Software Solutions to Problems on Heat Transfer

Boiling and Condensation

Dr. M. Thirumaleshwar

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Boiling and Condensation

(Pool Boiling and Flow Boiling, Condensation on Vertical plates and Cylinders, outside of Horizontal cylinders, Horizontal Tube Banks in a vertical tier, inside horizontal tubes etc.)

Software Solutions to Problems on Heat Transfer – Boiling and Condensation
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Contents

Preface to Vol. 3

This is Vol. 3 of the book **"Software Solutions to Problems on Heat Transfer".**

In Vol. 1, problems on various aspects of CONDUCTION heat transfer were solved with Mathcad, EES, FEHT and EXCEL.

Vol. 2 contained solved problems on the topics of CONVECTION (i.e. Forced convection, Natural or Free convection).

Present Vol. viz. BOILING & CONDENSATION contains problems solved on following sub-topics:

Vol. 3: BOILING & CONDENSATION:

3.1. Boiling heat transfer:

3.1. Boiling heat transfer Equation summary

Problems on: Pool Boiling and Flow Boiling

Problems solved with Mathcad

Problems solved with EES

Problems solved with EXCEL

3.2. Condensation heat transfer:

3.2. Condensation heat transfer Equation summary

Problems on: Condensation on Vertical plates and Cylinders, outside of Horizontal cylinders, Horizontal Tube Banks in a vertical tier, inside horizontal tubes etc.

Problems solved with Mathcad

Problems solved with EES

Problems solved with EXCEL

References

Here also, problems are solved using the popular software, viz. "Mathcad", "Engineering Equation Solver (EES)", and MS EXCEL spreadsheet**. Comments are included generously in the codes so that the logic behind the solutions is clear. An introductory chapter in Part-I gives a brief overview of the software used.**

As in Vol. I and II, emphasis is given not only to solving a given problem but also to parametric analysis and graphical representation of results. Advantage of using Software to solve a variety of problems thus becomes evident. Also, problems with EXCEL spreadsheet are solved in greater details with relevant screen shots for immediate help to students, since EXCEL is available in practically every Personal Computer.

Acknowledgements: Firstly, I thank my students, since it is they who inspired me and motivated me. Next, my thanks are due to the authorities at St. Joseph Engineering College, for their constant encouragement.

Also, my sincere thanks to **Bookboon.com** for publishing this book on the Internet. **Ms. Sophie** and her editorial staff have to be specially mentioned for their cooperation, suggestions and support.

Finally, my heartfelt appreciation to **my wife, Kala,** for her unfailing and thoughtful support and encouragement.

M. Thirumaleshwar

Author

August 2013

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.

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

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

He has also written and published three book-lets 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. Finite Element Heat Transfer (FEHT) (Ref: www.fchart.com)
4. MS EXCEL – (2007) Spreadsheet (Ref: Microsoft)

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

See Part-I of this book for brief introduction to these four software.

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

To the Student

Dear Student:

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

(i) you are thorough with the derivations, and
(ii) skillful in solving numerical problems.

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

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

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 in the minds of students and encourages them to be creative and work further

How to use this Book?

You need not worry if you don't know about these softwares. 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, *'there is no gain without pain!'*

Lastly, I would like to tell you how greatly I enjoyed solving the problems presented in this book using the softwares mentioned.

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

Good Luck!

Author

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3 Boiling And Condensation

Learning objectives:

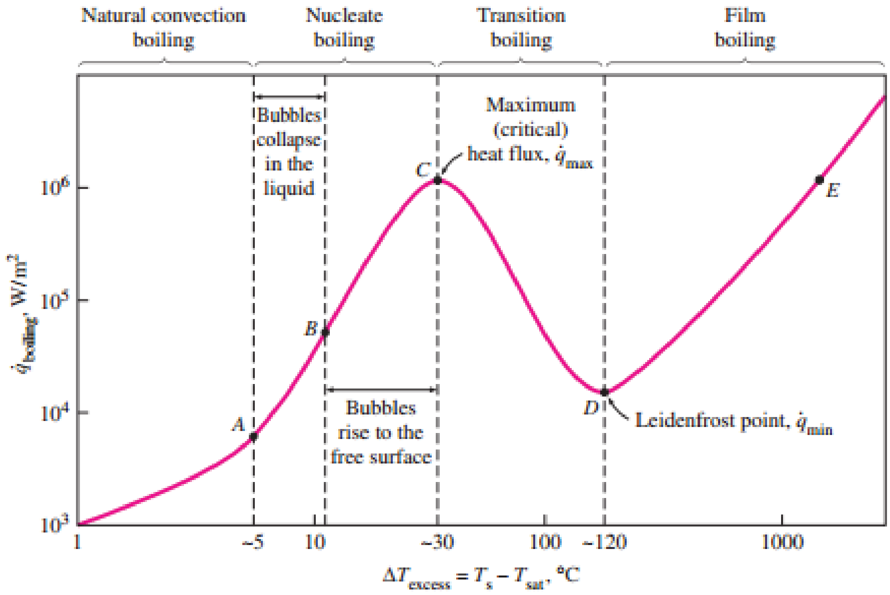
1. In Chapter 2, while dealing with convection (either Natural or Forced), the fluid involved was homogeneous and in single phase.
2. But, there are many important practical cases which involve heat transfer with a change of phase of the fluid, e.g. boiling where the liquid changes to vapour and condensation where the vapour condenses into a liquid.
3. Some of the applications of boiling and condensation are:
   i) Evaporators and condensers of a vapour compression refrigerating system
   ii) Boilers and condensers of a steam power plant
   iii) Reboilers and condensers of distillation columns of cryogenic and petrochemical plants
   iv) Cooling of nuclear reactors and rocket motors
   v) Process heating and cooling etc.
4. Unique features of boiling and condensation are:
   i) heat transfer, practically at a constant temperature, because of change of phase
   ii) latent heat and surface tension come into play in addition to buoyancy driven flow effects, resulting in larger heat transfer rates and heat transfer coefficients compared to the usual free or forced convection
   iii) *high heat transfer rates* with small temperature difference
5. We have mostly empirical relations for Boiling and Condensation. We will also need properties of Water and steam (at 1 atm. and sat. conditions), since in most of the cases we deal with water. Of course, there are other cases where boiling or condensation of other fluids, such as refrigerants or cryogenic fluids also have to be dealt with.
6. We will solve problems with these empirical relations and the functions for properties of water, written in EES, Mathcad or EXCEL.

3.1 Boiling:

Formulas used:

1. **Boiling regimes and boiling curve: (Ref. 2)**

For Water at 1 atm:



In general, four different boiling regimes are observed depending upon the *excess temperature* (ΔT_e) imposed, viz.

i) natural convection boiling (ΔT_e upto about 5 deg.C)
ii) nucleate boiling (ΔT_e from 5 deg to about 30 deg. C)
iii) transition boiling (ΔT_e from 30 deg to about 120 deg. C), and
iv) film boiling (ΔT_e beyond 120 deg. C)

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2. **Heat transfer correlations for pool boiling: (Ref: 1)**

2.1 Natural convection boiling regime:(i.e. up to an excess temperature of about 5 deg. C). In this regime, the correlations already presented in the previous chapter on 'Natural (or, Free) convection' may be used.

2.2 Nucleate boiling regime: (i.e. excess temperature varying from about 5 deg. up to about 30 deg. C).

Correlation proposed by Rohsenow in 1952, is the most widely used one, for heat flux in the nucleate boiling regime:

$$q_{nucleate} = \mu_L \cdot h_{fg} \cdot \left[\frac{g \cdot (\rho_L - \rho_V)}{\sigma} \right]^{\frac{1}{2}} \cdot \left[\frac{C_{pL} \cdot (T_s - T_{sat})}{C_{sf} \cdot h_{fg} \cdot Pr_L^{\,n}} \right]^3 \quad \text{W/m2........(11.5)}$$

where, $q_{nucleate}$ = nucleate boiling heat flux, W/m^2

μ_L = viscosity of liquid, kg/ (m.s)

h_{fg} = enthalpy of vapourization, J/kg

g = gravitational acceleration, m/s^2

ρ_L = density of liquid, kg/m^3

ρ_V = density of vapour, kg/m^3

C_{pL} = Sp. Heat of liquid, J/(kg.C)

σ = surface tension of liquid – vapour interface, N/m

T_s = surface temperature of heater, deg.C

T_{sat} = saturation temperature of fluid, deg.C

C_{sf} = a constant depending upon the specific surface-fluid combination

Pr_L = Prandtl number of liquid

n = 1 for water, and 1.7 for all other liquids

Subscripts L and V refer to liquid and vapour respectively.

Experiments show that nucleate boiling heat flux is not very much dependent on the geometry or orientation of the heater surface.

Therefore, the correlation given above is valid for flat plates, cylinders and other geometries.

Since water is one of the most common fluids used, it is useful to have its surface tension and the constant Csf for water – surface combination, readily available.

Surface tension and latent heat of water at a few temperatures are given in Table 11.1 below:

Sat. temp. (Tsat), deg.C	Surface tension (σ), N/m	Latent heat (hfg), kJ/kg
0	0.0755	2500.8
20	0.0729	2453.7
40	0.0695	2406.2
60	0.0661	2357.9
80	0.0627	2308.3
100	0.0589	2256.7
150	0.0487	2113.4
200	0.0378	1939.3
250	0.0261	1714.7
300	0.0143	1406.2
350	0.0036	916.1
374	0.0	0.0

Table 11.1: σ and h_{fg} for water

Also, surface tension of water (σ) can be quickly determined by the following equation:

σ = 0.0808 * (1 – 0.00267 * T), N/m where T is in deg. C

Experimentally determined values of constant C_{sf} for a few liquid-surface combinations are given in Table 11.2:

Fluid and surface	C_{sf}
Water-copper:	
Scored surface	0.0068
Polished surface	0.0130
Water-stainless steel:	
Teflon coated surface	0.0058
Ground & polished surface	0.0068
Mechanically polished surface	0.0130
Chemically etched surface	0.0130
Water-brass	0.0060
Water-nickel	0.0060
Water-platinum	0.0130
n-pentane-copper:	
Lapped surface	0.0049
Polished surface	0.0154
n-pentane-chromium	0.0150
Ethyl alcohol-chromium	0.0027

Table 11.2: C_{sf} for a few liquid-surface combinations

Note that Rohsenow eqn. (11.5) is applicable for clean surfaces and for relatively smooth surfaces.

To calculate the heat flux in nucleate boiling, Collier recommends the following eqn. which is simpler to use as compared to eqn. (11.5):

$$q_{nucleate} = 0.000481 \cdot \Delta T_e^{3.33} \cdot P_{cr}^{2.3} \cdot \left[1.8 \cdot \left(\frac{P}{P_{cr}} \right)^{0.17} + 4 \cdot \left(\frac{P}{P_{cr}} \right)^{1.2} + 10 \cdot \left(\frac{P}{P_{cr}} \right)^{10} \right]^{3.33} \quad \text{W/m}^2 \text{....(11.7)}$$

where ΔT_e is the excess temp. in deg. C, P is the operating pressure in atm., P_{cr} is the critical pressure in atm.

Based on Russian literature, following calculation formulas are recommended specifically for water in nucleate boiling, in the pressure range 0.2–100 ata:

$$h_{nucleate} = 3.133 \cdot q^{0.7} \cdot P^{0.15} \quad \text{W/(m}^2\text{.C)...for water..(11.10,a)}$$

and,

$$h_{nucleate} = 45.054 \cdot \Delta T^{2.33} \cdot P^{0.5} \quad \text{W/(m}^2\text{.C)....for water.(11.10,b)}$$

In the above eqns. q is the heat flux in W/m², P is the pressure in bar, and ΔT is the excess temp. in deg.C.

Peak (or, maximum) heat flux in nucleate pool boiling:

Leinhard and Dhir (1973) give the following correlation for peak heat flux in nucleate pool boiling:

$$q_{max} = C_o \cdot h_{fg} \cdot \rho_V \cdot \left[\frac{\sigma \cdot g \cdot (\rho_L - \rho_V)}{\rho_V^2} \right]^{\frac{1}{4}} \quad \text{W/m}^2\text{.....(11.11)}$$

where $C_o = 0.149$ for a large horizontal surface

and, $C_o = 0.116$ for a large horizontal cylinder

Unlike the nucleate boiling flux, peak heat flux depends on heater geometry and orientation.

Another relation for **peak heat flux on horizontal cylinders**, which fits experimental data very well, is presented by Sun and Lienhard:

$$\frac{q_{max}}{q_{maxF}} = 0.89 + 2.27 \cdot \exp\left(-3.44 \cdot \sqrt{R'}\right)$$ W/m^2...for 0.15 < R' < 3.47.......(11.12, a)

$$\frac{q_{max}}{q_{maxF}} = 0.894$$ W/m^2...for R' > 3.47.......(11.12, b)

where R′ is a dimensionless radius defined as:

$$R' = R \cdot \left[\frac{g \cdot \left(\rho_L - \rho_V\right)}{\sigma}\right]^{\frac{1}{2}}$$

and q_{maxF} is the peak heat flux on an infinite horizontal plate, given as:

$$q_{maxF} = 0.131 \cdot \sqrt{\rho_V} \cdot h_{fg} \cdot \left[\sigma \cdot g \cdot \left(\rho_L - \rho_V\right)\right]^{\frac{1}{4}}$$ W/m^2....for infinite horizontal plate.....(11.13)

Cengel (Ref. 2) gives following relation of Zuber and a Table due to Lienhard et al for Max. heat flux:

$$\dot{q}_{max} = C_{cr}\, h_{fg}[\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4} \quad \text{(10-3)}$$

TABLE 10–4

Values of the coefficient C_{cr} for use in Eq. 10–3 for maximum heat flux (dimensionless parameter $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$)

Heater Geometry	C_{cr}	Charac. Dimension of Heater, L	Range of L^*
Large horizontal flat heater	0.149	Width or diameter	$L^* > 27$
Small horizontal flat heater[1]	$18.9K_1$	Width or diameter	$9 < L^* < 20$
Large horizontal cylinder	0.12	Radius	$L^* > 1.2$
Small horizontal cylinder	$0.12L^{*-0.25}$	Radius	$0.15 < L^* < 1.2$
Large sphere	0.11	Radius	$L^* > 4.26$
Small sphere	$0.227L^{*-0.5}$	Radius	$0.15 < L^* < 4.26$

[1] $K_1 = \sigma/[g(\rho_l - \rho_v)A_{heater}]$

Minimum heat flux:

This occurs at point D in Fig. (11.2); minimum heat flux represents the lower limit of heat flux in film boiling. For a **large, horizontal plate**, Zuber derived the following relation (modified by Berenson in 1961) for minimum heat flux:

$$q_{min} = 0.09 \cdot \rho_V \cdot h_{fg} \cdot \left[\frac{\sigma \cdot g \cdot (\rho_L - \rho_V)}{(\rho_L + \rho_V)^2} \right]^{\frac{1}{4}} \quad \text{W/m}^2 \text{.....(11.15)}$$

Film boiling:

Heat transfer coefficient in stable film boiling regime on a horizontal cylinder or sphere is predicted by Bromley's correlation:

$$h_{film} = C_o \cdot \left[\frac{g \cdot \rho_V \cdot (\rho_L - \rho_V) \cdot h'_{fg} \cdot k_V^3}{\mu_V \cdot (T_s - T_{sat}) \cdot L} \right]^{\frac{1}{4}} \quad \text{W/(m}^2\text{.C).....(11.16)}$$

where $h'_{fg} = h_{fg} + 0.4 \cdot C_{pV} \cdot (T_s - T_{sat})$

C_o = 0.62 and L = D ....for a horizontal cylinder

C_o = 0.67 and L = D ....for a sphere

For a very large diameter tube (diameter D) or a horizontal surface, eqn. (11.16) is valid, with the following value for C_o (Westwater and Breen, 1962):

$$C_o = \left(0.59 + \frac{0.69 \cdot \lambda}{D} \right) \quad \text{and,} \quad L = \lambda$$

and, $$\lambda = 2 \cdot \pi \cdot \left[\frac{\sigma}{g \cdot (\rho_L - \rho_V)} \right]^{\frac{1}{2}}$$

Note that *for a horizontal surface*, C_o = 0.59, since $D \to \infty$

Vapour properties in eqn. (11.16) are evaluated at the *mean film temperature*, $T_f = (T_s + T_{sat})/2$, and *at a pressure* P_{sat} *corresponding to temp* T_{sat}.

