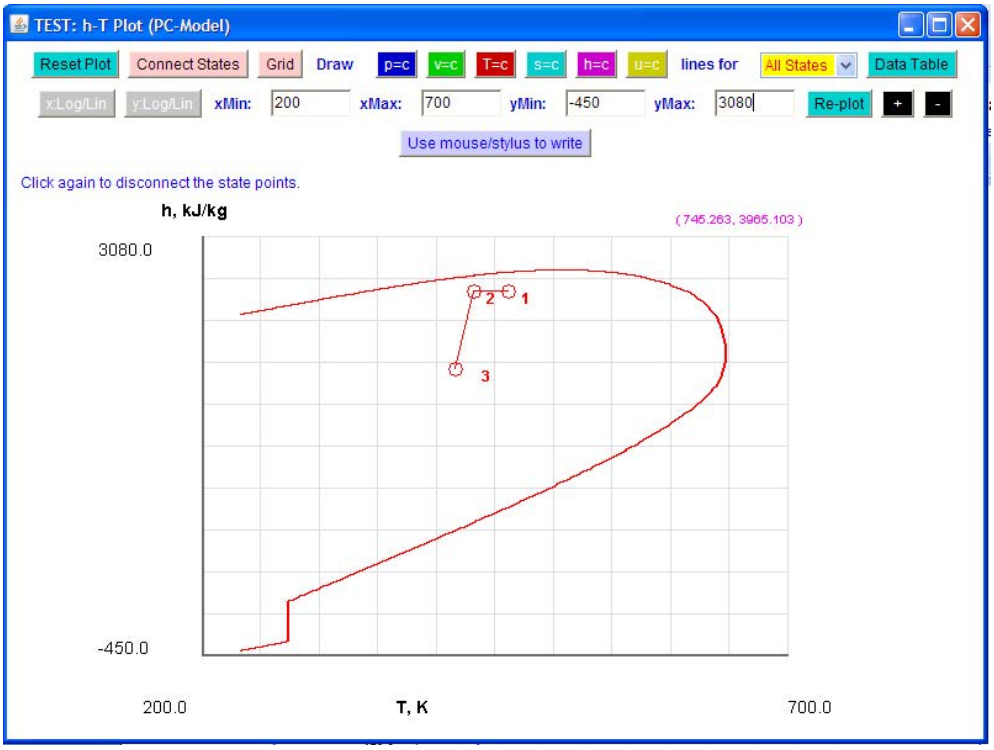
☑ p3: 4.0 bar
☐ T3: 143.61063 deg-C
☐ x3: 0.6385 fraction
☐ y3: 0.99868 fraction
☐ v3: 0.29594 m^3/kg
☐ u3: 1848.8472 kJ/kg
☐ h3: 1967.1146 kJ/kg
☐ s3: 5.04547 kJ/kg.K
☑ Vel3: 0.0 m/s
☑ z3: 0.0 m
☐ e3: 1848.8472 kJ/kg
☐ j3: 1967.1146 kJ/kg
phi3: kJ/kg
psi3: kJ/kg
☑ m3: =m2 kg
☑ Vol3: =Vol1 m^3
MM3: 18.0 kg/kmol

Fig. 3.37c. Properties of H2O with TEST – state 3

Note from the above that steam quality, **x3 = 0.6385**.Therefore, we have the results:

i. Quantity of steam blown off = (m1-m2) = 2.781 kg.
ii. Quality of steam in the vessel after cooling = x3 = 0.6385
iii. Quantity of steam in the vessel after cooling = x3.m3 = 1.834 kg of dry steam

The entire process can be shown on a h-T diagram by selecting the h-T plot in TEST as shown below. In the plot: 1–2 is blowing off at constant enthalpy and 2–3 is cooling at constant volume.



xMin: 200
xMax: 700
yMin: -450
yMax: 3080

Click again to disconnect the state points.

Fig. 3.37d. Properties of H2O with TEST – (h-T) plot

Problem 3.8: A rigid tank of 2 m^3 volume is filled with dry sat. steam at 0.2 MPa. Owing to poor insulation of the tank, the pressure of steam is found to be 0.1 MPa after some time. Determine the final state of the steam and the amount of energy transferred as heat to the surroundings. [VTU, 2001]

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at P1 = 0.2 MPa, Vol1 = 2.0 m^3, x1 = 1, since dry saturated. Enter these values and press 'Calculate'. All properties at state 1 are presented immediately:

x1 = 1.0 fraction [Quality of saturated mixture]

Saturated Vapor
H2O

☑ p1: 0.2 MPa
☐ T1: 120.22643 deg-C
☑ x1: 1.0 fraction
☐ y1: 1.0 fraction
☐ v1: 0.88626 m^3/kg
☐ u1: 2529.5012 kJ/kg
☐ h1: 2706.6245 kJ/kg
☐ s1: 7.12725 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 2529.5012 kJ/kg
☐ j1: 2706.6245 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☐ m1: 2.25666 kg
☑ Vol1: 2.0 m^3
MM1: 18.0 kg/kmol

Fig. 3.38a. Properties of H2O with TEST – state 1

Note that mass of steam, m1 = 2.25666 kg, and internal energy of steam, u1 = 2529.5012 kJ/kg.

Now, select state 2, and enter the known conditions, i.e. Vol2 = Vol1, m2 = m1 and P2 = 0.1 MPa. Click on 'Calculate'. We get:

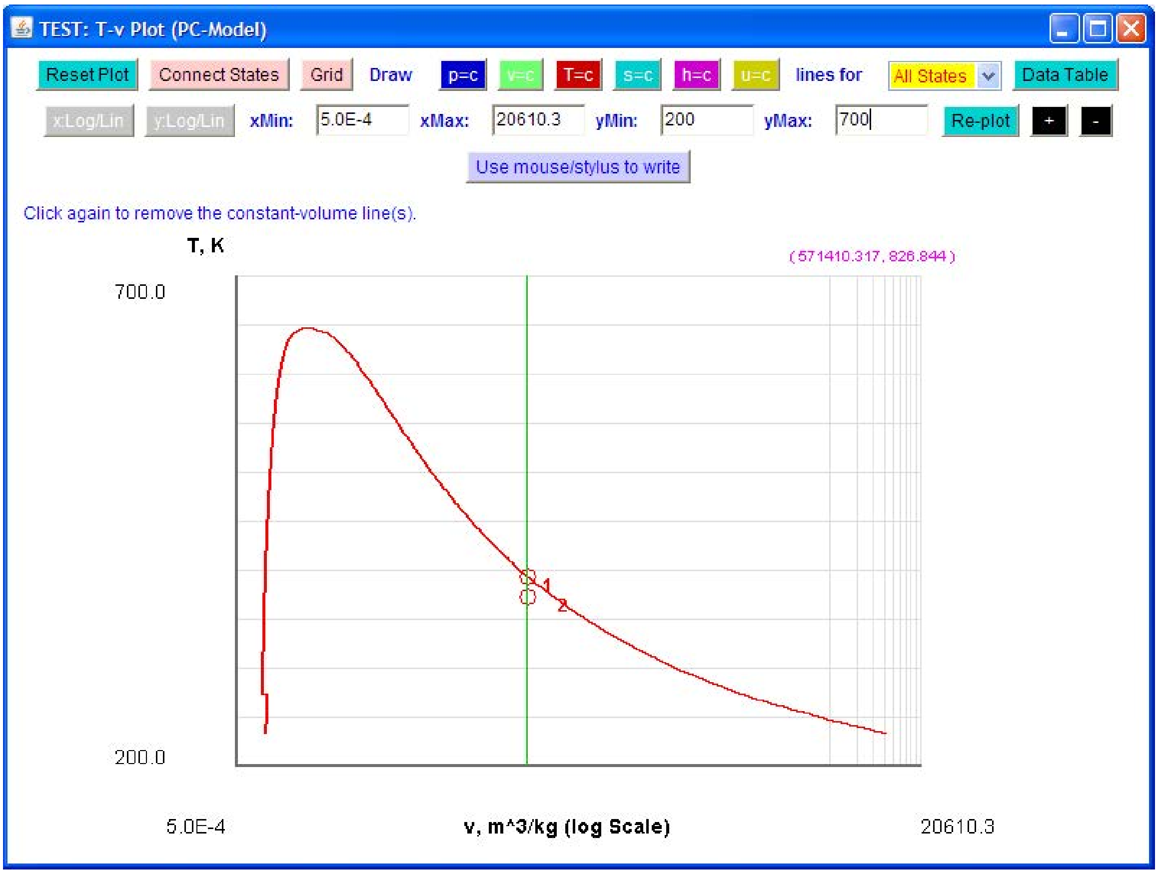
v2 = 0.8862638 m^3/kg [Specific volume]

✓ p2	☐ T2	☐ x2	☐ y2	☐ v2
0.1 MPa	99.61999 deg-C	0.52288 fraction	0.99944 fraction	0.88626 m^3/kg
☐ u2	☐ h2	☐ s2	✓ Vel2	✓ z2
1509.4971 kJ/kg	1598.1234 kJ/kg	4.46951 kJ/kg.K	0.0 m/s	0.0 m
☐ e2	☐ j2	phi2	psi2	✓ m2
1509.4971 kJ/kg	1598.1234 kJ/kg	kJ/kg	kJ/kg	=m1 kg
✓ Vol2	MM2			
=Vol1 m^3	18.0 kg/kmol			

Fig. 3.38b. Properties of H2O with TEST – state 2

We read: **u2 = 1509.4971 kJ/kg. and quality, x2 = 0.52288.** Energy transferred to surroundings = m.(u2 – u1) = -2.25666 kg x 1020 kJ/kg = **-2301.79 kJ. (-ve sign indicates that heat is rejected.)**

Finally, the process can be shown on (T-v) plot as shown below:



TEST: T-v Plot (PC-Model)

xMin: 5.0E-4 xMax: 20610.3 yMin: 200 yMax: 700

Click again to remove the constant-volume line(s).