As stated earlier, during stable film boiling, at high temperatures (> 300 C), thermal radiation effects become significant and Bromley suggested using an overall heat transfer coefficient given by:

$$h = h_{film} + 0.75 \cdot h_{rad} \quad \text{....(11.17)}$$

and, h_{rad} is given by:

$$h_{rad} = \frac{\sigma \cdot \varepsilon \cdot \left(T_s^{\,4} - T_{sat}^{\,4}\right)}{\left(T_s - T_{sat}\right)} \quad \text{W/(m}^2\text{.C).....(11.18)}$$

where $\sigma = 5.67 \cdot 10^{-8}$ $W/(m^2.K^4)$....Stefan-Boltzmann const.

and, ε is the emissivity of the heated surface

Also, remember that in eqn. (11.18), the temperatures Ts and Tsat must be in Kelvin.

Heat flux in stable film boiling is easily calculated, once the heat transfer coeff. is determined. i.e.

$$q_{film} = h \cdot (T_s - T_{sat}) \quad W/m^2 .....(11.19)$$

Simplified correlations for boiling with water:

Since water is one of the most commonly used fluids in practice, it is useful to have some simplified correlations for boiling water.

Jakob and Hawkins (1957) presented following simple relations for water boiling at atmospheric pressure on submerged surfaces:

Type of surface	Range of validity (kW/m2)	h (W/m2.K)
Horizontal:	$q_s < 15.8$	$1040 \times (\Delta T_e)^{1/3}$
	$15.8 < q_s < 236$	$5.56 \times (\Delta T_e)^3$
Vertical:	$q_s < 3.15$	$539 \times (\Delta T_e)^{1/7}$
	$3.15 < q_s < 63.1$	$7.95 \times (\Delta T_e)^3$

Table 11.4: Simplified relations for boiling heat transfer coeff. for water at one atm. pressure

Heat transfer coefficients at pressures other than atmospheric may be calculated using the following empirical equation:

$$h_p = h_a \cdot \left(\frac{p}{p_a}\right)^{0.4} \quad ...(11.20)$$

where, h_p = heat transfer coeff. at any pressure p,

h_a = heat transfer coeff. at pressure p_a (= 1 atm.) from Table 11.4.

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Note: All the above relations are for submerged bodies in pool boiling.

Now, let us consider 'Flow boiling', where the fluid is in motion while boiling occurs:

Flow Boiling:

In flow boiling, a fluid is forced to move over a heated surface while the phase change occurs. Therefore, combined effects of natural/forced convection and pool boiling come into play.

Flow boiling is classified as:

i) External flow boiling, and
ii) Internal flow boiling

(i) External flow boiling:

In external flow boiling, flow occurs over the surface of a plate or cylinder; there are the flow regimes similar to that in pool boiling, but due to the effect of flow velocity, both the nucleate boiling heat flux and the critical heat flux get enhanced. See Fig. 11.5. For water in external flow boiling, critical heat flux value as high as 35 MW/m^2 has been obtained (as compared to the value of 1.3 MW/m^2 in pool boiling at one atm.).

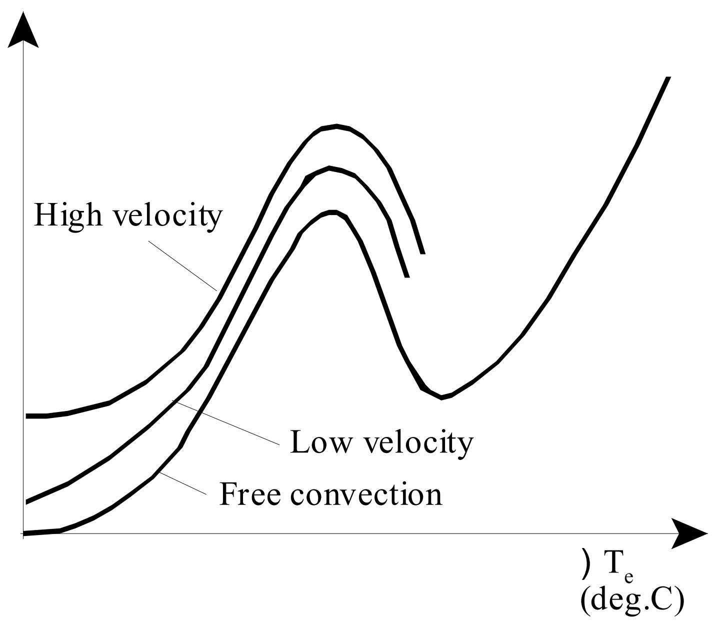


Fig. 11.5 Effet of flow veloity in external flow boiling

For cross flow over a cylinder of diameter D, Lienhard and Eichhorn have given following correlations for max. (or critical) heat flux, depending upon whether the fluid velocity is 'low' or 'high'.

Criterion to determine if the velocity is low or high is:

$$\frac{q_{max}}{\rho_V \cdot h_{fg} \cdot V} > \left[\left(\frac{0.275}{\pi}\right) \cdot \left(\frac{\rho_L}{\rho_V}\right)^{\frac{1}{2}} + 1\right]$$ ......low velocity

and,

$$\frac{q_{max}}{\rho_V \cdot h_{fg} \cdot V} < \left(\frac{0.275}{\pi}\right) \cdot \left(\frac{\rho_L}{\rho_V}\right)^{\frac{1}{2}} + 1 \qquad \text{......high velocity}$$

Correlation for Low velocity:

$$\frac{q_{max}}{\rho_V \cdot h_{fg} \cdot V} = \frac{1}{\pi} \cdot \left[1 + \left(\frac{4}{We_D}\right)^{\frac{1}{3}}\right] \qquad \text{.....(11.21)}$$

Correlation for High velocity:

$$\frac{q_{max}}{\rho_V \cdot h_{fg} \cdot V} = \frac{\left(\frac{\rho_L}{\rho_V}\right)^{\frac{3}{4}}}{169 \cdot \pi} + \frac{\left(\frac{\rho_L}{\rho_V}\right)^{\frac{1}{2}}}{19.2 \cdot \pi \cdot We_D^{\frac{1}{3}}} \qquad \text{....(11.22)}$$

Here, V is he fluid velocity and We_D is the **Weber number**, defined as the ratio of inertia forces to surface tension forces, i.e.

$$We_D = \frac{\rho_V \cdot V^2 \cdot D}{\sigma} \quad ....(11.23)$$

(ii) Internal flow boiling:

Internal forced convection boiling refers to flow inside a tube. This is more complicated since, now, there is no free surface for the vapour to escape and results in two phase flow inside the tube. There are different flow regimes occurring inside the tube depending upon the 'quality' of the fluid. ('Quality' is defined as the ratio of mass of vapour to the total mass of fluid at a given location). This is illustrated in Fig. 11.6, which also shows a qualitative graph of variation of heat transfer coeff. with local quality.

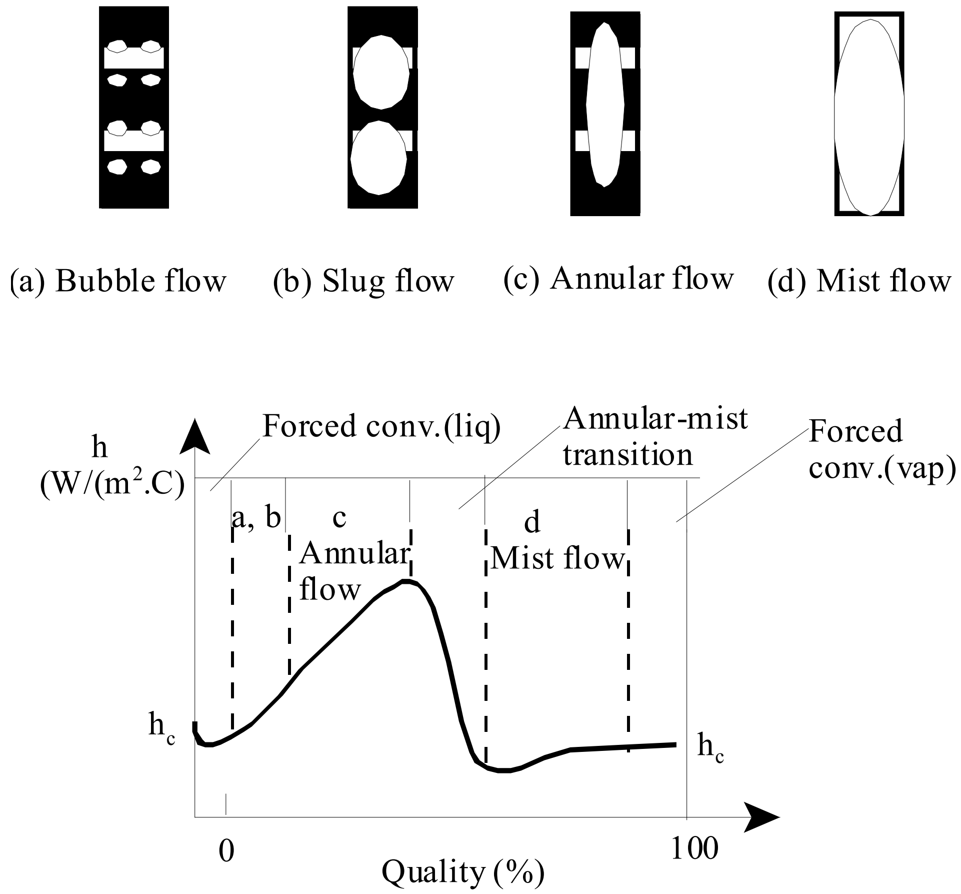


Fig. 11.6 Flow regimes and heat transfer coefficient inforced convection flow in a vertical tube

Consider a fluid, at a temperature below its boiling point, entering a vertical, heated tube. Progressive vapourization occurs along the length of the tube and the 'quality' increases. Upto a short distance from the inlet, heat transfer coeff. for the single phase fluid may be predicted using the Dittus-Boelter equation.

Bubble – flow regime: Soon, the bulk temperature reaches the saturation point, and bubbles are formed at the nucleation sites on the wall and are carried into the main stream, as in nucleate boiling. This is known as the 'bubble flow regime' (see fig. 11.6(a)) and the heat transfer coeff. increases. **Heat transfer coeff. in this range can be predicted by superimposing the liquid-forced convection and nucleate pool boiling equations.**

Slug – flow regime: Further along the distance, vapour fraction increases and individual bubbles agglomerate and slugs of vapour are formed. This regime is known as 'slug flow regime'. See Fig. 11.6(b). Fluid velocity increases and since the slugs of vapour are compressible, flow oscillations may occur. Mass fraction of vapour in this regime is around 1%, but volume fraction of vapour may be even upto 50%. **In this regime also, heat transfer coeff. may be calculated by superimposing the liquid-forced convection and nucleate pool boiling equations.** Heat transfer coeff. increases because of increased velocity.

Annular – flow regime: As the fluid progresses further up the tube, quality increases due to further addition of heat and vapour forms the core and a film of liquid flows on the inner wall surface. Vapour core travels at a higher velocity than the liquid and vapours are formed primarily at the liquid-vapour interface and not at the wall surface. Quality in this flow regime may be upto 25%. See Fig. 11.6(c).

Transition – flow regime: Now, as the quality increases, there is a sudden drop in the value of heat transfer coefficient. Heat flux at this point is known as 'critical heat flux'. This is the point of dryout. This sudden drop happens since the liquid film at the wall is now replaced by a vapour film, which has a poor thermal conductivity. *There may be sharp increase in the wall temperature and even burn-out may occur.*

Mist – flow regime: Now, the tube is fully occupied by the vapour, which may contain droplets of liquid. This is known as mist-flow regime. See Fig. 11.6(d). Heat transfer from the wall is to the vapour directly, and then from the vapour, heat is transferred to the droplets of liquid contained in the vapour.

From the annular-flow regime onwards, prediction of heat transfer coefficient is a little difficult and uncertain due to problems of two phase flow.

Two phase flow is beyond the scope of this book.

Correlations to find out heat transfer coefficient in *nucleate flow boiling* only are presented below:

Correlations for nucleate flow boiling:

Rosenhow and Griffith (1955) have suggested that total heat flux be calculated by adding the nucleate pool boiling flux (from eqn. (11.5)) and the forced convection effect (from Dittus-Boelter eqn. with the coeff. 0.023 replaced by 0.019),

i.e.

$$q_{total} = q_{nucleate} + q_{forced\_convection} \quad ....(11.24)$$

For forced convection flow **inside vertical tubes**, following correlation is recommended:

$$h = 2.54 \cdot (\Delta T_e)^3 \cdot e^{\frac{p}{1.551}} \quad W/(m^2.K)....(11.25)$$

where, $\Delta T_e = T_s - T_{sat}$, and p = pressure in mega pascals.

Above eqn. is valid for the pressure range of 5 to 170 bar.

For horizontal tubes, McAdams et.al. suggest following relation for low pressure boiling water:

$$q_{total} = q_{conv} + q_{boiling}$$

q_{conv} is calculated using:

$$Nu = 0.019 \cdot Re^{0.8} \cdot Pr^{0.4} \quad ..Nusselts\ No. = (h * D) / k\_liq$$

$$Re = \frac{G \cdot (1 - x) \cdot D}{\mu_{liq}} \quad \text{where x = dryness, G = mass velocity (kg/m^2.s)}$$

$$q_{boiling} = 2.253 \cdot \Delta T_e^{3.96} \quad \text{W/m^2...for } 0.2 < P < 0.7 \text{ MPa}$$

$$q_{boiling} = 283.2 \cdot P^{\frac{4}{3}} \cdot \Delta T_e^{3} \quad \text{W/m^2....for } 0.7 < P < 4 \text{ MPa}$$

Here, the pressure P is in mega-Pascals.

==

Prob.3.1.1: Water at a pressure of one atm. is boiled in a polished copper pan, 300 mm dia. If the surface temperature of the pan is 110 C, (a) calculate the boiling heat flux and the heat transfer coefficient. What is the evaporation rate of water? (b) compare the nucleate boiling flux with the max. heat flux.

We shall solve this problem with Mathcad.

Since Mathcad does not have built-in functions for properties of Water, we will have to write them.

Remember that we wrote a few Functions in Mathcad for properties of sat. water earlier (See prob. 2A2.2.4, for example). However, there we wrote Functions only for sat.water, liquid; and, the Functions were written using the curve-fit equations.

Now, for a change, we will use interpolation from Data Tables for Sat. water (Ref: Incropera, Ref. 3) and write Functions for both sat. liquid and sat. vapour.