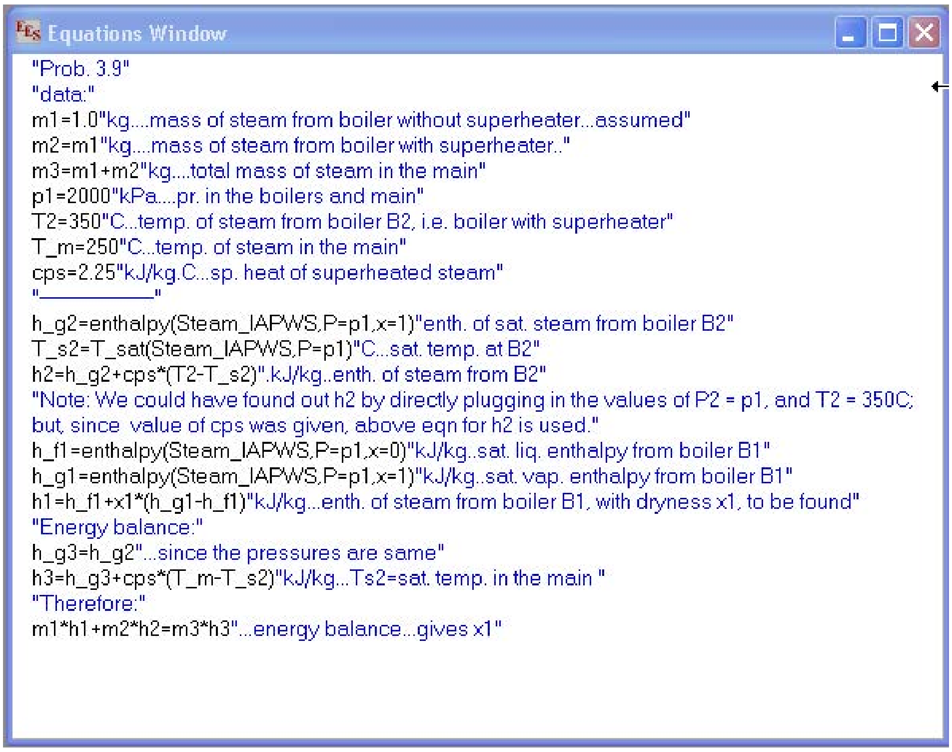
Fig. 3.38c. Properties of H2O with TEST – (T-v) plot

Problem 3.9: Two boilers, one with a super-heater and the other without superheater, are delivering equal quantities of steam into a common main. The pressure in the boiler and main is 20 bar. The temperature of steam from the boiler with super-heater is 350 deg.C and temperature of steam in the main is 250 deg.C. Determine the quality of steam supplied by the other boiler. Take cp,s = 2.25 kJ/kg.C…..[VTU, 2001]

Solution: First, let us solve this problem with EES.

Let 1, 2, 3 denote boiler without super-heater, boiler with super-heater and the main.

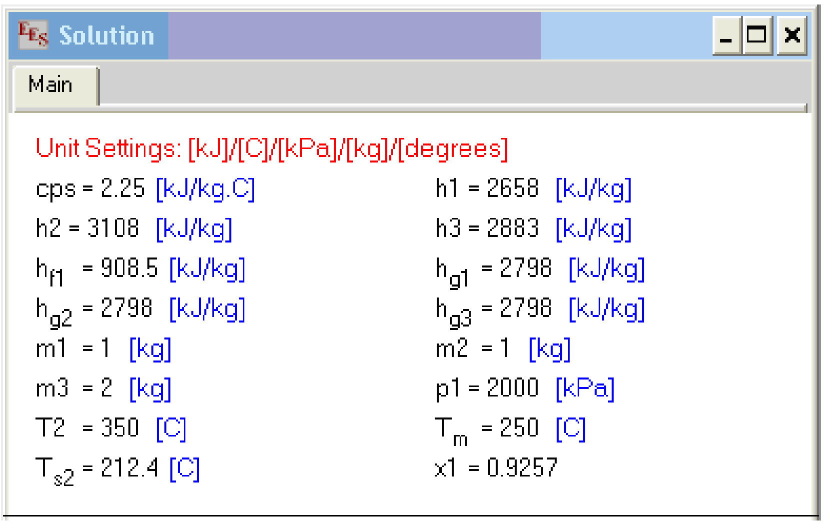
In Equation window of EES, enter the following code. Read the explanatory comments against each equation:



```
"Prob. 3.9"
"data:"
m1=1.0"kg....mass of steam from boiler without superheater...assumed"
m2=m1"kg....mass of steam from boiler with superheater.."
m3=m1+m2"kg....total mass of steam in the main"
p1=2000"kPa....pr. in the boilers and main"
T2=350"C...temp. of steam from boiler B2, i.e. boiler with superheater"
T_m=250"C...temp. of steam in the main"
cps=2.25"kJ/kg.C...sp. heat of superheated steam"
"____________"
h_g2=enthalpy(Steam_IAPWS,P=p1,x=1)"enth. of sat. steam from boiler B2"
T_s2=T_sat(Steam_IAPWS,P=p1)"C...sat. temp. at B2"
h2=h_g2+cps*(T2-T_s2)".kJ/kg..enth. of steam from B2"
"Note: We could have found out h2 by directly plugging in the values of P2 = p1, and T2 = 350C;
but, since  value of cps was given, above eqn for h2 is used."
h_f1=enthalpy(Steam_IAPWS,P=p1,x=0)"kJ/kg..sat. liq. enthalpy from boiler B1"
h_g1=enthalpy(Steam_IAPWS,P=p1,x=1)"kJ/kg..sat. vap. enthalpy from boiler B1"
h1=h_f1+x1*(h_g1-h_f1)"kJ/kg...enth. of steam from boiler B1, with dryness x1, to be found"
"Energy balance:"
h_g3=h_g2"...since the pressures are same"
h3=h_g3+cps*(T_m-T_s2)"kJ/kg...Ts2=sat. temp. in the main "
"Therefore:"
m1*h1+m2*h2=m3*h3"...energy balance...gives x1"
```

Fig. 3.39a. Properties of H2O with EES

Now, press F2 to get solution:



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

cps = 2.25 [kJ/kg.C]   h1 = 2658 [kJ/kg]

h2 = 3108 [kJ/kg]   h3 = 2883 [kJ/kg]

h_{f1} = 908.5 [kJ/kg] h_{g1} = 2798 [kJ/kg]

h_{g2} = 2798 [kJ/kg] h_{g3} = 2798 [kJ/kg]

m1 = 1 [kg]   m2 = 1 [kg]

m3 = 2 [kg]   p1 = 2000 [kPa]

T2 = 350 [C] T_m = 250 [C]

T_{s2} = 212.4 [C]   x1 = 0.9257

Fig. 3.39b. Solution with EES

It may be observed from the solution that quality of steam supplied by boiler-1 is 0.9257.

Now, let us verify this solution with TEST:

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at P1 = 20 bar, m1 = 1 kg, x1 = to be determined. Temperature T1 is also not known. However, from energy balance, we have:

$$m1 \cdot h1 + m2 \cdot h2 = m3 \cdot h3$$

i.e. $$h1 = \frac{(m3 \cdot h3 - m2 \cdot h2)}{m1}$$

Enter these values for P1, m1 and h1, and press 'Calculate'. We see that all properties can not be calculated at this stage:

s1 = NaN kJ/kg.K [Specific entropy]

Sat.Mixture: Liq.+Vap.

H2O

☑ p1 = 20.0 bar

☐ T1 = 212.42111 deg-C

☐ x1 = NaN fraction

☐ y1 = NaN fraction

☐ v1 = NaN m^3/kg

☐ u1 = NaN kJ/kg

☑ h1 = *h3 - m2*h2)/m1 kJ/kg

☐ s1 = NaN kJ/kg.K

☑ Vel1 = 0.0 m/s

☑ z1 = 0.0 m

☐ e1 = NaN kJ/kg

☐ j1 = NaN kJ/kg

phi1 = kJ/kg

psi1 = kJ/kg

☑ m1 = 1.0 kg

☐ Vol1 = NaN m^3

MM1 = 18.0 kg/kmol

Fig. 3.40a. Solution with TEST-state 1

However, we proceed to states 2 and 3 and 'Supercalculate' and TEST will refer back to state 1 and calculate properties at state 1 at that stage.