Interpolation in Mathcad is very simple:

The format is:

Y = linterp (Vx,Vy, X), where

Vx is the vector of x-values
Vy is the vector of y-values
X is the value of X at which the y-value is desired
Y is the value of interpolated y value

First, properties given in data Table from Incropera (say, from an EXCEL file) are copied to Mathcad as two Matrices M1 and M2 as shown:

Units for various quantities in the following Table are:

Units: T(K), v_f *10^3 (m^3/kg), v_g (m^3/kg), h_fg (kJ/kg), cp_f(kJ/kg.K), cp_g (kJ/kg.K), mu_f *10^6 (N.s/m^2), mu_g*10^6 (N.s/m^2), k_f*10^3 (W/m.K), k_g*10^3, (W/m.K), Pr_f, sigma_f*10^3 (N/m), beta_f*10^6 (1/K):

M1 :=

T (K)	v_f	v_g	h_fg	cp_f	cp_g
273.15	1	206.3	2502	4.217	1.854
275	1	181.7	2497	4.211	1.855
280	1	130.4	2485	4.198	1.858
285	1	99.4	2473	4.189	1.861
290	1.001	69.7	2461	4.184	1.864
295	1.002	51.94	2449	4.181	1.868
300	1.003	39.13	2438	4.179	1.872
305	1.005	29.74	2426	4.178	1.877
310	1.007	22.93	2414	4.178	1.882
315	1.009	17.82	2402	4.179	1.888
320	1.011	13.98	2390	4.18	1.895
325	1.013	11.06	2378	4.182	1.903
330	1.016	8.82	2366	4.184	1.911
335	1.018	7.09	2354	4.186	1.92
340	1.021	5.74	2342	4.188	1.93
345	1.024	4.683	2329	4.191	1.941
350	1.027	3.846	2317	4.195	1.934
355	1.03	3.18	2304	4.199	1.968
360	1.034	2.645	2291	4.203	1.983
365	1.038	2.212	2278	4.209	1.999
370	1.041	1.861	2265	4.214	2.017
373.15	1.044	1.679	2257	4.217	2.029
375	1.04	1.574	2252	4.22	2.036
380	1.049	1.337	2239	4.226	2.057
400	1.067	0.731	2183	4.256	2.158
420	1.088	0.425	2123	4.302	2.291
440	1.11	0.261	2059	4.36	2.46
460	1.137	0.167	1989	4.44	2.68
480	1.167	0.111	1912	4.53	2.94
500	1.203	0.0766	1825	4.66	3.27
520	1.244	0.0525	1730	4.84	3.7
540	1.294	0.0375	1622	5.08	4.27
560	1.355	0.0269	1499	5.43	5.09
580	1.433	0.0193	1353	6	6.4
600	1.541	0.0137	1176	7	8.75
620	1.705	0.0094	941	9.35	15.4
640	2.075	0.0057	560	26	42
645	2.351	0.0045	361	90	$1.00\cdot10^{10}$
647.3	3.17	0.0032	0	$1.00\cdot10^{10}$	$1.00\cdot10^{10}$

M2 :=

mu_f	mu_g	k_f	k_g	Pr_f	sigma_f
1750	8.02	569	18.2	12.99	75.5
1652	8.09	574	18.3	12.22	75.3
1422	8.29	582	18.6	10.26	74.8
1225	8.49	590	18.9	8.81	74.3
1080	8.69	598	19.3	7.56	73.7
959	8.89	606	19.5	6.62	72.7
855	9.09	613	19.6	5.83	71.7
769	9.29	620	20.1	5.2	70.9
695	9.49	628	20.4	4.62	70
631	9.69	634	20.7	4.16	69.2
577	9.89	640	21	3.77	68.3
528	10.09	645	21.3	3.42	67.5
489	10.29	650	21.7	3.15	66.6
453	10.49	656	22	2.88	65.8
420	10.69	660	22.3	2.66	64.9
389	10.89	668	22.6	2.45	64.1
365	11.09	668	23	2.29	63.2
343	11.29	671	23.3	2.14	62.3
324	11.49	674	23.7	2.02	61.4
306	11.69	677	24.1	1.91	60.5
289	11.89	679	24.5	1.8	59.5
279	12.02	680	24.8	1.76	58.9
274	12.09	681	24.9	1.7	58.6
260	12.29	683	25.4	1.61	57.6
217	13.05	688	27.2	1.34	53.6
185	13.79	688	29.8	1.16	49.4
162	14.5	682	31.7	1.04	45.1
143	15.19	673	34.6	0.95	40.7
129	15.88	660	38.1	0.89	36.2
118	16.59	642	42.3	0.86	31.6
108	17.33	621	47.5	0.84	26.9
101	18.1	594	54	0.86	22.1
94	19.1	563	63.7	0.9	17.3
88	20.4	528	76.7	0.99	12.8
81	22.7	497	92.9	1.14	8.4
72	25.9	444	114	1.52	4.5
59	32	367	155	4.2	0.8
54	37	331	178	12	0.1
45	45	238	238	$1.00\cdot10^{10}$	0

Now, each column is extracted as a vector and then the interpolation function ‘linterp’ is used for linear interpolation.

For example, zeroth column of M1 is Temp in Kelvin. It is extracted as:

$$TempK := M1^{\langle 0 \rangle}$$

This means: 0th column of M1 is assigned as a vector called TempK. (Note: In Mathcad, by default, the column and row numbers start from 0 and *not* 1).

Similarly, v_f, the specific volume of liquid, is in the 1st column of M1. It is extracted as:

$$H2Ov\_f := M1^{\langle 1 \rangle}$$

which means that values of sp. vol. of liquid, which are in the 1st column of M1 are read as a column vector H2Ov_f.

Now, at any given temp T, value of v_f is obtained by linear interpolation, by writing:

$$vf := \mathrm{linterp}(TempK, H2Ov\_f, T) \cdot 10^{-3}$$

Similarly, we have vectors extracted for other properties:

$$TempK := M1^{\langle 0 \rangle} \quad H2Ov\_f := M1^{\langle 1 \rangle} \quad H2Ov\_g := M1^{\langle 2 \rangle} \quad H2Oh\_fg := M1^{\langle 3 \rangle}$$

$$H2Ocp\_f := M1^{\langle 4 \rangle} \quad H2Ocp\_g := M1^{\langle 5 \rangle} \quad H2Omu\_f := M2^{\langle 0 \rangle} \quad H2Omu\_g := M2^{\langle 1 \rangle}$$

$$H2Ok\_f := M2^{\langle 2 \rangle} \quad H2Ok\_g := M2^{\langle 3 \rangle} \quad H2OPr\_f := M2^{\langle 4 \rangle} \quad H2Osigma\_f := M2^{\langle 5 \rangle}$$

For the property, β i.e. coeff. of vol. expansivity, values are available in the Table from T = 273.15 K up to T = 420 K. So, we separately extract them as two vectors:

TempKelvin := (Temp (K)) H2Obeta_f := (beta_f * 10^6 (1/K))

Temp (K)	beta_f * 10^6 (1/K)
273.15	−68.05
275	−32.74
280	46.04
285	114.1
290	174
295	227.5
300	276.1
305	320.6
310	361.9
315	400.4
320	436.7
325	471.2
330	504
335	535.5
340	566
345	595.4
350	624.2
355	652.3
360	697.9
365	707.1
370	728.7
373.15	750.1
375	761
380	788
400	896
420	1010

And, Mathcad Functions are written for different properties by interpolation, using these vectors, as explained earlier:

Mathcad Functions for various properties are::

T (K) , beta_f (1/K) .:

```
beta_f_H2O(TempKelvin, H2Obeta_f, T) := | return "T must be between 273.15 K and 420 K !!" if T < 273.15
                                        | return "T must be between 273.15 K and 420 K !!" if T > 420
                                        | beta_f ← linterp(TempKelvin, H2Obeta_f, T)·10^-6 otherwise
```

Ex: beta_f_H2O(TempKelvin, H2Obeta_f, 385) = 8.15×10^{-4}

T (K) , v_f (m^3/kg) .:

```
vf_H2O(TempK, H2Ov_f, T) := | return "T must be between 273.15 K and 647.3 K !!" if T < 273.15
                            | return "T must be between 273.15 K and 647.3 K !!" if T > 647.3
                            | vf ← linterp(TempK, H2Ov_f, T)·10^-3 otherwise
```

Ex: vf_H2O(TempK, H2Ov_f, 642) = 2.185×10^{-3}

T (K) , v_g (m^3/kg) .:

$$vg\_H2O(TempK, H2Ov\_g, T) := \left| \begin{array}{l} \text{return "T must be between 273.15 K and 647.3 K !!"} \;\; \text{if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} \;\; \text{if } T > 647.3 \\ vg \leftarrow linterp(TempK, H2Ov\_g, T) \;\; \text{otherwise} \end{array} \right.$$

Ex: $vg\_H2O(TempK, H2Ov\_g, 290) = 69.7$

T (K) , h_fg (J/kg) .:

$$h\_fg\_H2O(TempK, H2Oh\_fg, T) := \left| \begin{array}{l} \text{return "T must be between 273.15 K and 647.3 K !!"} \;\; \text{if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} \;\; \text{if } T > 647.3 \\ h\_fg \leftarrow linterp(TempK, H2Oh\_fg, T) \cdot 10^3 \;\; \text{otherwise} \end{array} \right.$$

Ex: $h\_fg\_H2O(TempK, H2Ov\_f, 642) = 2.185 \times 10^3$

T (K) , cp_f (J/kg.K) .:

$$cp\_f\_H2O(TempK, H2Ocp\_f, T) := \left| \begin{array}{l} \text{return "T must be between 273.15 K and 647.3 K !!"} \;\; \text{if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} \;\; \text{if } T > 647.3 \\ cp\_f \leftarrow linterp(TempK, H2Ocp\_f, T) \cdot 10^3 \;\; \text{otherwise} \end{array} \right.$$

Ex: $cp\_f\_H2O(TempK, H2Ocp\_f, 642) = 5.16 \times 10^4$

T (K) , cp_g (J/kg.K) .:

$$cp\_g\_H2O(TempK, H2Ocp\_g, T) := \left| \begin{array}{l} \text{return "T must be between 273.15 K and 647.3 K !!"} \;\; \text{if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} \;\; \text{if } T > 647.3 \\ cp\_g \leftarrow linterp(TempK, H2Ocp\_g, T) \cdot 10^3 \;\; \text{otherwise} \end{array} \right.$$

Ex: $cp\_g\_H2O(TempK, H2Ocp\_g, 642) = 4 \times 10^{12}$

T (K) , mu_f (kg/m.s) .:

```
mu_f_H2O(TempK, H2Omu_f, T) := | return "T must be between 273.15 K and 647.3 K !!"  if T < 273.15
                               | return "T must be between 273.15 K and 647.3 K !!"  if T > 647.3
                               | mu_f ← linterp(TempK, H2Omu_f, T)·10^-6  otherwise
```

Ex: $mu\_f\_H2O(TempK, H2Omu\_f, 642) = 5.7 \times 10^{-5}$

T (K) , mu_g (kg/m.s) .:

```
mu_g_H2O(TempK, H2Omu_g, T) := | return "T must be between 273.15 K and 647.3 K !!"  if T < 273.15
                               | return "T must be between 273.15 K and 647.3 K !!"  if T > 647.3
                               | mu_g ← linterp(TempK, H2Omu_g, T)·10^-6  otherwise
```

Ex: $mu\_g\_H2O(TempK, H2Omu\_g, 642) = 3.4 \times 10^{-5}$

T (K) , k_f (W/m.K) .:

```
k_f_H2O(TempK,H2Ok_f,T) := | return "T must be between 273.15 K and 647.3 K !!"  if T < 273.15
                           | return "T must be between 273.15 K and 647.3 K !!"  if T > 647.3
                           | k_f ← linterp(TempK,H2Ok_f,T)·10^-3   otherwise
```

Ex: $k\_f\_H2O(TempK, H2Ok\_f, 642) = 0.353$

T (K) , k_g (W/m.K) .:

```
k_g_H2O(TempK,H2Ok_g,T) := | return "T must be between 273.15 K and 647.3 K !!"  if T < 273.15
                           | return "T must be between 273.15 K and 647.3 K !!"  if T > 647.3
                           | k_g ← linterp(TempK,H2Ok_g,T)·10^-3   otherwise
```

Ex: $k\_g\_H2O(TempK, H2Ok\_g, 642) = 0.164$

T (K) , Pr_f .:

```
Pr_f_H2O(TempK,H2OPr_f,T) := | return "T must be between 273.15 K and 647.3 K !!"  if T < 273.15
                             | return "T must be between 273.15 K and 647.3 K !!"  if T > 647.3
                             | Pr_f ← linterp(TempK,H2OPr_f,T)   otherwise
```

Ex: $Pr\_f\_H2O(TempK, H2OPr\_f, 642) = 7.32$

T (K) , sigma_f (N/m) .:

```
sigma_f_H2O(TempK,H2Osigma_f,T) := | return "T must be between 273.15 K and 647.3 K !!"  if T < 273.15
                                   | return "T must be between 273.15 K and 647.3 K !!"  if T > 647.3
                                   | sigma_f ← linterp(TempK,H2Osigma_f,T)·10^-3   otherwise
```

Ex: $sigma\_f\_H2O(TempK, H2Osigma\_f, 642) = 5.2 \times 10^{-4}$

We also need properties of Steam (i.e. water vapour) at 1 atm and different temperatures, while solving problems on Film boiling heat transfer.

So, let us write Mathcad Functions for properties of Steam at 1 atm as a function of temperature:

First, get the properties of Steam at 1 atm from an EXCEL Table (Ref: Incropera, Ref. 3):

Properties of Water vap, i.e. Steam at 1 atm. (Ref: Incropera, p. 921):

Units: T(K) , rho (kg/m^3), cp (kJ/kg.K), mu *10^7 (Ns/m^2), nu*10^6 (m^2/s), k*10^3 (W/m.K), alpha*10^6 (m^2/s), Pr:

M5 :=

T	rho	cp	mu	nu	k	alpha	Pr
380	0.5863	2.06	127.1	21.68	24.6	20.4	1.06
400	0.5542	2.014	134.4	24.25	26.1	23.4	1.04
450	0.4902	1.98	152.5	31.11	29.9	30.8	1.01
500	0.4405	1.985	170.4	38.68	33.9	38.8	0.998
550	0.4005	1.997	188.4	47.04	37.9	47.4	0.993
600	0.3652	2.026	206.7	56.6	42.2	57	0.993
650	0.338	2.056	224.7	66.48	46.4	66.8	0.996
700	0.314	2.085	242.6	77.26	50.5	77.1	1
750	0.2931	2.119	260.4	88.84	54.9	88.4	1
800	0.2739	2.152	278.6	101.7	59.2	100	1.01
850	0.2579	2.186	296.9	115.1	63.7	113	1.02

Then, extract the different columns as vectors:

$TKelvin := M5^{\langle 0 \rangle}$ $Steam\_rho := M5^{\langle 1 \rangle}$ $Steam\_cp := M5^{\langle 2 \rangle}$ $Steam\_mu := M5^{\langle 3 \rangle}$

$Steam\_nu := M5^{\langle 4 \rangle}$ $Steam\_k := M5^{\langle 5 \rangle}$ $Steam\_alpha := M5^{\langle 6 \rangle}$ $Steam\_Pr := M5^{\langle 7 \rangle}$

And, now write the Mathcad Functions to get different properties (i.e. rho, cp, mu and k) of Steam as functions of Temp by linear interpolation in Mathcad:

T (K) , rho_steam (kg/m^3).:

```
rho_steam(TKelvin, Steam_rho, T) := | return "T must be between 380 K  and  850 K !!"  if  T < 380
                                    | return "T must be between 380 K and 850 K !!"  if  T > 850
                                    | rho ← linterp(TKelvin, Steam_rho, T)  otherwise
```

Ex: rho_steam(TKelvin, Steam_rho, 498) = 0.442

T (K) , cp_steam (J/kg.K).:

$$\text{cp\_steam}(\text{TKelvin}, \text{Steam\_cp}, T) := \begin{array}{|l} \text{return "T must be between 380 K and 850 K !!" if } T < 380 \\ \text{return "T must be between 380 K and 850 K !!" if } T > 850 \\ cp \leftarrow \text{linterp}(\text{TKelvin}, \text{Steam\_cp}, T)\cdot 10^{3} \text{ otherwise} \end{array}$$

Ex: $\text{cp\_steam}(\text{TKelvin}, \text{Steam\_cp}, 498) = 1.985 \times 10^{3}$

T (K) , mu_steam (N.s/m^2).:

$$\text{mu\_steam}(\text{TKelvin}, \text{Steam\_mu}, T) := \begin{array}{|l} \text{return "T must be between 380 K and 850 K !!" if } T < 380 \\ \text{return "T must be between 380 K and 850 K !!" if } T > 850 \\ mu \leftarrow \text{linterp}(\text{TKelvin}, \text{Steam\_mu}, T)\cdot 10^{-7} \text{ otherwise} \end{array}$$

Ex: $\text{mu\_steam}(\text{TKelvin}, \text{Steam\_mu}, 498) = 1.697 \times 10^{-5}$

T (K) , k_steam (W/m.K).:

$$k\_steam(TKelvin, Steam\_k, T) := \begin{vmatrix} \text{return "T must be between 380 K and 850 K !!"} \quad \text{if } T < 380 \\ \text{return "T must be between 380 K and 850 K !!"} \quad \text{if } T > 850 \\ k \leftarrow linterp(TKelvin, Steam\_k, T) \cdot 10^{-3} \quad \text{otherwise} \end{vmatrix}$$

Ex: $k\_steam(TKelvin, Steam\_k, 498) = 0.0337$

Now, while solving problems on Boiling, we need to solve for Nucleate boiling flux, max. (or, Critical) heat flux for horizontal or cylindrical surfaces, min. heat flux, film boiling heat transfer coefficients for horizontal or cylindrical surfaces etc.

Since these equations are rather complicated, we shall write Mathcad Functions for them using the property Functions written above, so that it will be very convenient to solve problems, as illustrated below.

Now, let us solve the above problem.

It is stated again:

Prob.3.1.1: Water at a pressure of one atm. is boiled in a polished copper pan, 300 mm dia. If the surface temperature of the pan is 110 C, (a) calculate the boiling heat flux and the heat transfer coefficient. What is the evaporation rate of water? (b) compare the nucleate boiling flux with the max. heat flux.

Mathcad Solution:

Since ΔTe < 30 C, it is Nucleate boiling regime.

Let us write a Function for Nucleate boiling heat flux: (Remember that it is valid for all geometries)

Mathcad Function to find q_nucleate for Water boiling at 1 atm:

Input: Ts (C), Tsat (C), Csf --from Table for Surface-fluid combination

Output: q_nucleate (W/m^2)

$$\text{NucleateBoiling\_Water\_q\_nucleate}(T_s, T_{sat}, C_{sf}) :=$$

return "Use Film boiling correlations since (Ts - Tsat) > 30 C! " if $(T_s - T_{sat}) > 30$

$$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_{sat} + 273.15)}$$

$$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$$

$$cp_L \leftarrow cp\_f\_H2O(TempK, H2Ocp\_f, T_{sat} + 273.15)$$

$$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_{sat} + 273.15)$$

$$Pr_L \leftarrow Pr\_f\_H2O(TempK, H2OPr\_f, T_{sat} + 273.15)$$

$$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$$

$$sigma \leftarrow sigma\_f\_H2O(TempK, H2Osigma\_f, T_{sat} + 273.15)$$

$$n \leftarrow 1$$

$$g \leftarrow 9.81$$

$$A \leftarrow mu_L \cdot h_{fg}$$

$$B \leftarrow \left[\frac{g \cdot (rho_L - rho_V)}{sigma}\right]^{\frac{1}{2}}$$

$$C \leftarrow \left[\frac{cp_L \cdot (T_s - T_{sat})}{C_{sf} \cdot h_{fg} \cdot Pr_L^{\ n}}\right]^3$$

$$q_{nucleate} \leftarrow A \cdot B \cdot C$$

And, for max. heat flux for a Flat surface we write the Mathcad Function as:

Mathcad Function to find q_max (or, crit. heat flux) for Water, for a flat surface:

Input: Tsat (C)
Output: q_max (W/m^2)

$$\text{NucleateBoiling\_Water\_FlatSurface\_q\_max}(T_{sat}) :=$$

$$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_{sat} + 273.15)}$$

$$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$$

$$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_{sat} + 273.15)$$

$$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$$

$$sigma \leftarrow sigma\_f\_H2O(TempK, H2Osigma\_f, T_{sat} + 273.15)$$

$$g \leftarrow 9.81$$

$$A \leftarrow 0.149 \cdot h_{fg} \cdot rho_V$$

$$B \leftarrow \left[\frac{g \cdot sigma \cdot (rho_L - rho_V)}{rho_V^{\ 2}}\right]^{\frac{1}{4}}$$

$$q_{max} \leftarrow A \cdot B$$

And, for Min. heat flux, the Mathcad Function is:

Mathcad Function to find q_min (or, min.. heat flux) for Water, for a horizl. surface:

Input: Tsat (C)

Output: q_min (W/m^2)

$$
\text{NucleateBoiling\_Water\_HorizlPlate\_q\_min}(T_{sat}) := \left|
\begin{array}{l}
rho_L \leftarrow \dfrac{1}{\text{vf\_H2O}(\text{TempK}, \text{H2Ov\_f}, T_{sat} + 273.15)} \\
rho_V \leftarrow \dfrac{1}{\text{vg\_H2O}(\text{TempK}, \text{H2Ov\_g}, T_{sat} + 273.15)} \\
h_{fg} \leftarrow \text{h\_fg\_H2O}(\text{TempK}, \text{H2Oh\_fg}, T_{sat} + 273.15) \\
sigma \leftarrow \text{sigma\_f\_H2O}(\text{TempK}, \text{H2Osigma\_f}, T_{sat} + 273.15) \\
g \leftarrow 9.81 \\
A \leftarrow 0.09 \cdot rho_V \cdot h_{fg} \\
B \leftarrow sigma \cdot g \cdot (rho_L - rho_V) \\
C \leftarrow (rho_L + rho_V)^2 \\
q_{min} \leftarrow A \cdot \left(\dfrac{B}{C}\right)^{\frac{1}{4}} \\
q_{min}
\end{array}
\right.
$$

Now, we shall use these Functions to solve the above problem:

Data:

$T_s := 110$ C..temp. of surface

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$d := 0.3$ m....dia of pan

$C_{sf} := 0.013$ ...for water - polished copper combination

$h_{fg} := h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$ J/kg ... applying the Mathcad Function for h_fg

i.e. $h_{fg} = 2.257 \times 10^6$ J/kg

Since ΔT is 10 deg.C, it is reasonable to assume that correlation for nucleate boiling regime is applicable. Then:

We have the Mathcad Function for q in nucleate boiling:

Applying the same:

$q_{nucleate} := NucleateBoiling\_Water\_q\_nucleate(T_s, T_{sat}, C_{sf})$

i.e. $q_{nucleate} = 1.369 \times 10^5$ **W/m^2......Ans.**

Heat transfer coeff.:

We have: $h := \frac{q_{nucleate}}{(T_s - T_{sat})}$ W/(m².C)

i.e. $h = 1.369 \times 10^4$ **W/(m².C)....Ans.**

Evaporation rate:

Total amount of heat supplied: $Q := q_{nucleate} \cdot \left(\frac{\pi \cdot d^2}{4}\right)$ W

i.e. $Q = 9.678 \times 10^3$ W

Therefore, evap. rate of water: $m := \frac{Q}{h_{fg}}$ kg/s

i.e. $m = 4.288 \times 10^{-3}$ kg/s

i.e. $m = 15.742$ **kg/h....Ans.**

(b) Max. heat flux:

We have, from from the Mathcad Function for Max. heat fkux, q_max:

$q_{max} := \text{NucleateBoiling\_Water\_FlatSurface\_q\_max}(T_{sat})$ W/m2.....

i.e. $q_{max} = 1.259 \times 10^{6}$ **W/m2....Ans.**

Thus, actual heat flux (q_nucleate) is much smaller than the critical (max) heat flux.

(c) Min. heat flux:

We have, from from the Mathcad Function for Min. heat flux, q_min.:

$q_{min} := \text{NucleateBoiling\_Water\_HorizlPlate\_q\_min}(T_{sat})$ W/m2.....

i.e. $q_{min} = 1.895 \times 10^{4}$ **W/m2....Ans.**

Thus, we see that having Mathcad Functions made these calculations very easy.

===

Prob.3.1.2: Water at a pressure of one atm. is boiled in a mechanically polished stainless steel pan, 30 cm dia. If the heater is of 1.8 kW rating, assuming that all the heat supplied is transferred to the pan, determine the temp of inner surface of the pan. What will be evaporation rate of water?

Mathcad Solution:

Note: In Nucleate boiling regime, max. temp difference, ΔT_e is about 30 deg. C.

So, we will assume $\Delta T_e = 20$ C and, for polished S.S. take the value of $C_{sf} = 0.013$ from Table, and find q_s. Then, apply Solve Block of Mathcad to get correct value of T_s such that Q = 1.8 kW:

Data:

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$d := 0.3$ m....dia of pan

$C_{sf} := 0.013$ ...for water - polished SS combination

$h_{fg} := h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$ J/kg ... applying the Mathcad Function for h_fg

i.e. $h_{fg} = 2.257 \times 10^{6}$ J/kg

$Q_{heater} := 1.8 \cdot 10^{3}$ W.... by data

Now, first find the heat flux, qs:

$q_s := \dfrac{Q}{\left(\dfrac{\pi \cdot d^2}{4}\right)}$ i.e. $q_s = 1.369 \times 10^5$ W/m^2

In Nucleate boiling regime, we have:

$q_s = \text{NucleateBoiling\_Water\_q\_nucleate}(T_s, T_{sat}, C_{sf})$ ...using the Function for nucleate boiling flux

Here, qs is known, and Ts is the unknown.
So, apply 'Solve Block' construct of Mathcad to find Ts:

Start with the assumed value of Ts:

$T_s := 120$ C..temp. of surface... assumed, will be found out later.

Given

$q_s = \text{NucleateBoiling\_Water\_q\_nucleate}(T_s, T_{sat}, C_{sf})$

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

$T_s = 110$ **C .... temp of inner surface of pan .... Ans.**

Evaporation rate:

Total amount of heat supplied: $Q := 1800$ W

Therefore, evap. rate of water: $m := \dfrac{Q}{h_{fg}}$ kg/s

i.e. $m = 7.975 \times 10^{-4}$ kg/s

i.e. $m = 2.871$ **kg/h....Ans.**

==

Prob.3.1.3: A 65 cm long, 2 cm dia brass heater is used to boil water at 120 C. Surface temp of heater is not allowed to exceed 125 C. Determine the rate of steam production in the boiler in kg/h.

Mathcad Solution:

Note: In Nucleate boiling regime, max. temp difference, ΔTe is about 30 deg. C.
Here, we have, ΔTe = 5 C (i.e. < 30 C); **So, it is nucleate boiling regime.**
And, for water-brass combination, take the value of C_{sf} = 0.006 from Table, and find q_s.

Data:

$T_s := 125$ C.... surface temp of heater

$T_{sat} := 120$ C...sat. temp. of water.

$d := 0.02$ m....dia of heater

$C_{sf} := 0.006$ ...for water - brass combination

$h_{fg} := h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$ J/kg ... applying the Mathcad Function for h_fg

i.e. $h_{fg} = 2.202 \times 10^6$ J/kg

In Nucleate boiling regime, we have:

$q_s := NucleateBoiling\_Water\_q\_nucleate(T_s, T_{sat}, C_{sf})$ ...using the Function for nucleate boiling flux

Therefore,

$q_s = 2.951 \times 10^5$ **W/m^2......Ans.**

and, Heat supplied, Q = A * qs:

i.e. $Q := (\pi \cdot 0.02 \cdot 0.65) \cdot q_s$

i.e. $Q = 1.205 \times 10^4$ W

Therefore, evaporation rate:

$$m := \frac{Q}{h_{fg}}$$

---

i.e. $m = 5.474 \times 10^{-3}$ kg/s

i.e. $m \cdot 3600 = 19.705$ **kg/h .... Ans.**

==

Prob.3.1.4: A 20 mm dia, 0.75 m long copper tube is used to boil saturated water at 1 atm. Find the tube surface temp if heat flux is limited to 75 % of critical heat flux.
(b) Also, plot the surface temp. as function of heat flux for $0.25 < (q_s / q_{max}) < 0.90$.

Mathcad Solution:

Note: In Nucleate boiling regime, max. temp difference, ΔT_e is about 30 deg. C.

Here, *we assume* that it is nucleate boiling regime.
And, for water-copper combination, take the value of $C_{sf} = 0.013$ from Table.

Here, we need q_{max} for a horizontal cylinder.

Remember that max. heat flux depend on geometry of surface.

Now, we shall write a Function for max. flux for a horizl. Cylinder:

Mathcad Function to find q_max (or, crit. heat flux) for Water boiling for a horizl cylinder:

Input: Tsat (C), Radius, R(m)

Output: q_max (W/m^2)

NucleateBoiling_Water_HorizlCylinder_q_max(T_{sat}, R) :=

$$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_{sat} + 273.15)}$$
$$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$$
$$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_{sat} + 273.15)$$
$$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$$
$$sigma \leftarrow sigma\_f\_H2O(TempK, H2Osigma\_f, T_{sat} + 273.15)$$
$$g \leftarrow 9.81$$
$$q_{max\_F} \leftarrow 0.131 \cdot h_{fg} \cdot \sqrt{rho_V} \cdot \left[sigma \cdot g \cdot (rho_L - rho_V)\right]^{\frac{1}{4}}$$
$$R\_prime \leftarrow R \cdot \left[\frac{g \cdot (rho_L - rho_V)}{sigma}\right]^{\frac{1}{2}}$$
$$q_{max} \leftarrow q_{max\_F} \cdot 0.894 \ \text{ if } \ R\_prime > 3.47$$
$$q_{max} \leftarrow q_{max\_F} \cdot \left(0.89 + 2.27 \cdot \exp\left(-3.44 \cdot \sqrt{R\_prime}\right)\right) \ \text{ if } \ 0.15 < R\_prime < 3.47$$
$$q_{max}$$

Observe that much calculation effort is required to do this calculation.

However, having a Mathcad Function to do this, makes it simple to solve not only this problem, but all other similar problems.

Data:

$T_s := 105$ C.... surface temp of heater. .... asssumed

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$R := 0.01$ m....radius of copper tube

$C_{sf} := 0.013$ ...for water - copper combination

For critical (or, max.) heat flux, we have, the Mathcad Function already written::

$q_{max} := \text{NucleateBoiling\_Water\_HorizlCylinder\_q\_max}(T_{sat}, R)$ ...using the Function for nucleate boiling flux

Therefore,

$q_{max} = 9.893 \times 10^5$ **W/m^2......Ans.**

For Nucleate boiling, by data, q_s is 0.75 times q_{max}:

$q_s := 0.75 \cdot q_{max}$ i.e. $q_s = 7.42 \times 10^5$ W/m^2....Nucleate boiling flux

Now, use the Mathcad Function for Nucleate boiling heat flux and apply the Solve block to find surface temp, Ts.

Start with an assumed value of Ts:

$T_s := 105$ C.... surface temp of heater. .... asssumed

Given

$q_s = \text{NucleateBoiling\_Water\_q\_nucleate}(T_s, T_{sat}, C_{sf})$

$T_s(q_s) := \text{Find}(T_s)$

$T_s(q_s) = 117.564$ **C..... Surface temp...Ans.**

Note: We have written T_s as a function of q_s so that it will be easier to calculate values of T_s for different values of q_s (and plot the graph), by using the same Solve block.

To plot Ts for various values of (qs/qmax):

Use the solution of Solve Box obtained above, by entering q_s as a vector.