For state 2, we have: P2 = 20 bar, T2 = 350 C, m2 = m1. Enter these values and click on 'Calculate'. We get:

z2 = 0.0 m [Elevation above a datum]

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

State-2 | No-Plots | Superheated Vapor | H2O

☑ p2: 20.0 bar
☑ T2: 350.0 deg-C
☐ x2: fraction
☐ y2: fraction
☐ v2: 0.13857 m^3/kg
☐ u2: 2859.8027 kJ/kg
☐ h2: 3136.937 kJ/kg
☐ s2: 6.95616 kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: 2859.8027 kJ/kg
☐ j2: 3136.937 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☑ m2: =m1 kg
☐ Vol2: 0.13857 m^3
MM2: 18.0 kg/kmol

Fig. 3.40b. Solution with TEST-state 2

Next, for state 3 (i.e. Steam main), P3 = P1, T3 = 250 C, m3 = (m1 + m2). Enter these values and press 'Calculate'. We get:

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

State-3 | No-Plots | Superheated Vapor | H2O

☑ p3: =p1 bar
☑ T3: 250.0 deg-C
☐ x3: fraction
☐ y3: fraction
☐ v3: 0.11144 m^3/kg
☐ u3: 2679.5588 kJ/kg
☐ h3: 2902.4326 kJ/kg
☐ s3: 6.54515 kJ/kg.K
☑ Vel3: 0.0 m/s
☑ z3: 0.0 m
☐ e3: 2679.5588 kJ/kg
☐ j3: 2902.4326 kJ/kg
phi3: kJ/kg
psi3: kJ/kg
☑ m3: =(m1+m2) kg
☐ Vol3: 0.22287 m^3
MM3: 18.0 kg/kmol

Fig. 3.40c. Solution with TEST-state 3

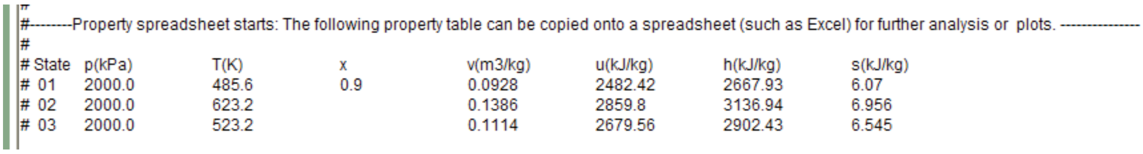
Now, click 'Supercalculate':Go to state 1 and following screen appears for state1:

☑ p1: 20.0 bar
☐ T1: 212.42111 deg-C
☐ x1: 0.93043 fraction
☐ y1: 0.99912 fraction
☐ v1: 0.09276 m^3/kg
☐ u1: 2482.4153 kJ/kg
☑ h1: =(m3*h3 - m2*h2 kJ/kg
☐ s1: 6.06998 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 2482.4153 kJ/kg
☐ j1: 2667.9282 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☑ m1: 1.0 kg
☐ Vol1: 0.09276 m^3
MM1: 18.0 kg/kmol

Fig. 3.40d. Solution with TEST-state 1

It may be seen that quality of steam supplied by the boiler with no super-heater is: **x1 = 0.93043.**

'Supercalculate' also generates TEST code which can be copied to a MS Word file and used to regenerate the results at a later date if required, and also a property table. The property table from the TEST report is reproduced below:



```
#
#--------Property spreadsheet starts: The following property table can be copied onto a spreadsheet (such as Excel) for further analysis or  plots. ---------------
#
# State  p(kPa)      T(K)       x        v(m3/kg)    u(kJ/kg)    h(kJ/kg)    s(kJ/kg)
# 01     2000.0      485.6      0.9      0.0928      2482.42     2667.93     6.07
# 02     2000.0      623.2               0.1386      2859.8      3136.94     6.956
# 03     2000.0      523.2               0.1114      2679.56     2902.43     6.545
```

Fig. 3.40e. Solution with TEST- property table

Problem 3.10: Temperature of feed water entering a boiler is 50 deg.C and the pressure of steam in the boiler is 13 bar. How much heat will be required to produce one kg of steam if the steam produced is:

i. 0.97 dry
ii. Dry saturated
iii. Superheated with 40 deg.C of superheat

Take cp for superheated steam as 2.1 kJ/kg.C and cp of water as 4.187 kJ/kg.C …[VTU, 2000]

Solution: First, let us solve this problem with Mathcad. In Mathcad, there are no built-in properties for steam. So, we will get the steam properties from 'SteamTab companion' and use them in Mathcad for further calculations. Mathcad worksheet is shown below:

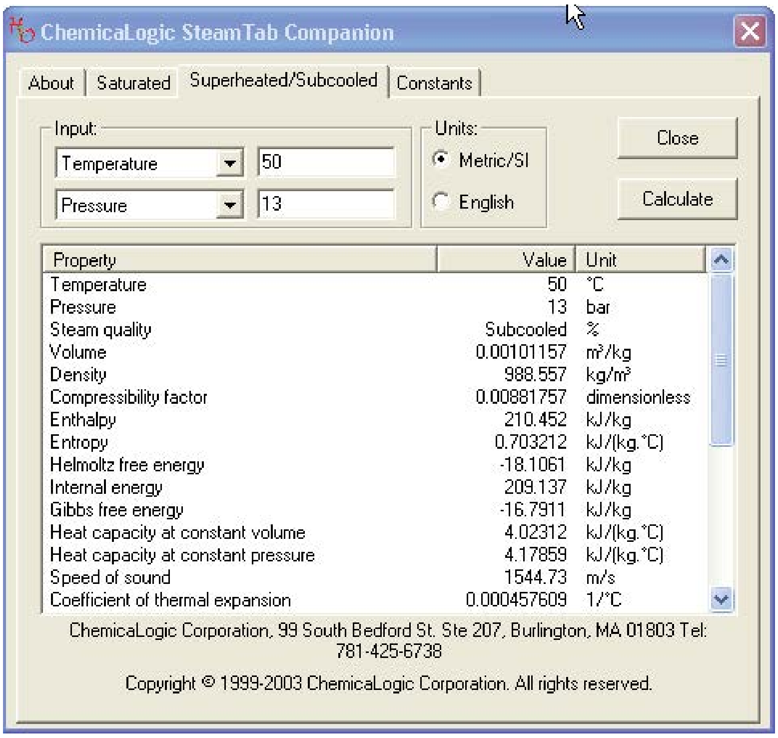
Let h1 = enthalpy of feed water at 50 C and 13 bar,

h2 = enthalpy of 0.97 dry steam

h3 = enthalpy of dry sat. steam

h4 = enthalpy of superheated steam with 40 deg. C superheat

Get h1: Entering the values of P and T in SteamTab companion and click 'Calculate'. We get:



Input:
Temperature 50
Pressure 13

Units: ● Metric/SI ○ English

Property	Value	Unit
Temperature	50	°C
Pressure	13	bar
Steam quality	Subcooled	%
Volume	0.00101157	m³/kg
Density	988.557	kg/m³
Compressibility factor	0.00881757	dimensionless
Enthalpy	210.452	kJ/kg
Entropy	0.703212	kJ/(kg.°C)
Helmoltz free energy	-18.1061	kJ/kg
Internal energy	209.137	kJ/kg
Gibbs free energy	-16.7911	kJ/kg
Heat capacity at constant volume	4.02312	kJ/(kg.°C)
Heat capacity at constant pressure	4.17859	kJ/(kg.°C)
Speed of sound	1544.73	m/s
Coefficient of thermal expansion	0.000457609	1/°C

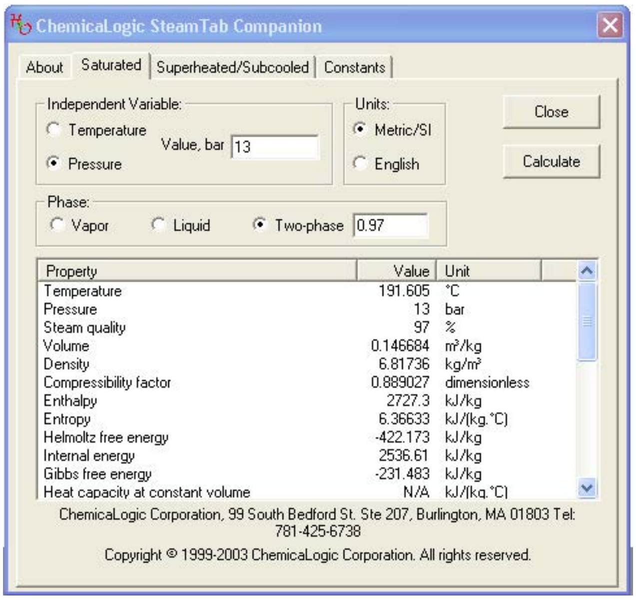
ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

Fig. 3.41a. Solution with Mathcad & SteamTab companion

i.e. $h1 := 210.452$ kJ/kg

Next, to get h2: In SteamTab companion, click on 'Saturated' tab; choose Pressure as 13 bar, select 'Two phase' and enter 0.97 (for dryness fraction value), and click 'Calculate'. We get:



Independent Variable: ○ Temperature ● Pressure
Value, bar 13

Units: ● Metric/SI ○ English

Phase: ○ Vapor ○ Liquid ● Two-phase 0.97

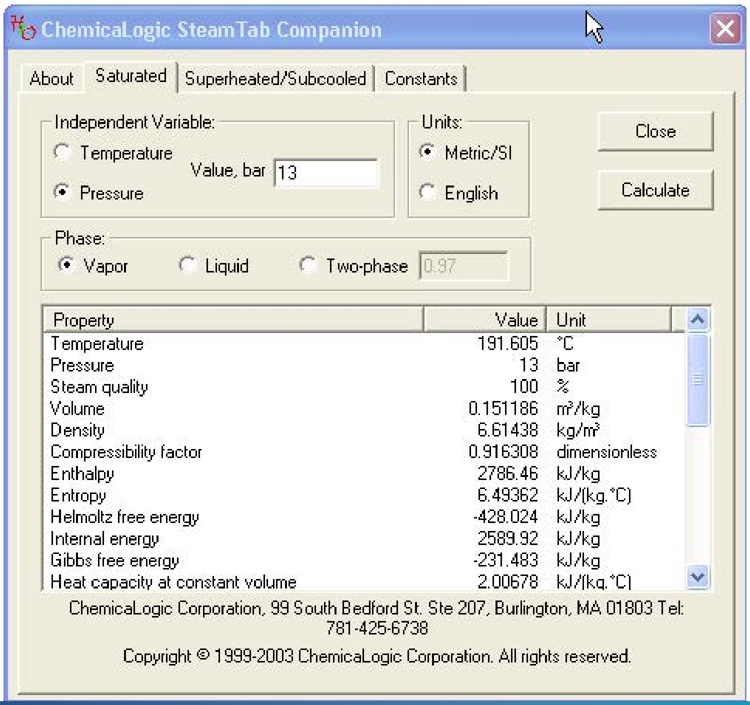
Property	Value	Unit
Temperature	191.605	°C
Pressure	13	bar
Steam quality	97	%
Volume	0.146684	m³/kg
Density	6.81736	kg/m³
Compressibility factor	0.889027	dimensionless
Enthalpy	2727.3	kJ/kg
Entropy	6.36633	kJ/(kg.°C)
Helmoltz free energy	-422.173	kJ/kg
Internal energy	2536.61	kJ/kg
Gibbs free energy	-231.483	kJ/kg
Heat capacity at constant volume	N/A	kJ/(kg.°C)

ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

Fig. 3.41b. Solution with Mathcad & SteamTab companion i.e. h2 := 2727.3 kJ/kg

Next, to get h3: This is equal to enthalpy of dry sat. steam at 13 bar. So, in the above screen, choose 'Vapor' and click 'Calculate' as shown below:



Independent Variable: ○ Temperature ● Pressure

Value, bar: 13

Units: ● Metric/SI ○ English

Phase: ● Vapor ○ Liquid ○ Two-phase 0.97

Property	Value	Unit
Temperature	191.605	°C
Pressure	13	bar
Steam quality	100	%
Volume	0.151186	m³/kg
Density	6.61438	kg/m³
Compressibility factor	0.916308	dimensionless
Enthalpy	2786.46	kJ/kg
Entropy	6.49362	kJ/(kg.°C)
Helmoltz free energy	-428.024	kJ/kg
Internal energy	2589.92	kJ/kg
Gibbs free energy	-231.483	kJ/kg
Heat capacity at constant volume	2.00678	kJ/(kg.°C)

ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738

Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

i.e. $h3 := 2786.46$ kJ/kg

Next, to get h4: This is equal to enthalpy of dry sat. steam at 13 bar plus cp.ΔT. So, we calculate h4 as follows:

$h4 := h3 + 2.1 \cdot 40$ i.e. $h4 = 2.87 \cdot 10^{3}$ kJ/kg

Now, we get the results:

$Q1 := h2 - h1$ ...Amount of heat reqd to get steam 0.97 dry

i.e. $Q1 = 2.517 \cdot 10^{3}$ kJ/kg

$Q2 := h3 - h1$ ...Amount of heat reqd to get dry steam

i.e. $Q2 = 2.576 \cdot 10^{3}$ kJ/kg

$Q3 := h4 - h1$ ...Amount of heat reqd to get superheated steam with 40 deg. superheat

i.e. $Q3 = 2.66 \cdot 10^{3}$ kJ/kg

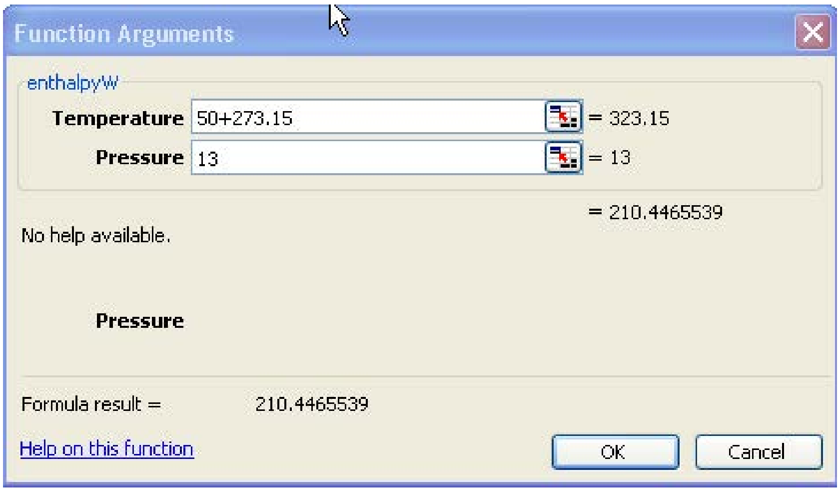
Alternatively:

Let us demonstrate this calculation in **MS Excel spreadsheet**.

Free Steam properties Add-in is available for Excel (i.e. Water97_v13.xla – Excel Add-In for Properties of Water and Steam in SI-Units, authored by Bernhard Spang, Hamburg, Germany, Ref: http://www.cheresources.com/staff.shtml).

The file Water97_v13.xla is put in the Add-In directory in Excel and is then available as a set of built-in functions.

Open Excel and first calculate h1. To calculate h1, we have to choose the relevant function from Add-in directory. Go to Excel > Insert > function and select 'User defined' category. Steam functions are presented. Select EnthalpyW and click OK. Enter values of T (in Kelvin) and P (in bar) as shown. Immediately, the result appears. You get:



enthalpyW

Temperature 50+273.15 = 323.15

Pressure 13 = 13

= 210.4465539

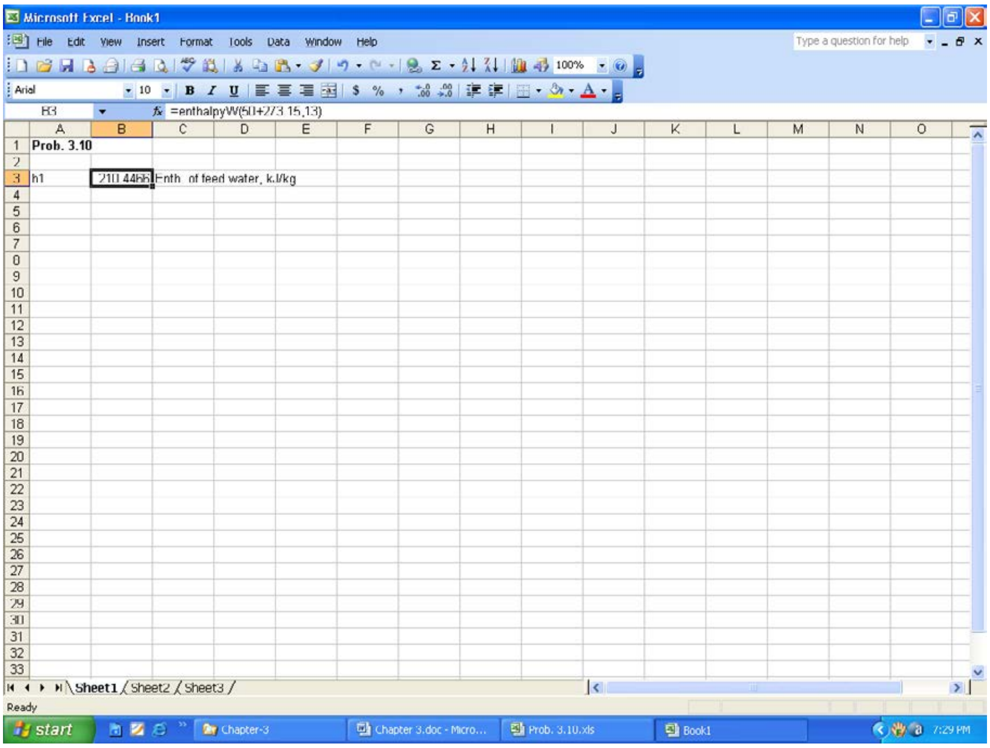
No help available.