Note the use of *'vectorize operator'* to get values of T_s for various values of q_{max}:

Here, first define Fraction as a vector, from 0.25 to 0.9, as required by the problem.
And, then, immediately, q_s is calculated as a vector:

$$Fraction := (0.25\ \ 0.3\ \ 0.35\ \ 0.4\ \ 0.45\ \ 0.5\ \ 0.55\ \ 0.6\ \ 0.65\ \ 0.7\ \ 0.75\ \ 0.8\ \ 0.85\ \ 0.9)$$ ...Fraction = qs/qmax

$$q_s := q_{max} \cdot Fraction$$ ....values of qs

Now, T_s as a function of q_s is easily calculated using the Solve block set up above. Note the use of vectorize operator (i.e. a horizontal arrow above T_s):

$\overrightarrow{T_s(q_{max} \cdot Fraction)} =$

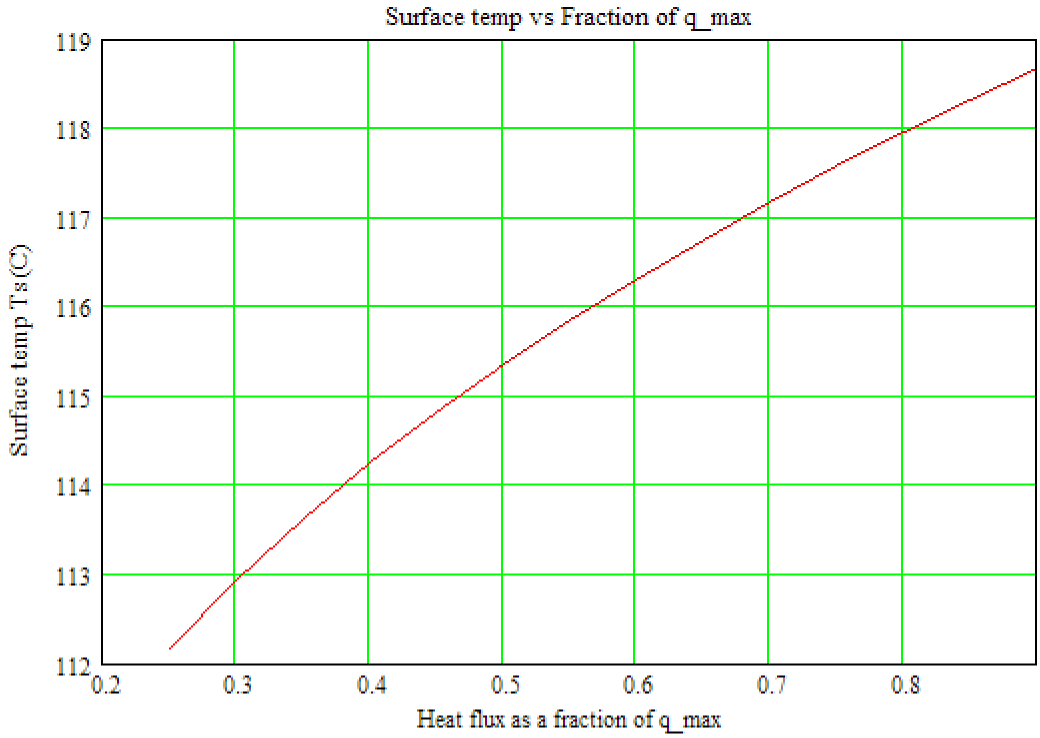
	0	1	2	3	4	5	6	7	8
0	112.179	112.942	113.624	114.244	114.814	115.344	115.839	116.305	116.746

Get the results neatly in columns (useful for plotting):

Results:

	Fraction of q_max $Fraction^T$	Values of qs (W) q_s^T	Values of Ts (C) $\left(\overrightarrow{T_s(q_{max} \cdot Fraction)}\right)^T$
0	0.25	$2.473 \cdot 10^5$	112.179
1	0.3	$2.968 \cdot 10^5$	112.942
2	0.35	$3.462 \cdot 10^5$	113.624
3	0.4	$3.957 \cdot 10^5$	114.244
4	0.45	$4.452 \cdot 10^5$	114.814
5	0.5	$4.946 \cdot 10^5$	115.344
6	0.55	$5.441 \cdot 10^5$	115.839
7	0.6	$5.936 \cdot 10^5$	116.305
8	0.65	$6.43 \cdot 10^5$	116.746
9	0.7	$6.925 \cdot 10^5$	117.165
10	0.75	$7.42 \cdot 10^5$	117.564
11	0.8	$7.914 \cdot 10^5$	117.946
12	0.85	$8.409 \cdot 10^5$	118.313
13	0.9	$8.904 \cdot 10^5$	118.665

And, plot Ts against Fraction, in Mathcad:



==

Prob.3.1.5: A nickel wire, 1 mm dia. and 300 mm long, is submerged in a water bath open to atmosphere.

What is the value of current flowing through the wire that will cause burnout, if the applied voltage is 10 V?

Mathcad Solution:

Data:

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$R := 0.0005$ m....radius of wire

$L := 0.3$ m....length of wire

$V := 10$ V....applied voltage

This is the case of a horizontal cylinder.

So, let us use the Mathcad Function, already written, for max. (or, critical) heat flux for a horizontal cylinder.

$q_{max} := \text{NucleateBoiling\_Water\_HorizlCylinder\_q\_max}(T_{sat}, R)$

i.e. $q_{max} = 1.525 \times 10^{6}$ **W/m^2....This is the value of 'Burn-out' flux**

If V is the voltage, and, I the current through the wire, we have:

$$q_{max} = \frac{V \cdot I}{2 \cdot \pi \cdot R \cdot L}$$

i.e. $I := \dfrac{q_{max} \cdot 2 \cdot \pi \cdot R \cdot L}{V}$ A.....current through the wire

i.e. $I = 143.723$ **A.....current through the wire...Ans.**

==

Prob.3.1.6: A horizontal, metal-clad heating element, 10 mm dia, and of surface emissivity 0.85, is submerged in a water bath. Surface temperature of the heating element is 300 C. If the water is at atmospheric pressure, calculate the power dissipation per unit length of the heater.

Mathcad Solution:

Because of high surface temp, we know that ΔT_e will be > 30 C, and it will be **Film boiling regime**.

In Film boiling regime for a horizontal cylinder, we will write a Mathcad Function to calculate heat transfer coefficient, h_{film}:

Mathcad Function to find h_film for Film boiling for Water boiling at 1 atm, for a horizl. cylinder:

Input: Ts, Tsat (C), dia D (m)

Output: h_film (W/m^2.C)

Note: Take vapour properties at Tf, at 1 atm

$$\text{FilmBoiling\_Water\_HorizlCylinder\_h\_film}(T_s, T_{sat}, D) := \begin{array}{|l} \text{return "Use Nucleate boiling correlations since (Ts - Tsat) < 30 C! " if } (T_s - T_{sat}) < 30 \\ T_f \leftarrow \dfrac{T_s + T_{sat}}{2} \\ rho_L \leftarrow \dfrac{1}{vf\_H2O(TempK, H2Ov\_f, T_{sat} + 273.15)} \\ rho_V \leftarrow rho\_steam(TKelvin, Steam\_rho, T_f + 273.15) \\ h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15) \\ mu_V \leftarrow mu\_steam(TKelvin, Steam\_mu, T_f + 273.15) \\ k_V \leftarrow k\_steam(TKelvin, Steam\_k, T_f + 273.15) \\ cp_V \leftarrow cp\_steam(TKelvin, Steam\_cp, T_f + 273.15) \\ sigma \leftarrow sigma\_f\_H2O(TempK, H2Osigma\_f, T_{sat} + 273.15) \\ h_{fg\_prime} \leftarrow h_{fg} + 0.4 \cdot cp_V \cdot (T_s - T_{sat}) \\ g \leftarrow 9.81 \\ C_0 \leftarrow 0.62 \\ B \leftarrow g \cdot rho_V \cdot (rho_L - rho_V) \cdot h_{fg\_prime} \cdot k_V^3 \\ C \leftarrow mu_V \cdot (T_s - T_{sat}) \cdot D \\ h_{film} \leftarrow C_0 \cdot \left(\dfrac{B}{C}\right)^{\frac{1}{4}} \\ h_{film} \end{array}$$

Now, let us solve the problem:

Data:

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$D := 0.01$ m....dia. of wire

$L := 1$ m....length of wire, assumed

$T_s := 300$ C....surface temp.

$\varepsilon := 0.85$ ...emissivity of surface

$\sigma := 5.67 \cdot 10^{-8}$ W/(m².K⁴)...Stefan-Boltzmann const.

Since the excess temp. is (300 – 100) = 200 C, it is **film boiling region.**

We will use the Mathcad Function already written for Film boiling on a cylinder:

$$h_{film} := \text{FilmBoiling\_Water\_HorizlCylinder\_h\_film}(T_s, T_{sat}, D)$$

i.e. $h_{film} = 198.709$ **W/m^2.C ..... film boiling heat transfer coeff.**

Note: In film boiling, since surface temp is generally high, we have to include the effect of radiation too:

Radiative heat transfer coeff. is given by:

$$h_{rad} := \frac{\sigma \cdot \varepsilon \cdot \left[\left(T_s + 273\right)^4 - \left(T_{sat} + 273\right)^4 \right]}{\left(T_s - T_{sat}\right)} \qquad \text{W/(m}^2\text{.C)....}$$

i.e. $h_{rad} = 21.313$ W/(m²\.C)

Note: Use absolute temperatures in eqn. for for radiative heat transfer

Therefore, the 'total' heat transfer coeff. is given by:

$$h := h_{film} + 0.75 \cdot h_{rad} \qquad \text{..W/m^2.C}$$

i.e. $h = 214.693$ W/(m^2.C)

Therefore, power dissipation per unit length of heater:

$$Q := h \cdot (\pi \cdot D \cdot L) \cdot (T_s - T_{sat}) \qquad \text{W/m}$$

i.e. $Q = 1.349 \times 10^3$ **W/m....Ans.**

==

Prob.3.1.7: A large, horizontal plate is kept immersed in a water bath boiling at 1 atm, 100 C. Surface temperature of the plate is 260 C. Calculate the heat transfer coeff. and the heat flux. Assume the emissivity of the surface as 0.9.

Mathcad Solution:

Because of high surface temp, we know that ΔT_e will be > 30 C, and it will be **Film boiling regime**.

In Film boiling regime for a horizontal plate, we will write a Mathcad Function to calculate heat transfer coefficient, h_{film}:

Mathcad Function to find h_film for Film boiling for Water boiling, for a horizl. surface:

Input: Ts, Tsat (C)

Output: h_film (W/m^2.C)

Note: Take vapour properties at Tf, at 1 atm

$$\text{FilmBoiling\_Water\_HorizlPlate\_h\_film}(T_s, T_{sat}) :=$$

```
return "Use Nucleate boiling correlations since (Ts - Tsat) < 30 C! "  if (Ts - Tsat) < 30
Tf ← (Ts + Tsat)/2
rhoL ← 1 / vf_H2O(TempK, H2Ov_f, Tsat + 273.15)
rhov ← rho_steam(TKelvin, Steam_rho, Tf + 273.15)
hfg ← h_fg_H2O(TempK, H2Oh_fg, Tsat + 273.15)
muv ← mu_steam(TKelvin, Steam_mu, Tf + 273.15)
kv ← k_steam(TKelvin, Steam_k, Tf + 273.15)
cpv ← cp_steam(TKelvin, Steam_cp, Tf + 273.15)
sigma ← sigma_f_H2O(TempK, H2Osigma_f, Tsat + 273.15)
hfg_prime ← hfg + 0.4·cpv·(Ts - Tsat)
g ← 9.81
C0 ← 0.59
B ← g·rhov·(rhoL - rhov)·hfg_prime·kv^3
C ← muv·(Ts - Tsat)·2·π·[sigma / (g·(rhoL - rhov))]^(1/2)
hfilm ← C0·(B/C)^(1/4)
hfilm
```

Now, solve the above problem:

Data:

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$T_s := 260$ C....surface temp.

$\varepsilon := 0.9$ ...emissivity of surface

Since the excess temp. is (260 – 100) = 160 C, it is **film boiling region.**

We will use the Mathcad Function already written for heat transfer coeff in film boiling for a flat surface in water:

$$h_{film} := \text{FilmBoiling\_Water\_HorizlPlate\_h\_film}(T_s, T_{sat})$$

i.e. $h_{film} = 174.934$ **W/m^2.C ..... film boiling heat transfer coeff.**

And, Radiative heat transfer coeff.:

$\sigma := 5.67 \cdot 10^{-8}$ W/(m².K⁴)...Stefan-Boltzmann const.

$$h_{rad} := \frac{\sigma \cdot \varepsilon \cdot \left[\left(T_s + 273\right)^4 - \left(T_{sat} + 273\right)^4 \right]}{\left(T_s - T_{sat}\right)} \quad \text{W/(m}^2\text{.C)...}$$

i.e. $h_{rad} = 19.567$ W/(m².C)

Note: Use absolute temperatures in eqn. for for radiative heat transfer

Therefore, the 'total' heat transfer coeff. is given by:

$$h := h_{film} + 0.75 \cdot h_{rad} \quad \text{....(11.17)}$$

i.e. $h = 189.609$ **W/(m².C).....Ans.**

And, the heat flux:

$$q := h \cdot (T_s - T_{sat}) \quad W/m^2$$

i.e. $q = 3.034 \times 10^4$ **W/m²...Ans.**

===

EES Procedures / Functions for Boiling heat transfer calculations:

EES has a great advantage that it has built-in functions for properties of a large number of fluids including Water/steam.

So, it is very easy to write Functions or Procedures for various boiling heat transfer calculations.

First, let us write Functions for Nucleate boiling heat flux, critical (or Max.) heat flux for a horizontal surface, for a horizontal cylinder, and for a Sphere:

```
$UnitSystem SI Pa C J

"EES Procedures for Boiling calculations:"

"Nucleate Boiling of Water – heat flux: valid for any geometry:"

FUNCTION NucleateBoiling_flux_water(T_sat, T_s, C_sf)

"Nucleate boiling of water – heat flux (W/m^2):"

"Note: C_sf is the surface-fluid combination factor-from Handbook"

g:= 9.81[m/s^2]
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"
rho_v:=Density(Steam_IAPWS,T=T_sat, x=1) "[kg/m^3]"
k_l:=Conductivity(Steam_IAPWS,T=T_sat, x = 0) "[W/m-C]"
mu_l:=Viscosity(Steam_IAPWS,T=T_sat,x=0) "[kg/m-s]"
h_g:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"
Pr_l:=Prandtl(Steam_IAPWS,T=T_sat,x=0)
sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"
cp_l:=SpecHeat(Steam_IAPWS,T=T_sat,x=0) "[J/kg-C]"
```

```
NucleateBoiling_flux_water:= mu_l * h_fg * (g * (rho_l – rho_v)/sigma)^(1/2) * (cp_l * (T_s – T_sat)/(C_sf * h_fg * Pr_l))^3

END

"-----------------------------------------------------------------------------------------------------------"

"Nucleate Boiling of Water – Critical heat flux: depends on geometry:"

"For large, horizontal surface:"

FUNCTION Water_horizl_surface_q_max(T_sat)

"Nucleate boiling of water – critical heat flux (W/m^2):"

g:= 9.81[m/s^2]
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"
rho_v:=Density(Steam_IAPWS,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"
sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"
{q_max:= 0.149 * h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)}

Water_horizl_surface_q_max=0.149 * h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)

END

"-----------------------------------------------------------------------------------------------------------"

"Nucleate Boiling of Water – Critical heat flux: depends on geometry:"

"For horizontal cylinder:"

FUNCTION Water_horizl_cylinder_q_max (T_sat,R)

"Nucleate boiling of water – critical heat flux (W/m^2):"

g:= 9.81[m/s^2]
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"
rho_v:=Density(Steam_IAPWS,T=T_sat, x=1) "[kg/m^3]"
```

```
h_g:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) “[J/kg]”
h_f:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) “[J/kg]”
h_fg:= h_g – h_f “[J/kg]”
sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) “N/m”

R_star:=R*(g*(rho_l-rho_v)/sigma)^0.5
If R_star > 1.2 Then
    C_cr:=0.12
    Water_horizl_cylinder_q_max:=C_cr*h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)
EndIf
If (R_star < 1.2) And (R_star > 0.15) Then
    C_cr:=0.12 * R_star^(-0.25)
    Water_horizl_cylinder_q_max:=C_cr*h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)
EndIf

END
```