Pressure

Formula result = 210.4465539

Fig. 3.41d. Solution with Excel

Now, click OK and the value is transferred to the cell in the worksheet:

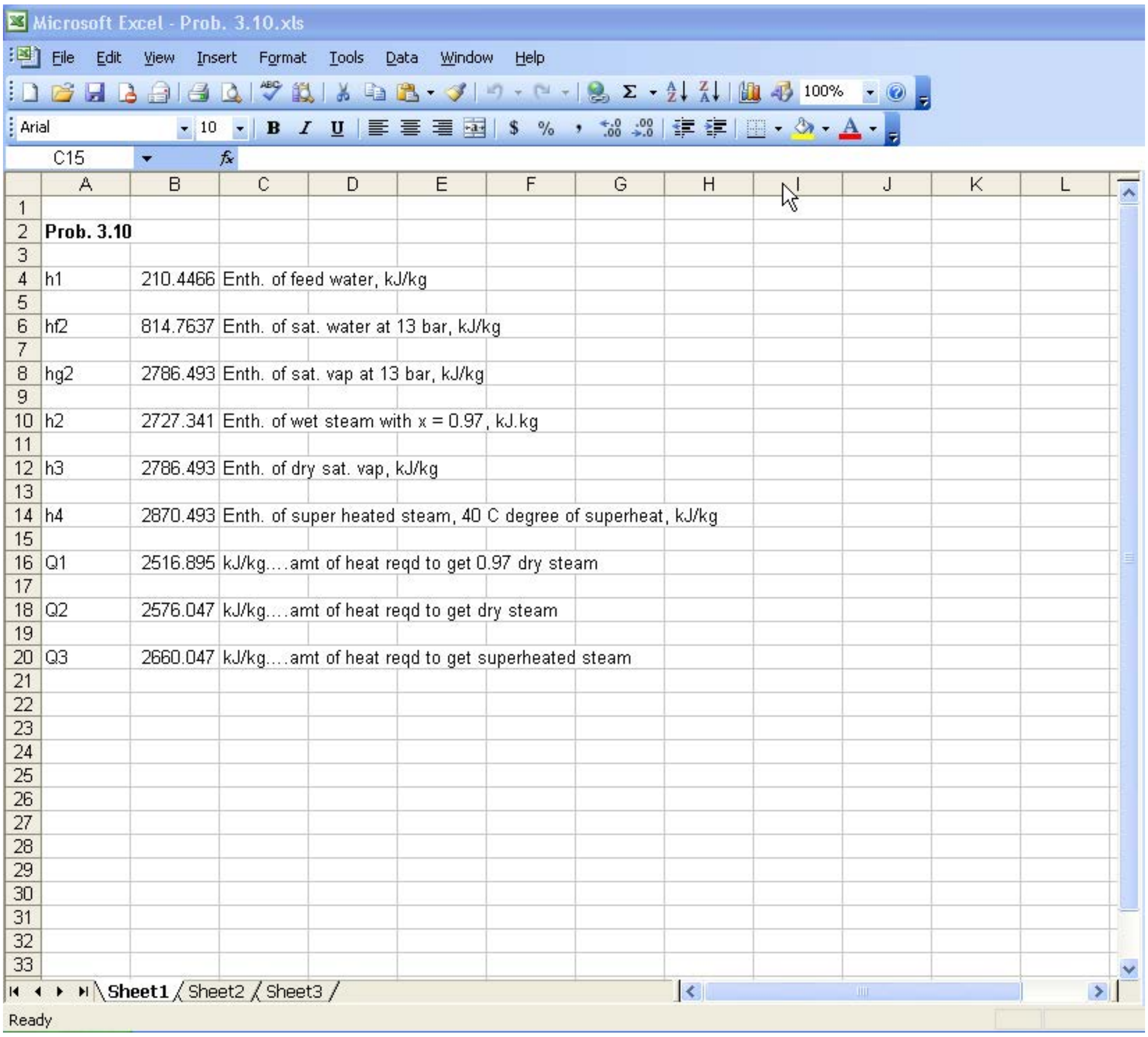


B3 =enthalpyW(50+273.15,13)

	A	B	C
1	**Prob. 3.10**		
2			
3	h1	210.4466	Enth. of feed water, kJ/kg

Fig. 3.41e. Solution with Excel

In a similar manner, calculate other values:



	A	B	C
2	**Prob. 3.10**		
4	h1	210.4466	Enth. of feed water, kJ/kg
6	hf2	814.7637	Enth. of sat. water at 13 bar, kJ/kg
8	hg2	2786.493	Enth. of sat. vap at 13 bar, kJ/kg
10	h2	2727.341	Enth. of wet steam with x = 0.97, kJ.kg
12	h3	2786.493	Enth. of dry sat. vap, kJ/kg
14	h4	2870.493	Enth. of super heated steam, 40 C degree of superheat, kJ/kg
16	Q1	2516.895	kJ/kg....amt of heat reqd to get 0.97 dry steam
18	Q2	2576.047	kJ/kg....amt of heat reqd to get dry steam
20	Q3	2660.047	kJ/kg....amt of heat reqd to get superheated steam

Fig. 3.41f. Solution with Excel

Note that values for Q1, Q2, Q3 obtained by Mathcad and Excel agree.

3.6 Determination of 'quality' (or dryness fraction) of wet steam:

3.6.1 Throttling calorimeter:

Here, wet steam from the steam mains(state 1) is throttled in a throttling valve in such a way that the final state 2 is in the super-heated region. Throttling is a constant enthalpy process. In state 1, P and T are interdependent; so, P1 is measured. In state 2, both P2 and T2 are measured. See fig. 3.44a and 3.44b. Then, h2 can easily be calculated (or found out from steam tables). Since h1 = h2, we can write:

$$h_1 = h_{f1} + x_1 \cdot h_{fg1}$$

i.e. $$h_1 = h_{f1} + x_1 \cdot \left(h_{g1} - h_{f1}\right) \qquad .....(3.9)$$

and, $$x_1 = \frac{h_1 - h_{f1}}{h_{g1} - h_{f1}} \qquad ......(3.10)$$

Knowing P1, sat. liq. enthalpy h_{f1} and sat. vap. enthalpy h_{g1} are easily determined and thus the quality of steam in the mains, x_1 is determined.

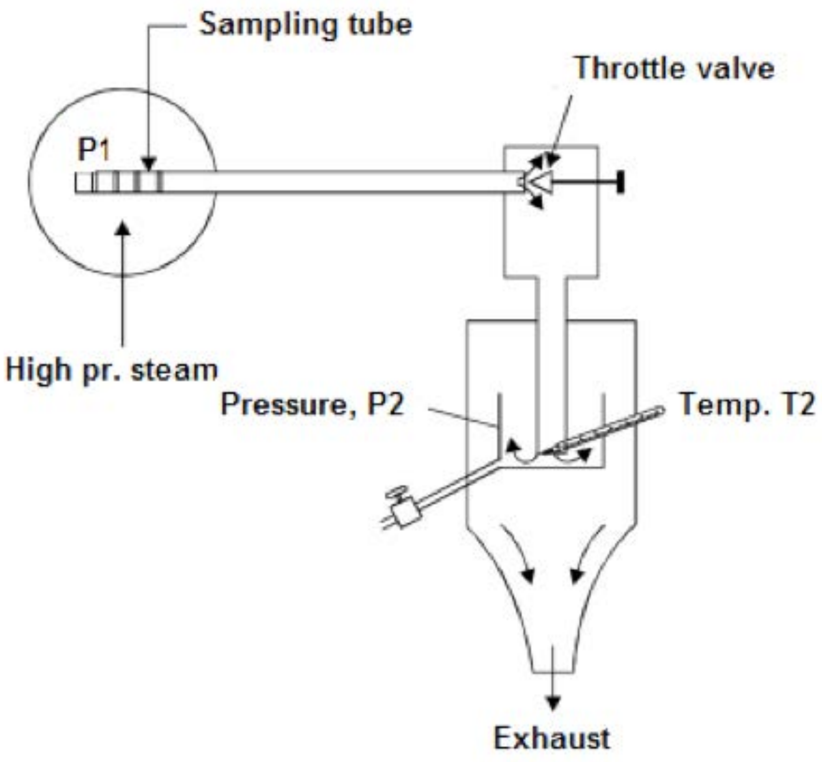


Fig. 3.42a. Throttling calorimeter

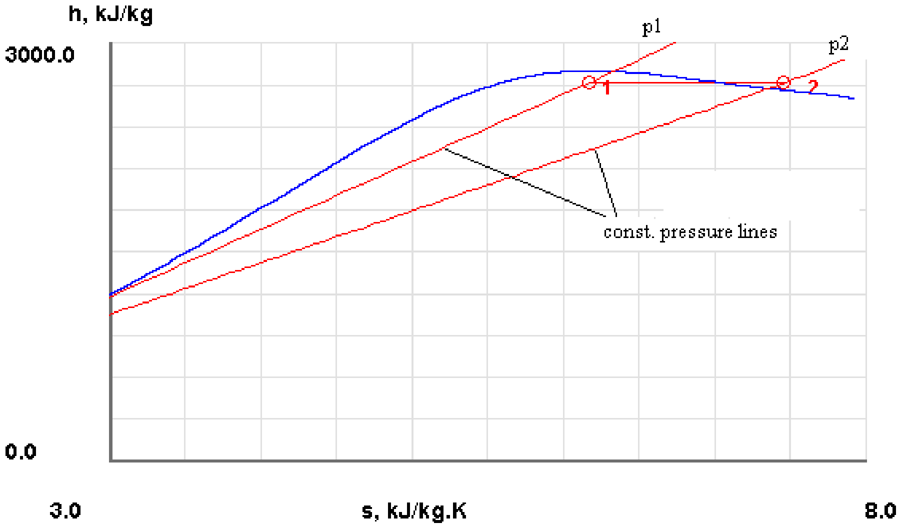
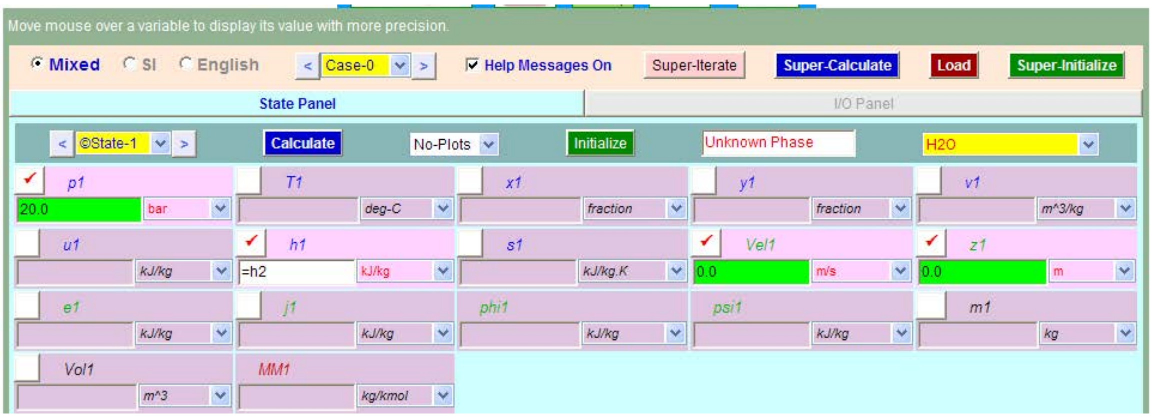


Fig. 3.42b. (h-s) diagram for Throttling calorimeter (from TEST)

Problem 3.11: In a throttling calorimeter, pressure in the steam mains is 20 bar and the pressure and temperature after throttling are 1 bar and 125 C. What is the quality of steam in the mains?

Solution: This problem is worked out easily using TEST.

Go to TEST > Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at P1 = 20 bar, x1 = to be determined. Temperature T1 is also not known. However, we know h1 = h2, where h2 will be determined later. So, enter the value of P1 and for h1 enter h1 = h2. Click 'Calculate'. We see that all properties can not be calculated at this stage. We get:



Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

State-1

No-Plots

Unknown Phase

H2O

☑ p1: 20.0 bar

☑ h1: =h2 kJ/kg

☑ Vel1: 0.0 m/s

☑ z1: 0.0 m

Fig. 3.43a. Throttling calorimeter – properties at state 1 (from TEST)

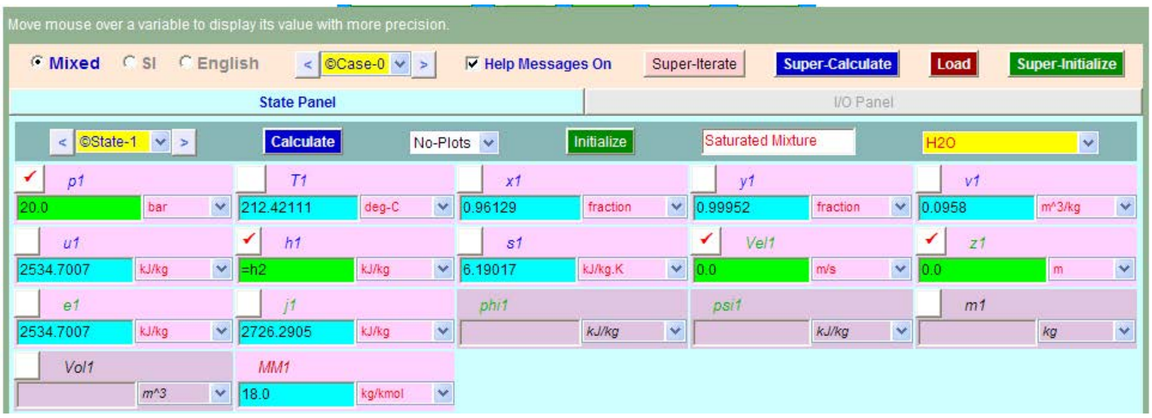
Next, we proceed to state 2. Enter values of P2 and T2. Click 'Calculate'. Properties at state2 are immediately calculated.

● Mixed ○ SI ○ English
Case-0
☑ Help Messages On
State-2
No-Plots
Superheated Vapor
H2O

✓ p2: 1.0 bar	✓ T2: 125.0 deg-C	x2: fraction	y2: fraction	v2: 1.81607 m^3/kg
u2: 2544.6836 kJ/kg	h2: 2726.2905 kJ/kg	s2: 7.48723 kJ/kg.K	✓ Vel2: 0.0 m/s	✓ z2: 0.0 m
e2: 2544.6836 kJ/kg	j2: 2726.2905 kJ/kg	phi2: kJ/kg	psi2: kJ/kg	m2: kg
Vol2: m^3	MM2: 18.0 kg/kmol			

Fig. 3.43b. Throttling calorimeter – properties at state 2 (from TEST)

Now, click on 'Supercalculate' and TEST refers back to state 1 with h1 = h2, and calculates all properties. Now, if we go back to state 1, we see:



● Mixed ○ SI ○ English
Case-0
☑ Help Messages On
State-1
No-Plots
Saturated Mixture
H2O

✓ p1: 20.0 bar	T1: 212.42111 deg-C	x1: 0.96129 fraction	y1: 0.99952 fraction	v1: 0.0958 m^3/kg
u1: 2534.7007 kJ/kg	✓ h1: =h2 kJ/kg	s1: 6.19017 kJ/kg.K	✓ Vel1: 0.0 m/s	✓ z1: 0.0 m
e1: 2534.7007 kJ/kg	j1: 2726.2905 kJ/kg	phi1: kJ/kg	psi1: kJ/kg	m1: kg
Vol1: m^3	MM1: 18.0 kg/kmol			

Fig. 3.43c. Throttling calorimeter properties at state 1 (from TEST)

Observe that h1 = h2 = 2726.29 and x1, the quality of steam in the steam mains, is 0.961.

(h-s) plot for this throttling calorimeter is shown below:

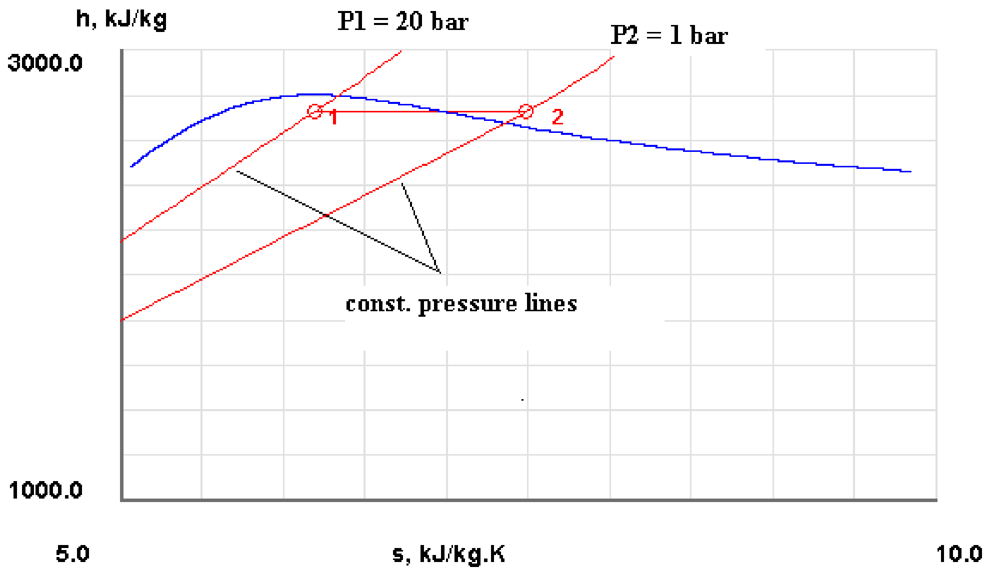


Fig. 3.43d. Throttling calorimeter – (h-s) plot from TEST

Note: While using throttling calorimeter, it is important that the exit state 2 is in the super-heated region. Also, at least 5 deg. Superheat must be provided in state 2. Then, if the exit P2 is 1 bar (with Tsat = 99.61 C), T2 should be, say, 105 C. Now, if the inlet pressure from mains, P1 is 20 bar, we see by a similar calculation in TEST that max. dryness fraction that can be measured with the throttling calorimeter is 0.94.

3.6.2 Separating and Throttling calorimeter:

If the steam in the mains is very wet, i.e. by throttling the state 2 does not reach superheated region, we use a Separating and Throttling calorimeter, where excess water is separated in the separating section and the wet steam is then throttled in a throttle valve (TV) in the throttling section. See fig. below. Pressures P1, P2, P3 and temperature T3 are measured. Also, the moisture separated out in the separating calorimeter, m_s, is measured; steam after throttling is condensed and this amount, m_c, is also measured.