« --- »

```
"Nucleate Boiling of Water – Critical heat flux: depends on geometry:"

"For a Sphere:"

 FUNCTION Water_sphere_q_max (T_sat,R)

"Nucleate boiling of water – critical heat flux (W/m^2):"

g:= 9.81[m/s^2]
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"
rho_v:=Density(Steam_IAPWS,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"
sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"

R_star:=R * (g * (rho_l – rho_v) / sigma)^0.5
If R_star > 4.26 Then
    C_cr:=0.11
    Water_sphere_q_max:=C_cr*h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)
EndIf
If (R_star < 4.26) And (R_star > 0.15) Then
    C_cr:=0.227 * R_star^(-0.5)
    Water_sphere_q_max:=C_cr*h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)
EndIf

END

"-------------------------------------------------------------------------------------------------------------------------"
```

Now, let us write Functions in EES for Film boiling heat transfer coeff./heat flux:

```
"Film Boiling of Water – heat flux: depends on geometry:"

"For horizontal cylinder:"

FUNCTION Water_horizl_cylinder_q_film (T_sat, T_s, D)
```

```
"Film boiling of water – heat flux (W/m^2):"

P_sat:=P_sat(Steam_IAPWS,T=T_sat) "[Pa]"
g:= 9.81[m/s^2]
T_f:=(T_s + T_sat) / 2 "[C]….film temp"
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"

"Properties of vap. at film temp T_f, and at a pressure of P_sat corresponding to T_sat:"

rho_v:=Density(Steam_IAPWS,T=T_f, P=P_sat) "[kg/m^3]"
cp_v:=Cp(Steam_IAPWS,T=T_f,P=P_sat) "[J/kg-C]"
mu_v:=Viscosity(Steam_IAPWS,T=T_f,P=P_sat) "[kg/m-s]"
k_v:=Conductivity(Steam_IAPWS,T=T_f,P=P_sat) "[W/m-C]"

"To determine h_fg:"

h_vap:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_liq:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_vap – h_liq "[J/kg]"

sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"
AA:= g * k_v^3 * rho_v * (rho_l – rho_v)
BB:= h_fg + 0.4 * cp_v * (T_s – T_sat)
CC: = mu_v * D * (T_s – T_sat)

Water_horizl_cylinder_q_film:=0.62 * (AA * BB / CC)^(1/4) * (T_s – T_sat)

END

"-----------------------------------------------------------------------------------------------------------------"

"Film Boiling of Water – heat flux: depends on geometry:"

"For horizontal surface:"

PROCEDURE Water_horizl_surface_q_film (T_sat, T_s: h_film, q_film)

"Film boiling of water –

Input: T-sat, T_s (deg.C)

Output: h_film (W/m^2-C) and heat flux (W/m^2):"
```

P_sat:=P_sat(Steam_IAPWS,T=T_sat) "[Pa]"
g:= 9.81[m/s^2]
T_f:=(T_s + T_sat) / 2 "[C]….film temp"
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"

"Properties of vap. at film temp T_f, and at a pressure of P_sat corresponding to T_sat:"

rho_v:=Density(Steam_IAPWS,T=T_f, P=P_sat) "[kg/m^3]"
cp_v:=Cp(Steam_IAPWS,T=T_f,P=P_sat) "[J/kg-C]"
mu_v:=Viscosity(Steam_IAPWS,T=T_f,P=P_sat) "[kg/m-s]"
k_v:=Conductivity(Steam_IAPWS,T=T_f,P=P_sat) "[W/m-C]"

"To determine h_fg:"

h_vap:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_liq:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_vap – h_liq "[J/kg]"

sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"

```
C_0:=0.59 "..for horizl surface:"

Lambda:= 2 * pi * (sigma / (g * (rho_l – rho_v)))^(1/2)

AA:= g * rho_v * (rho_l – rho_v)*k_v^3
BB:= h_fg + 0.4 * cp_v * (T_s – T_sat)
CC: = mu_v * Lambda * (T_s – T_sat)

h_film:=C_0 * ( AA * BB / CC)^(1/4) "[W/m^2-C]"

q_film:=h_film * (T_s – T_sat) "[W/m^2]"

END

"-------------------------------------------------------------------------------------------------------------"
```

Now, let us solve some problems in EES using these Functions/Procedures:

Prob.3.1.8: Water at a pressure of one atm. is boiled in a polished copper pan, 150 mm dia. If the surface temperature of the pan is 115 C, (a) calculate the boiling heat flux and the heat transfer coefficient. What is the evaporation rate of water? (b) compare the nucleate boiling flux with the max. (or critical) heat flux.

(c) what pan temp is required to achieve the critical heat flux?

EES Solution:

```
"Data:"

T_s = 115 [C]

T_sat = 100 [C]

D = 0.15 [m]

C_sf = 0.013 "…for water – polished copper combination"

"Let us use the EES Functions/Procedures written above:"

"Nucleate boiling heat flux:"

q_s = NucleateBoiling_flux_water(T_sat, T_s, C_sf)
```

h_nucleate = q_s/(T_s – T_sat) "[W/m^2-C]"

Q = q_s * (pi * D^2 /4) "[W] …. Total heat tr to pan"

h_liq = Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"

h_vap=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"

h_fg = h_vap – h_liq "[J/kg]"

"Evaporation rate:"

m_evap = (Q / h_fg) * 3600 "[kg/s]"

"Max. or critical heat flux:"

"Using the EES Function written above:"

q_max = Water_horizl_surface_q_max(T_sat) "[W/m^2]"

"What is the pan temp when critical heat flux is reached?"

"Put q_s = q_max in the relation for Nucleate boiling flux:"

q_max = NucleateBoiling_flux_water(T_sat, T_max, C_sf) "…determines T_max when q_max is reached"

Results:

Main | NucleateBoiling_flux_water | Water_horizl_surface_q_max

Unit Settings: SI C Pa J mass deg

C_{sf} = 0.013	D = 0.15 [m]	h_{fg} = 2.256E+06 [J/kg]
h_{liq} = 419169 [J/kg]	$h_{nucleate}$ = 31693 [W/m2-C]	h_{vap} = 2.676E+06 [J/kg]
m_{evap} = 13.4 [kg/h]	Q = 8401 [W]	q_{max} = 1.261E+06 [W/m2]
q_s = 4.75391E+05 [W/m2]	T_{max} = 120.8 [C]	T_s = 115 [C]
T_{sat} = 100 [C]		

Main | NucleateBoiling_flux_water | Water_horizl_surface_q_max

Local variables in Function NucleateBoiling_flux_water (19 calls, 0.03 sec)

cp_l =4216 [J/kg-C]

C_{sf} =0.013

g=9.81 [m/s^2]

h_f =419169 [J/kg]

h_{fg} =2.256E+06 [J/kg]

h_g=2.676E+06 [J/kg]

k_l =0.6791 [W/m-C]

μ_l =0.0002817 [kg/m-s]

$NucleateBoiling_{flux,water}$=1.261E+06 [W/m^2]

Pr_F1.749

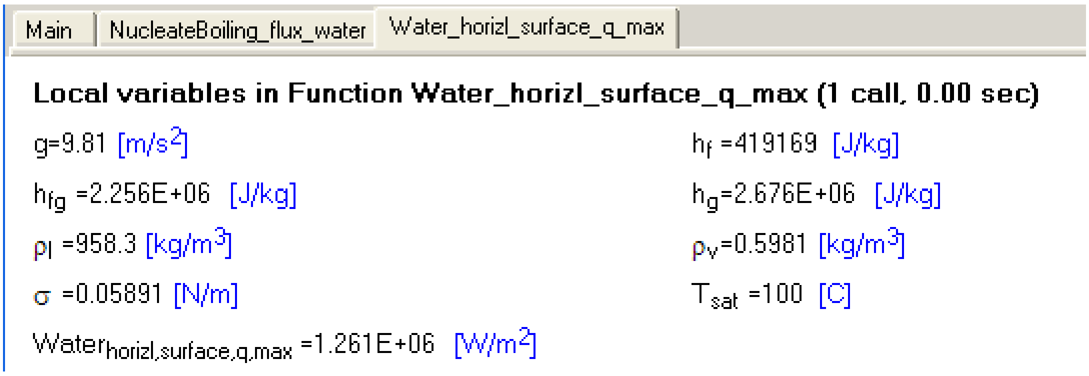
ρ_l =958.3 [kg/m^3]

ρ_v=0.5981 [kg/m^3]

σ =0.05891 [N/m]

T_s=120.8 [C]

T_{sat} =100 [C]



Thus:

q_nucleate = q_s = 4.75391E05 W/m^2 …. Ans.

h_nucleate = 31693 W/m^2-C … Ans.

m_evap = 13.4 kg/h …. Ans.

q_max = 1.261E06 W/m^2 ….Ans.

T_max = 120.8 C … Ans.

==

Prob.3.1.9: Water at atmospheric pressure is to be boiled in a polished copper pan. Dia of the pan is 350 mm and is kept at 115 C. Assume C_sf = 0.013. Assuming Rosenhow relation holds good for Nucleate boiling conditions, calculate:

i) Power of the burner, Q
ii) Rate of evaporation of water, and
iii) Critical heat flux for these conditions.

EES Solution:

"Data:"

T_s = 115 [C]

T_sat = 100 [C]

D = 0.35 [m]

C_sf = 0.013 "…for water – polished copper combination"

"Let us use the EES Functions/Procedures written above:"

"Nucleate boiling heat flux:"

q_s = NucleateBoiling_flux_water(T_sat, T_s, C_sf)

h_nucleate = q_s/(T_s – T_sat) "[W/m^2-C]"

"Power of the burner:"

Q = q_s * (pi * D^2 /4) "[W] …. Power of the burner"

h_liq = Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"

h_vap=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"

h_fg = h_vap – h_liq "[J/kg]"

"Evaporation rate:"

m_evap = (Q / h_fg) "[kg/s]"

"Max. or critical heat flux:"

"Using the EES Function written above:"

q_max = Water_horizl_surface_q_max(T_sat) "[W/m^2]"

Results:

Main | NucleateBoiling_flux_water | Water_horizl_surface_q_max

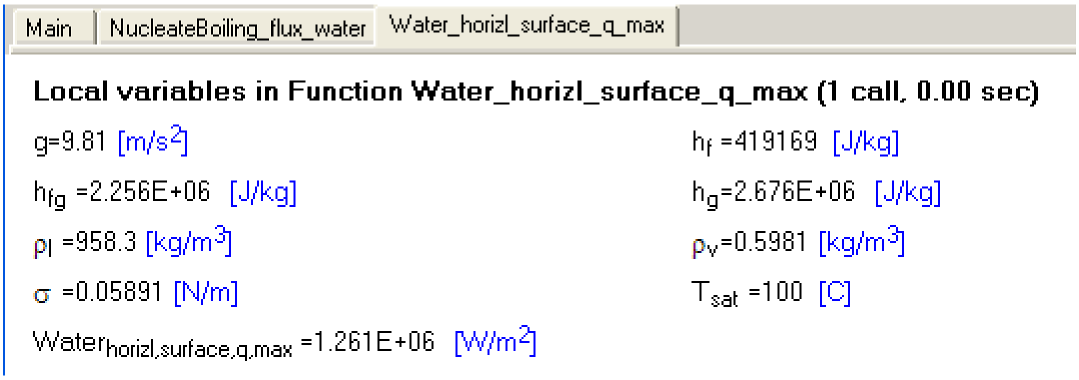
Unit Settings: SI C Pa J mass deg

C_{sf} = 0.013	D = 0.35 [m]	h_{fg} = 2.256E+06 [J/kg]
h_{liq} = 419169 [J/kg]	$h_{nucleate}$ = 31693 [W/m^2-C]	h_{vap} = 2.676E+06 [J/kg]
m_{evap} = 0.02027 [kg/s]	Q = 45738 [W]	q_{max} = 1.261E+06 [W/m^2]
q_s = 4.75391E+05 [W/m^2]	T_s = 115 [C]	T_{sat} = 100 [C]

Main | NucleateBoiling_flux_water | Water_horizl_surface_q_max

Local variables in Function NucleateBoiling_flux_water (1 call, 0.00 sec)

cp_l =4216 [J/kg-C]	C_{sf} =0.013
g=9.81 [m/s^2]	h_f =419169 [J/kg]
h_{fg} =2.256E+06 [J/kg]	h_g=2.676E+06 [J/kg]
k_l =0.6791 [W/m-C]	μ_l =0.0002817 [kg/m-s]
$NucleateBoiling_{flux,water}$=475391 [W/m^2]	Pr_l=1.749
ρ_l =958.3 [kg/m^3]	ρ_v=0.5981 [kg/m^3]
σ =0.05891 [N/m]	T_s=115 [C]
T_{sat} =100 [C]	



Thus:

q_nucleate = q_s = 4.75391E05 W/m^2 …. Ans.

Q = 45738 W … Ans.

m_evap = 0.02027 kg/s …. Ans.

q_max = 1.261E06 W/m^2 ….Ans.

==

"**Prob.3.1.10:** Sat. water at T_sat = 100 C is boiled inside a copper pan having a heating surface area 0f 0.05 m^2, which is maintained at a uniform surface temp of T_s = 110 C. Calculate:

i) the surface heat flux, q
ii) rate of evaporation of water. [VTU – Dec. 2009/Jan. 2010]"

"Data:"

T_s = 110 [C]

T_sat = 100 [C]

A_s = 0.05 [m^2]

A_s = pi * D^2 / 4 "….finds dia D [m]"

C_sf = 0.013 "…for water – polished copper combination"

"Let us use the EES Functions/Procedures written above:"

"Nucleate boiling heat flux:"

q_s = NucleateBoiling_flux_water(T_sat, T_s, C_sf)

h_nucleate = q_s/(T_s – T_sat) "[W/m^2-C]"

"Power of the burner:"

Q = q_s * A_s "[W] …. Power of the burner"

h_liq = Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"

h_vap=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"

h_fg = h_vap – h_liq "[J/kg]"

"Evaporation rate:"

m_evap = (Q / h_fg) "[kg/s]"

Results:

Main | NucleateBoiling_flux_water

Unit Settings: SI C Pa J mass deg

A_s = 0.05 [m^2]	C_{sf} = 0.013	D = 0.2523 [m]
h_{fg} = 2.256E+06 [J/kg]	h_{liq} = 419169 [J/kg]	$h_{nucleate}$ = 14086 [W/m^2-C]
h_{vap} = 2.676E+06 [J/kg]	m_{evap} = 0.003121 [kg/s]	Q = 7043 [W]
q_s = 1.40857E+05 [W/m^2]	T_s = 110 [C]	T_{sat} = 100 [C]

Main | NucleateBoiling_flux_water

Local variables in Function NucleateBoiling_flux_water (1 call, 0.00 sec)

cp_l =4216 [J/kg-C]	C_{sf} =0.013
g=9.81 [m/s^2]	h_f =419169 [J/kg]
h_{fg} =2.256E+06 [J/kg]	h_g=2.676E+06 [J/kg]
k_l =0.6791 [W/m-C]	μ_l =0.0002817 [kg/m-s]
$NucleateBoiling_{flux,water}$=140857 [W/m^2]	Pr=1.749
ρ_l =958.3 [kg/m^3]	ρ_v=0.5981 [kg/m^3]
σ =0.05891 [N/m]	T_s=110 [C]
T_{sat} =100 [C]	

Thus:

q_nucleate = q_s = 1.40857E05 W/m^2 …. Ans.

Q = 7043 W … Ans.

m_evap = 0.003121 kg/s …. Ans.

==

"**Prob.3.1.11:** A nickel wire 1 mm dia and 400 mm long, is submerged in a water bath at 1 atm pressure. Calculate the current carried when burn-out occurs, if the applied voltage is 10 V."

EES Solution:

"Data:"

T_sat = 100 [C]

D = 0.001[m]

R = D/2 "[m]….radius of wire"

L = 0.4 [m]

V = 10 [V]

"Use the EES Function for q_max for a horizl cylinder, written above:"

q_max = Water_horizl_cylinder_q_max (T_sat,R) "[W/m^2]….burn out flux"

"Equate q_max to the surface heat flux at burn out:"

q_max = (V * I) / (pi * D * L) " finds the current, I [amp]"

Results:

Main | Water_horizl_cylinder_q_max

Unit Settings: SI C Pa J mass deg

D = 0.001 [m]	I = 190.9 [A]	L = 0.4 [m]
q_{max} = 1.519E+06 [W/m^2]	R = 0.0005 [m]	T_{sat} = 100 [C]
V = 10 [V]		

Main | Water_horizl_cylinder_q_max

Local variables in Function Water_horizl_cylinder_q_max (1 call, 0.00 sec)

C_{cr} =0.1795	g=9.81 [m/s^2]
h_f =419169 [J/kg]	h_{fg} =2.256E+06 [J/kg]
h_g=2.676E+06 [J/kg]	R =0.0005 [m]
ρ_l =958.3 [kg/m^3]	ρ_v=0.5981 [kg/m^3]
R_{star}=0.1997	σ =0.05891 [N/m]
T_{sat} =100 [C]	$Water_{horizl,cylinder,q,max}$ =1.519E+06 [W/m^2]

Thus:

Burn–out flux = q_max = 1.519 W/m^2 …. Ans.

Current at burn-out = 190.9 A …. Ans.

===

"**Prob.3.1.12:** Water is boiled at a rate of 25 kg/h in a polished copper pan, 280 mm in dia. at atmospheric pressure. Assuming nucleate boiling conditions, determine the temp of bottom surface of the pan."

EES Solution:

"Data:"

T_sat = 100 [C]

D = 0.28[m]

C_sf = 0.013 "..for polished copper – Water combination"

h_fg = 2.256E06 [J/kg] "…heat of vapourization of water at 1 atm."

Q = 25 * 2.256E06 / 3600 "[W]… total heat supplied to boil 25 kg/h of water"

q_s = Q / (pi * D^2 / 4) "[W/m^2]…..heat flux"

"Use the EES Function for q_s , nucleate boiling flux, written above:"

q_s= NucleateBoiling_flux_water(T_sat, T_s, C_sf) "[W/m^2]….nucleate boiling flux"

"In the above, T_s is the only un-known; so, it is calculated."

Results:

Main | NucleateBoiling_flux_water

Unit Settings: SI C Pa J mass deg

C_{sf} = 0.013	D = 0.28 [m]	h_{fg} = 2.256E+06 [J/kg]
Q = 15667 [W]	q_s = 2.54431E+05 [W/m^2]	T_s = 112.2 [C]
T_{sat} = 100 [C]		

Main | NucleateBoiling_flux_water

Local variables in Function NucleateBoiling_flux_water (19 calls, 0.02 sec)

cp_l =4216 [J/kg-C]	C_{sf} =0.013
g=9.81 [m/s^2]	h_f =419169 [J/kg]
h_{fg} =2.256E+06 [J/kg]	h_g=2.676E+06 [J/kg]
k_l =0.6791 [W/m-C]	μ_l =0.0002817 [kg/m-s]
$NucleateBoiling_{flux,water}$=254431 [W/m^2]	Pr_l=1.749
ρ_l =958.3 [kg/m^3]	ρ_v=0.5981 [kg/m^3]
σ =0.05891 [N/m]	T_s=112.2 [C]
T_{sat} =100 [C]	

Thus:

Surface temp. T_s = 112.2 C …. Ans.

==

"**Prob.3.1.13:** A metal clad heating element of 10 mm dia and of emissivity 0.9 is submerged in a water bath horizontally. If the surface temp is 300 C, calculate the power dissipation per unit length of the heater. Water is at atm. pressure."

EES Solution:

"Data:"

T_s = 300 [C]

T_sat = 100 [C]

D = 0.01[m]

epsilon = 0.9

sigma = 5.67E-08 [W/m^2-K^4] "…Stefan-Boltzmann const."

"Use the EES Function for q_film , film boiling flux, written above, for a horizl cylinder:"

q_film= Water_horizl_cylinder_q_film (T_sat, T_s, D) "[W/m^2]….film boiling flux"

"Therefore:"

h_film = q_film / (T_s – T_sat) "[W/m^2-C]…. conv. heat transfer coeff."

h_rad = sigma * epsilon * ((T_s + 273)^4 – (T_sat + 273)^4) / (T_s – T_sat) "[W/m^2-C]…radn. heat tr. coeff."

"Total h:"

h_tot = h_film + 0.75 * h_rad "[W/m^2-C]…total heat tr. coeff."

"Therefore:

Power dissip. per unit length of heater:"

Q = h_tot * (pi * D * 1)* (T_s – T_sat) "[W/m]"

Results:

Main | Water_horizl_cylinder_q_film

Unit Settings: SI C Pa J mass deg

D = 0.01 [m]	ε = 0.9	h_{film} = 205.5 [W/m^2-C]
h_{rad} = 22.57 [W/m^2-C]	h_{tot} = 222.5 [W/m^2-C]	Q = 1398 [W/m]
q_{film} = 41108 [W/m^2]	σ = 5.670E-08 [W/m^2-K^4]	T_s = 300 [C]
T_{sat} = 100 [C]		

Main | Water_horizl_cylinder_q_film

Local variables in Function Water_horizl_cylinder_q_film (1 call, 0.02 sec)

AA =0.1619	BB =2.415E+06
CC =0.00003235	cp_v=1976 [J/kg-C]
D =0.01 [m]	g=9.81 [m/s^2]
h_{fg} =2.256E+06 [J/kg]	h_{liq} =419169 [J/kg]
h_{vap} =2.676E+06 [J/kg]	k_v=0.03329 [W/m-C]
μ_v=0.00001618 [kg/m-s]	P_{sat} =101418 [Pa]
ρ_l =958.3 [kg/m^3]	ρ_v=0.4669 [kg/m^3]
σ =0.05891 [N/m]	T_f=200 [C]
T_s=300 [C]	T_{sat} =100 [C]
$Water_{horizl,cylinder,q,film}$=41108 [W/m^2]	

Thus:

Power dissip. per unit length of heater = Q = 1398 W/m …. Ans.

==

"**Prob.3.1.14:** An electrical conductor, 2 mm dia and of emissivity 0.5 is submerged in a water bath horizontally. If the surface temp is 555 C, calculate the power dissipation per unit length of the heater. Water is at atm. pressure.

(b) Also, plot the Power dissipation per unit length as a function of surface temp (T_s varying from 250 C to 650 C) for conductor diameters of: 1.5 mm, 2 mm and 2.5 mm."

EES Solution:

"Data:"

T_s = 555 [C]

T_sat = 100 [C]

D = 0.002[m]

epsilon = 0.5

sigma = 5.67E-08 [W/m^2-K^4] "…Stefan-Boltzmann const."

"Use the EES Function for q_film , film boiling flux, written above, for a horizl cylinder:"

q_film= Water_horizl_cylinder_q_film (T_sat, T_s, D) "[W/m^2]….film boiling flux"

"Therefore:"

h_film = q_film / (T_s – T_sat) "[W/m^2-C]…. conv. heat transfer coeff."

h_rad = sigma * epsilon * ((T_s + 273)^4 – (T_sat + 273)^4) / (T_s – T_sat) "[W/m^2-C]…radn. heat tr. coeff."

"Total h:"

h_tot = h_film + 0.75 * h_rad "[W/m^2-C]…total heat tr. coeff."

"Therefore:

Power dissip. per unit length of heater:"

Q = h_tot * (pi * D * 1)* (T_s – T_sat) "[W/m]"

Results:

Main | Water_horizl_cylinder_q_film

Unit Settings: SI C Pa J mass deg

D = 0.002 [m]	ε = 0.5	h_{film} = 287.8 [W/m^2-C]
h_{rad} = 28.08 [W/m^2-C]	h_{tot} = 308.9 [W/m^2-C]	Q = 883.1 [W/m]
q_{film} = 130961 [W/m^2]	σ = 5.670E-08 [W/m^2-K^4]	T_s = 555 [C]
T_{sat} = 100 [C]		

Main | Water_horizl_cylinder_q_film

Local variables in Function Water_horizl_cylinder_q_film (1 call, 0.00 sec)

AA =0.3451	BB =2.625E+06
CC =0.0000195	cp_v=2027 [J/kg-C]
D =0.002 [m]	g=9.81 [m/s^2]
h_{fg} =2.256E+06 [J/kg]	h_{liq} =419169 [J/kg]
h_{vap} =2.676E+06 [J/kg]	k_v=0.04644 [W/m-C]
μ_v=0.00002143 [kg/m-s]	P_{sat} =101418 [Pa]
ρ_l =958.3 [kg/m^3]	ρ_v=0.3666 [kg/m^3]
σ =0.05891 [N/m]	T_f=327.5 [C]
T_s=555 [C]	T_{sat} =100 [C]
$Water_{horizl,cylinder,q,film}$=130961 [W/m^2]	

Now, to plot Q vs T_s: Produce 3 parametric Tables, each for D = 0.0015 m, 0.002 m, and 0.0025 m:

For D = 0.0015 m:

Table 1-D = 0.002 m | Table 2-D = 0.0015 m | Table 3-D = 0.0025 m

1..9	T_s [C]	h_{film} [W/m2-C]	h_{rad} [W/m2-C]	Q [W/m]
Run 1	250	345.3	10.48	249.6
Run 2	300	330.3	12.54	320.1
Run 3	350	321.2	14.89	391.5
Run 4	400	315.5	17.56	464.7
Run 5	450	312.1	20.56	540.2
Run 6	500	310.2	23.93	618.5
Run 7	550	309.3	27.68	700
Run 8	600	309.3	31.84	784.9
Run 9	650	309.8	36.41	873.7

For D = 0.002 m:

Table 1-D = 0.002 m | Table 2-D = 0.0015 m | Table 3-D = 0.0025 m

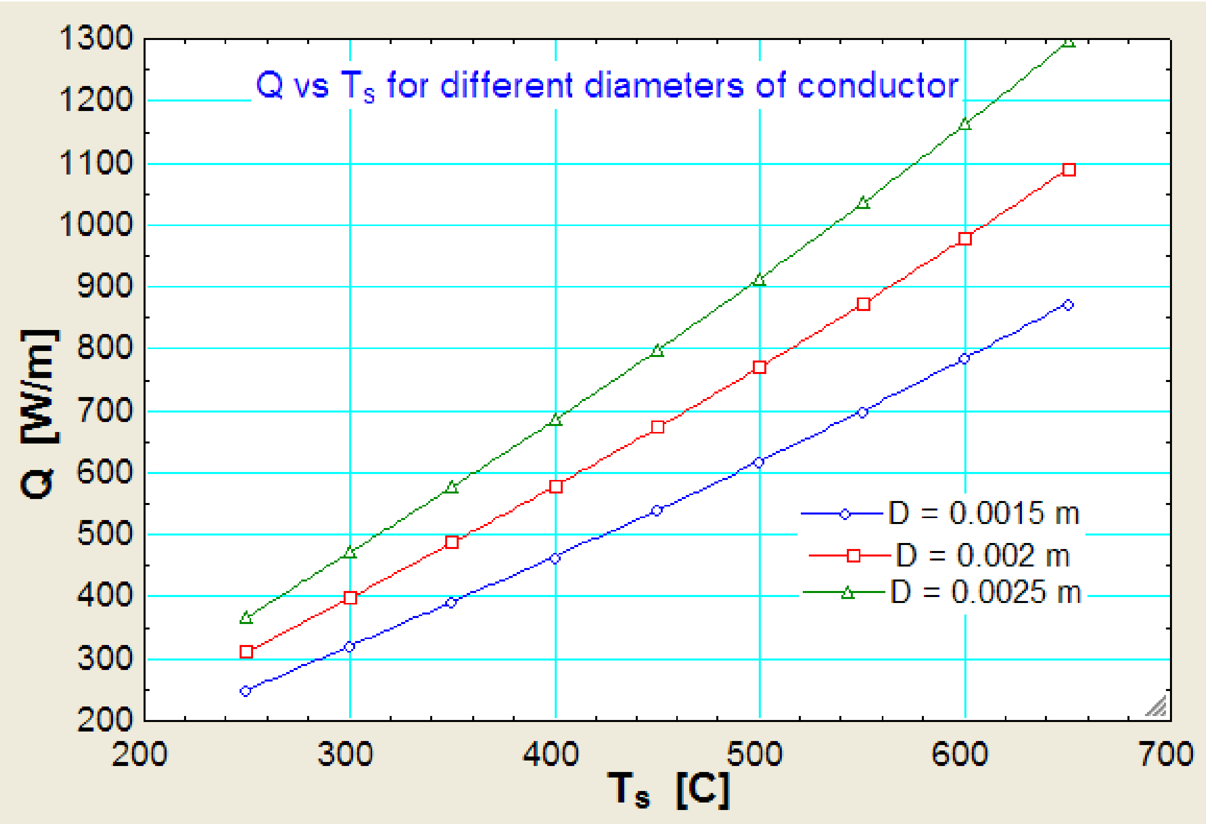
1..9	T_s [C]	h_{film} [W/m2-C]	h_{rad} [W/m2-C]	Q [W/m]
Run 1	250	321.4	10.48	310.3
Run 2	300	307.4	12.54	398.1
Run 3	350	298.9	14.89	487
Run 4	400	293.6	17.56	578.3
Run 5	450	290.4	20.56	672.6
Run 6	500	288.7	23.93	770.6
Run 7	550	287.9	27.68	872.6
Run 8	600	287.8	31.84	979.2
Run 9	650	288.3	36.41	1091

For D = 0.0025 m:

Table 1-D = 0.002 m | Table 2-D = 0.0015 m | Table 3-D = 0.0025 m

1..9	T_s [C]	h_{film} [W/m2-C]	h_{rad} [W/m2-C]	Q [W/m]
Run 1	250	303.9	10.48	367.3
Run 2	300	290.7	12.54	471.4
Run 3	350	282.7	14.89	576.9
Run 4	400	277.7	17.56	685.3
Run 5	450	274.7	20.56	797.5
Run 6	500	273	23.93	914
Run 7	550	272.2	27.68	1036
Run 8	600	272.2	31.84	1163
Run 9	650	272.6	36.41	1296

Now, plot them on the same graph:



==

Prob.3.1.15: A 20 mm dia, 0.75 m long copper tube is used to boil saturated water at 1 atm. Find the tube surface temp if heat flux is limited to 75% of critical heat flux.

(b) Also, plot the surface temp. as function of heat flux for 0.25 < (q_s / q_{max}) < 0.90.

Note: This problem is the same as Prob.3.1.4, which was solved with Mathcad.

But, now, we will solve it with EXCEL:

EXCEL Solution:

Following are the steps in EXCEL solution:

1. Set up the EXCEL worksheet, enter data and name the cells:

Since the heat flux, q_s is less than q_max (or, q_crit) by data, the boiling regime is Nucleate boiling (i.e. ΔT_e < = 30 C).