P2 is approximately equal to P1, since the pressure drop in the separator is generally quite small.

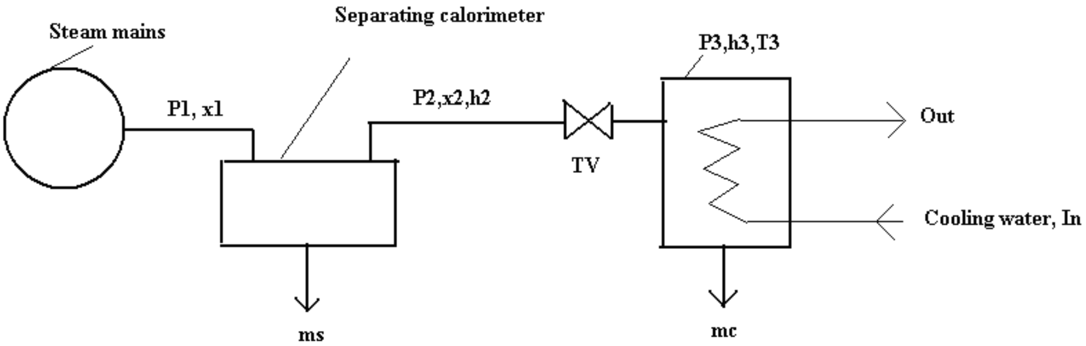


Fig. 3.44a. Separating and Throttling calorimeter

(h-s) plot for this case of separating and throttling calorimeter is shown below:

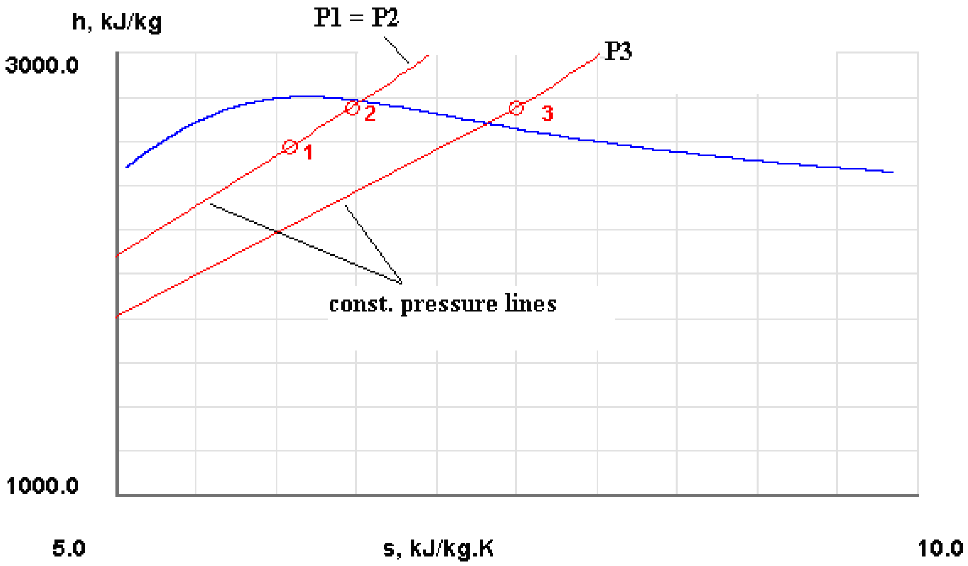


Fig. 3.44b. Separating and Throttling calorimeter-(h-s) plot from TEST

Then, since P3, T3 are measured, h3 can be calculated. Also, h2 = h3 for throttling. Further,

$$h_2 = h_{f2} + x_2 \cdot (h_{g2} - h_{f2})$$

i.e. $$x_2 = \frac{h_2 - h_{f2}}{h_{g2} - h_{f2}} \qquad ...(3.11)$$

Therefore, x_2 can be calculated. Then, $x_2.m_c$ = amount of dry steam at state 2. This must also be the amount of dry steam at state 1. Therefore, quality of steam at state 1 is calculated as:

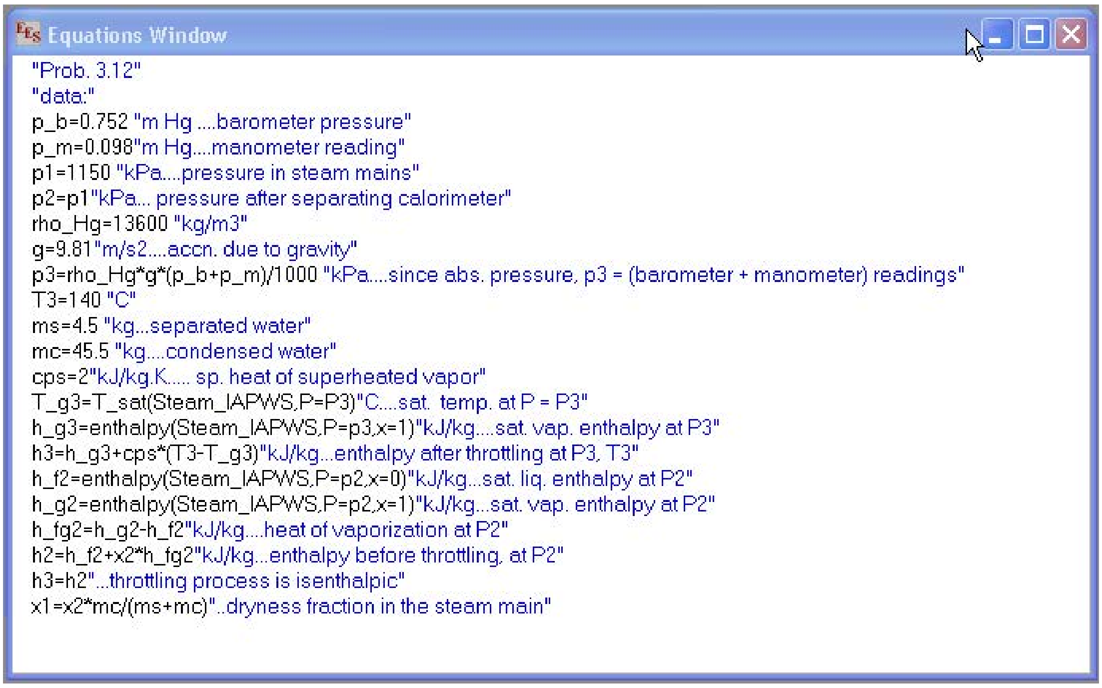
$$x_1 = \frac{x_2 \cdot m_c}{m_s + m_c} \qquad ....(3.12)$$

Problem 3.12: In a test conducted to determine the dryness fraction of steam using combined separating and throttling calorimeter, following observations were recorded:

Water collected in separating calorimeter = 4.5 kg; steam condensed after throttling = 45.5 kg; Initial pressure of steam = 11.5 bar; temp. of steam after throttling = 140 C; manometer reading = 98 mm Hg; barometer reading = 752 mm Hg. Estimate the dryness fraction of steam as it enters the throttling calorimeter. Also, determine the dryness fraction of steam entering the separating calorimeter. Take cp for superheated steam as 2.0 kJ/kg.K….[VTU, 2005]

Solution:

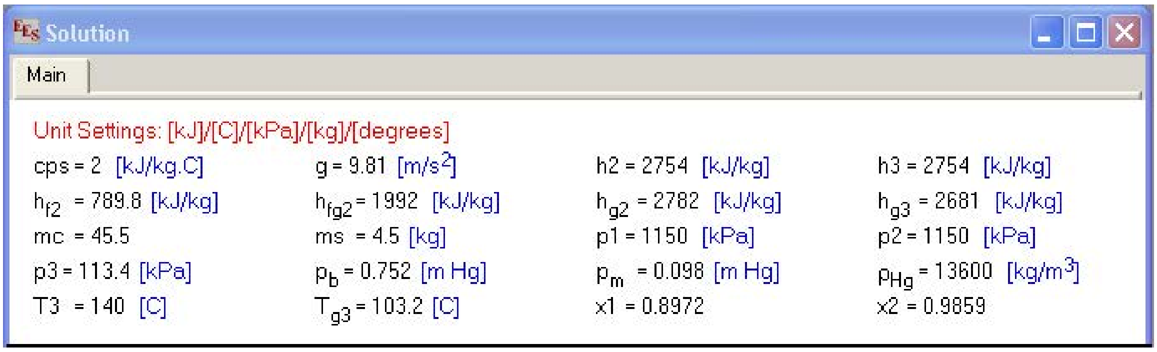
We shall solve this problem in EES. In the Eqns. Window of EES, enter the code as shown below. Read the explanatory comments given in each line.



```
"Prob. 3.12"
"data:"
p_b=0.752 "m Hg ....barometer pressure"
p_m=0.098"m Hg....manometer reading"
p1=1150 "kPa....pressure in steam mains"
p2=p1"kPa... pressure after separating calorimeter"
rho_Hg=13600 "kg/m3"
g=9.81"m/s2....accn. due to gravity"
p3=rho_Hg*g*(p_b+p_m)/1000 "kPa....since abs. pressure, p3 = (barometer + manometer) readings"
T3=140 "C"
ms=4.5 "kg...separated water"
mc=45.5 "kg....condensed water"
cps=2"kJ/kg.K..... sp. heat of superheated vapor"
T_g3=T_sat(Steam_IAPWS,P=P3)"C....sat.  temp. at P = P3"
h_g3=enthalpy(Steam_IAPWS,P=p3,x=1)"kJ/kg....sat. vap. enthalpy at P3"
h3=h_g3+cps*(T3-T_g3)"kJ/kg...enthalpy after throttling at P3, T3"
h_f2=enthalpy(Steam_IAPWS,P=p2,x=0)"kJ/kg...sat. liq. enthalpy at P2"
h_g2=enthalpy(Steam_IAPWS,P=p2,x=1)"kJ/kg...sat. vap. enthalpy at P2"
h_fg2=h_g2-h_f2"kJ/kg....heat of vaporization at P2"
h2=h_f2+x2*h_fg2"kJ/kg...enthalpy before throttling, at P2"
h3=h2"...throttling process is isenthalpic"
x1=x2*mc/(ms+mc)"..dryness fraction in the steam main"
```

Fig. 3.45a. Separating and Throttling calorimeter-EES code

Now, press F2 to get the solution:



```
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
cps = 2  [kJ/kg.C]        g = 9.81  [m/s2]          h2 = 2754  [kJ/kg]        h3 = 2754  [kJ/kg]
hf2  = 789.8 [kJ/kg]      hfg2 = 1992  [kJ/kg]      hg2 = 2782  [kJ/kg]       hg3 = 2681  [kJ/kg]
mc  = 45.5                ms  = 4.5 [kg]            p1 = 1150  [kPa]          p2 = 1150  [kPa]
p3 = 113.4 [kPa]          pb = 0.752  [m Hg]        pm  = 0.098 [m Hg]        ρHg = 13600  [kg/m3]
T3  = 140  [C]            Tg3 = 103.2 [C]           x1 = 0.8972               x2 = 0.9859
```

Fig. 3.45b. Separating and Throttling calorimeter-Solution from EES

It may be observed that dryness fraction of steam entering the throttling calorimeter = x2 = 0.9859 and dryness fraction of steam entering the separating calorimeter (i.e. in the steam mains) = x1 = 0.8972. (h-s) plot for this case is shown below:

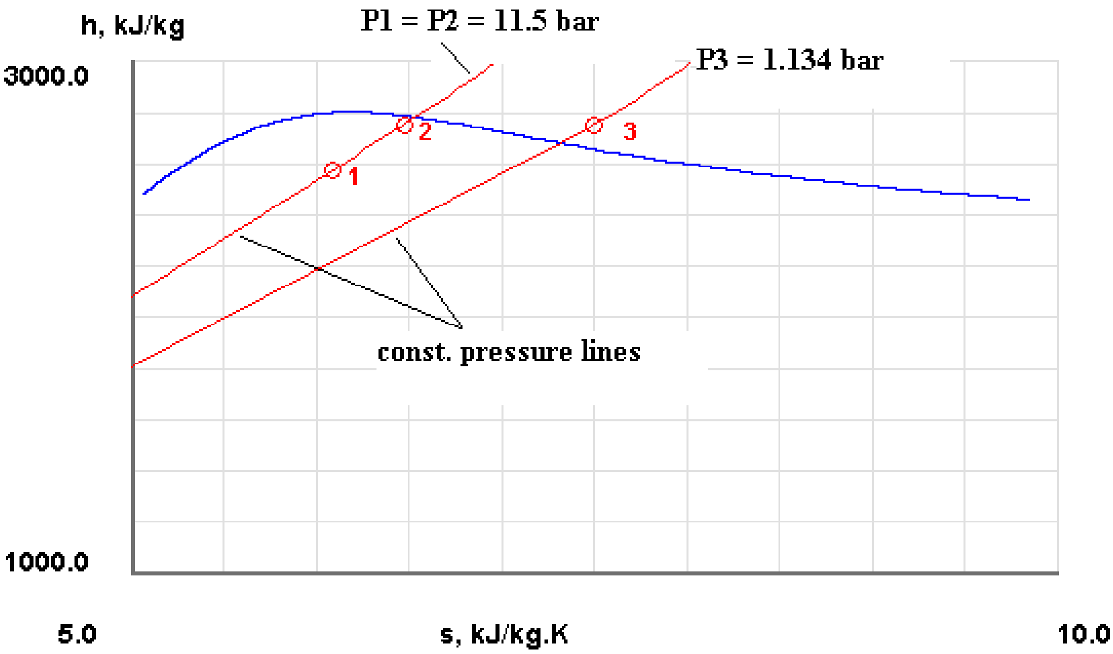


Fig. 3.45c. Separating and Throttling calorimeter-(h-s) plot from TEST

3.7 Conclusion:

In this chapter, we studied about pure fluids. Various property diagrams were explained, with particular reference to water. Use of software to plot property diagrams for different substances was demonstrated. Methods of finding out property values and generating property tables were also shown using different software. Determination of dryness fraction (or quality) of steam with 'throttling calorimeter' as well as 'separating and throttling calorimeter' was explained.

3.8 References:

1. Y.A. Cengel and M.A. Boles. *Thermodynamics – An Engineering Approach*. 4th ed. New Delhi: Tata McGraw-Hill, 2003
2. Sonntag et. al. *Fundamentals of Thermodynamics. 5th ed.* Singapore: John Wiley & Sons, 1999
3. http://www.engineering.uiowa.edu/fluidslab/referenc/physprop.html
4. http://webbook.nist.gov/chemistry/fluid/
5. http://properties.nist.gov/
6. http://www.cheresources.com/iapwsif97.shtml (For prop. of Water/Steam & Excel Add-in)
7. http://www.x-eng.com/Download_XSteam.htm (For prop. of Water/Steam & Excel Add-in)
8. http://www.mathpad.com/index.html (Free Applet for Steam properties)
9. http://www.science.uwaterloo.ca/~cchieh/cact/c123/phasesdgm.html
10. http://www.eng.usf.edu/~campbell/ThermoI/Proptut/tut1.html
11. http://hyperphysics.phy-astr.gsu.edu/Hbase/thermo/pvtexp.html#c1
12. http://www.chemguide.co.uk/physical/phaseeqia/phasediags.html#top
13. http://twt.mpei.ac.ru/ochkov/WSPHB/Engindex.html(IAPWS-IF97-Moscow Power Engg. Institute- Mathcad server)
14. http://www.spiraxsarco.com/resources/steam-tables.asp
15. www.spreadsheetworld.com ((for free Excel Add-In: XLThermalFluids which gives values of P, v, T, s, u, h and x for 37 common fuids)

3.9 Exercise Problems:

1. A 200-m^3 rigid tank is filled with saturated liquid-vapor mixture of water at 125°C. If 25% of the mass is liquid and the 75% of the mass is vapor, find out the total mass in the tank.
2. Water is boiled at 300 kPa pressure in a pressure cooker. The cooker initially contains 2.5 kg of water. Once boiling started, it is observed that half of the water in the cooker evaporated in 20 minutes. If the heat loss from the cooker is negligible, find the average rate of energy transfer to the cooker.
3. A 0.25-m^3 rigid tank contains 8.5 kg of water (in any phase or phases) at 500 kPa. Find the temperature in the tank.
4. A rigid tank contains 0.7 kg of steam at 9 MPa and 300°C. What is the volume of the tank?

5. Fill up the following Table:

Fluid	**P(kPa)**	**T(deg.C)**	**v(m3/kg)**	**x**	**Phase**
R-22	100	-25			
H2O		120	0.5		
H2O	100		1.8		
NH3	100	20			
R-134a		50		0.8	
R-134a			0.005	0.5	
R-12	350		0.036		
N2	100	-75			
R-22		50	0.05		
NH3	550		0.31		

6. A rigid vessel has a volume of 0.01 m^3 and contains 4 kg of water at 40 deg. C. Calculate the quality and masses of liquid and vapor.
7. A pressure cooker contains 1.5 kg of sat. steam at 5 bar pressure. Find the quantity of heat which must be rejected so that the quality of steam becomes 0.6 dry. Determine the pressure and temperature at new state.
8. The dryness fraction of steam at a pressure of 22 bar is measured with a throttling calorimeter. After throttling, pressure in the calorimeter is 13 bar and the temperature is 115 C. Find the dryness fraction of steam entering the calorimeter.
9. What is the dryness fraction that can theoretically be determined in a throttling calorimeter if the steam to be tested is at a pressure of 15 bar and the pressure after throttling is 1.1 bar, with 5 degree C superheat?
10. Following data are obtained with a separating and throttling calorimeter:
    Pressure in the mains: 15 bar; condition after throttling: 1 bar, 115 degree C; Moisture collected in the separator in 5 min: 155 cm^3 at 70 degree C; steam condensed after throttling, in 5 min: 3.2 kg. Find the quality of steam in the mains.

To see Part II, download:
Basic Thermodynamics: Software Solutions – Part II