So, to start with, we will assume a value for T_s and later find the correct value of T_s by applying Goal Seek in EXCEL.

g | f_x 9.81

	A	B	C	D	E
209					
210		**Data:**	**Fluid =**	**Water**	
211		**Surface temp...assumed**	**T_s**	**120**	C
212		**Sat. temp.**	**T_sat**	**100.0**	C
213			**n**	**1.0**	For Water
214		**Radius of cyl.**	**Rad**	**0.0100**	m
215		Water-brass combination	**C_sf**	**0.013**	
216		accn. Due to gravity	**g**	**9.810**	m/s^2

2. We need properties of Sat. water. We use the VBA Functions already written for properties of Sat. water:

sigma_L | f_x =SatH2O_sigmaf_T((T_sat+273.15))

	A	B	C	D	E	F	G
217		**Calculations:**					
218		density_liq	**rho_L**	**957.8544061**	kg/m^3		
219		density_vap	**rho_V**	**0.5956**	kg/m^3		
220		dyn. Visc_liq	**mu_L**	**0.000279**	N.s/m^2		
221		th. conductivity_liq	**k_L**	**0.68**	W/m.C	Using VBA Functions for Props. of Sat. water	
222		th. conductivity_vap	**k_V**	**0.0248**	W/m.C		
223		sp.heat_liq	**cp_L**	**4217**	J/kg.K		
224		sp.heat_vap	**cp_V**	**2029**	J/kg.K		
225		Heat of vaporization	**h_fg**	**2257000**	J/kg		
226		Prandtl No._liq	**Pr_L**	**1.76**			
227		Surface tension	**sigma_L**	**0.0589**	N/m		

3. Now, first, calculate the Max. or critical heat flux, q_max, for a horizontal cylinder, as shown below. The formulas used are also shown, for clarity:

q_max | f_x =IF(R_prime>3.74,CC,DD)

	A	B	C	D	E	F	G
228							
229							
230							
231		**To calculate q_max (Max. or Critical heat flux) for horizl cyl:**					
232			**AA**	**228179.9637**			
233			**BB**	**4.849572083**			
234			**q_max_F**	**1106575.182**			
235			**R_prime**	**3.9929**			
236			**CC**	**989278.2124**			
237			**DD**	**9.87450E+05**			
238			**q_max**	**9.89278E+05**	**W/m^2**		

$$R\_prime = Rad \cdot \left[\frac{g \cdot (rho\_L - rho\_V)}{sigma\_L}\right]^{0.5}$$

$$AA = 0.131 \cdot h_{fg} \cdot \sqrt{rho\_V}$$

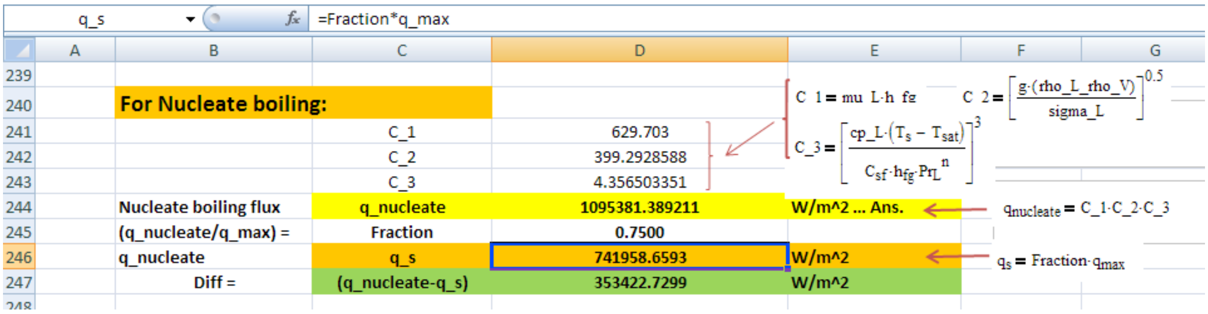
$$BB = [sigma\_L \cdot g \cdot (rho\_L - rho\_V)]^{\frac{1}{4}}$$

$$CC = q\_max\_F \cdot 0.894$$

$$DD = \left(0.89 + 2.27 \cdot \exp\left(-3.44 \cdot \sqrt{R\_prime}\right)\right) \cdot q\_max\_F$$

Remember q_max depends only on T_sat and the geometry.

4. Now, continue the calculations for Nucleate boiling on the horizontal cylinder:



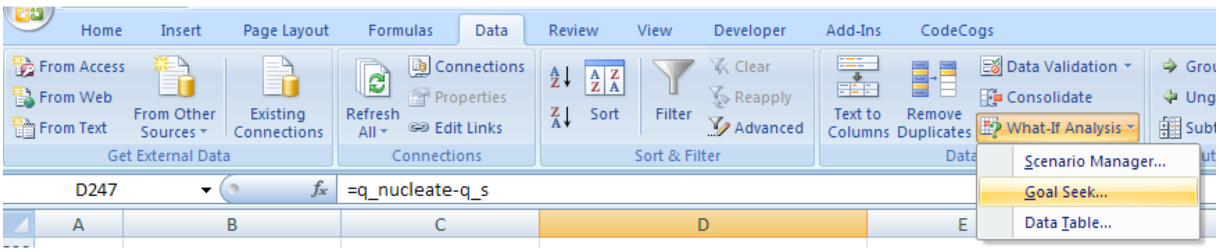
In the above, in cell D244, we have the Nucleate boiling flux, as per the equations provided.

The, in cell D246, we have q_s (i.e. Nucleate boiling flux) as a Fraction of Q_max.

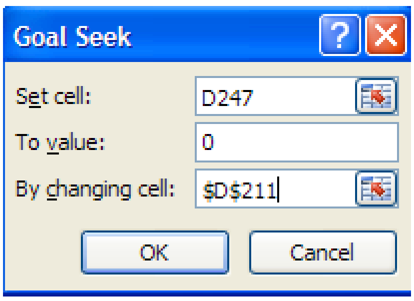
We equate them and find the required value of T_s to meet this condition i.e. cell D247 contains the difference between cells D244 and D246, and in Goal Seek operation we set it equal to zero to get correct value of T_s (i.e. cell D211).

5. Following is the Goal Seek operation:

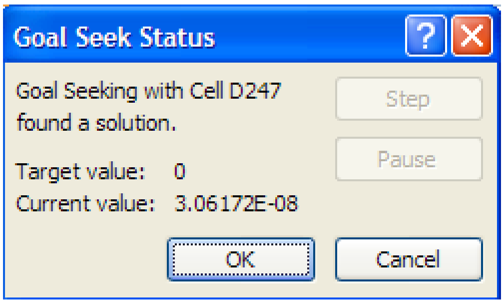
Go to Data – WhatIf Analysis – GoalSeek:



Click on Goal Seek. You get the following screen. Fill it up as shown:



Click OK. We get:



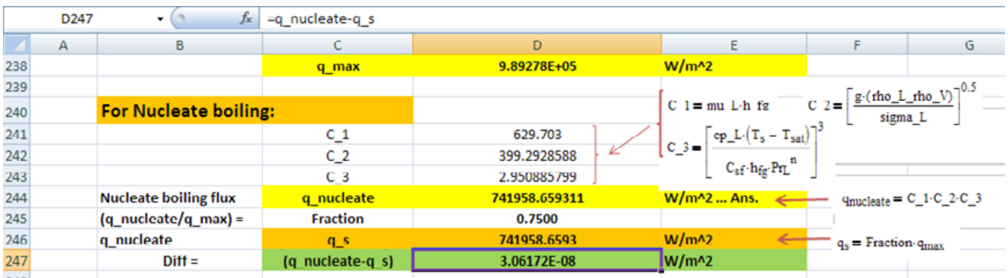
Goal Seek has found a solution. Click OK, and see the value of T_s in cell D211 as 117.564 C.

Also, observe that all related calculations are immediately updated:

T_s — fx 117.564459051131

	A	B	C	D	E
211		Surface temp...assumed	T_s	117.5644591	C
212		Sat. temp.	T_sat	100.0	C
213			n	1.0	For Water
214		Radius of cyl.	Rad	0.0100	m
215		Water-brass combination	C_sf	0.013	
216		accn. Due to gravity	g	9.810	m/s^2
217		Calculations:			
218		density_liq	rho_L	957.8544061	kg/m^3
219		density_vap	rho_V	0.5956	kg/m^3
220		dyn. Visc_liq	mu_L	0.000279	N.s/m^2
221		th. conductivity_liq	k_L	0.68	W/m.C
222		th. conductivity_vap	k_V	0.0248	W/m.C
223		sp.heat_liq	cp_L	4217	J/kg.K
224		sp.heat_vap	cp_V	2029	J/kg.K
225		Heat of vaporization	h_fg	2257000	J/kg
226		Prandtl No._liq	Pr_L	1.76	
227		Surface tension	sigma_L	0.0589	N/m
228					

And:



D247 — fx =q_nucleate-q_s

	A	B	C	D	E	F	G
238			q_max	9.89278E+05	W/m^2		
239							
240		For Nucleate boiling:					
241			C_1	629.703			
242			C_2	399.2928588			
243			C_3	2.950885799			
244		Nucleate boiling flux	q_nucleate	741958.659311	W/m^2 ... Ans.		
245		(q_nucleate/q_max) =	Fraction	0.7500			
246		q_nucleate	q_s	741958.6593	W/m^2		
247		Diff =	(q_nucleate-q_s)	3.06172E-08	W/m^2		

$$C\_1 = mu\_L \cdot h\_fg \qquad C\_2 = \left[\frac{g\cdot(rho\_L\_rho\_V)}{sigma\_L}\right]^{0.5}$$

$$C\_3 = \left[\frac{cp\_L\cdot(T_s - T_{sat})}{C_{sf}\cdot h_{fg}\cdot Pr_L{}^n}\right]^3$$

$$q_{nucleate} = C\_1\cdot C\_2\cdot C\_3$$

$$q_s = Fraction\cdot q_{max}$$

Thus: Tube surface temp when q_s is 75% of q_max is: T_s = 117.564 C … Ans.

To plot the surface temp. as function of heat flux for 0.25 < (qs / qmax) < 0.90:

6. First, set up a Table containing the values of Fraction, as shown:

D258 fx 0.25

	C	D	E	F
253				
254				
255		Plot T_s (deg.C) against Fraction (=q_nucleate/q_max) :		
256				
257		Fraction	q_nucleate(W/m^2)	T_s(deg.C)
258		0.25		
259		0.3		
260		0.35		
261		0.4		
262		0.45		
263		0.5		
264		0.55		
265		0.6		
266		0.65		
267		0.7		
268		0.75		
269		0.8		
270		0.85		
271		0.9		
272		0.95		

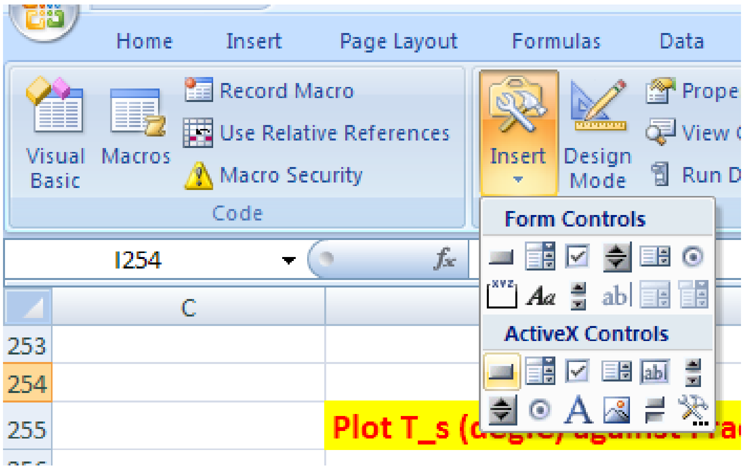
Now, we shall write a small VBA program to read these values of Fraction, one at a time, and copy to cell D245. Then immediately cell D246 (= Fraction * q_max) will change and the the difference, Diff in cell D247 will also change. Now, apply Goal Seek to make cell D247 zero by changing cell D211 (i.e. value of T_s). When this is done, all other related values will get immediately updated. Now, copy the values of q_Nucleate and T_s to their respective places in the Table.

And this program should be executed with a Command Button:

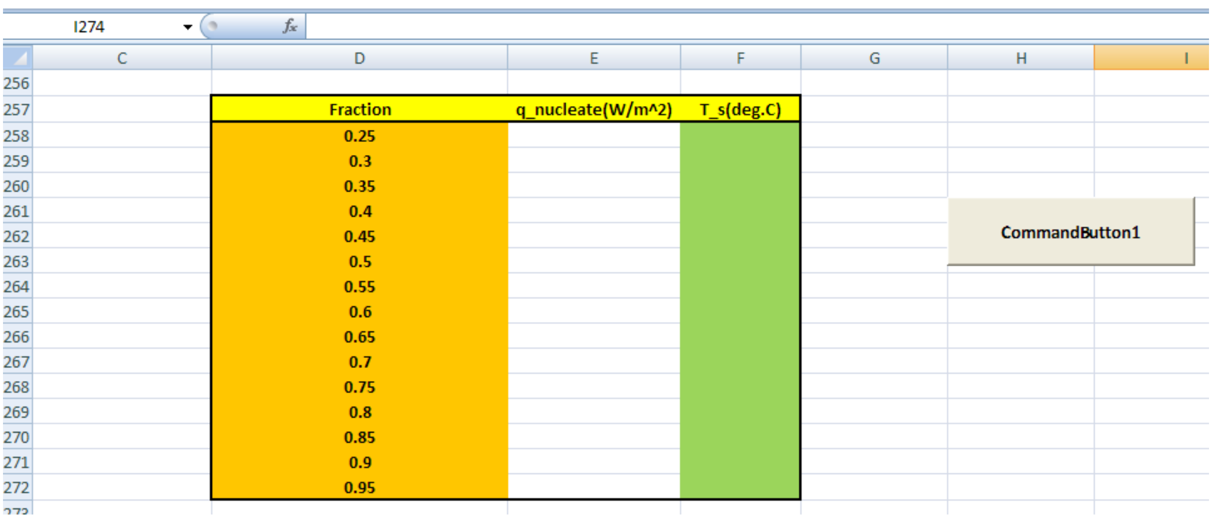
Let us write the VBA program to do the above jobs:

First, to set up the Command Button:

Go to Developer – Insert – ActiveX controls:



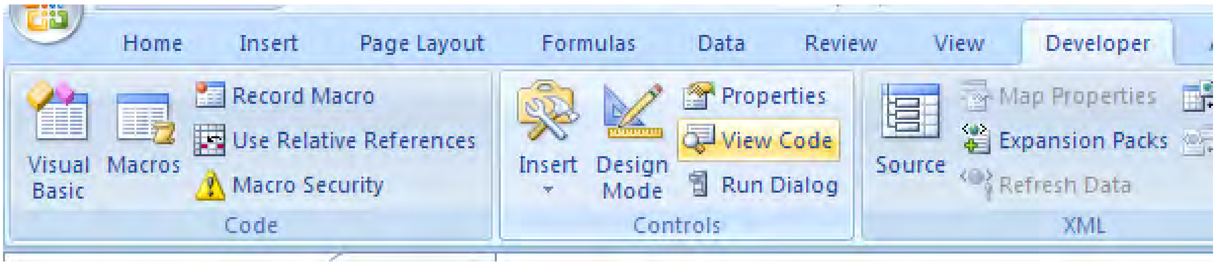
Click on first top left button. And, draw the Command Button in the worksheet to the required size, at the required place:



	Fraction	q_nucleate(W/m^2)	T_s(deg.C)
258	0.25		
259	0.3		
260	0.35		
261	0.4		
262	0.45		
263	0.5		
264	0.55		
265	0.6		
266	0.65		
267	0.7		
268	0.75		
269	0.8		
270	0.85		
271	0.9		
272	0.95		

CommandButton1

Click on Developer-View Code:



And, we get the code already written for the Command button:

```
CommandButton1                                    Click

Private Sub CommandButton1_Click()

End Sub
```

Now, complete the code to do the desired jobs as mentioned under point 4 above:

```
CommandButton1                                    Click

Private Sub CommandButton1_Click()

Dim i As Integer

For i = 0 To 14
 Range("D245") = Cells(258 + i, 4)

 Range("D247").GoalSeek Goal:=0, ChangingCell:=Range("D211")

 Cells(258 + i, 5) = Range("D244")
 Cells(258 + i, 6) = Range("D211")

Next i

End Sub
```

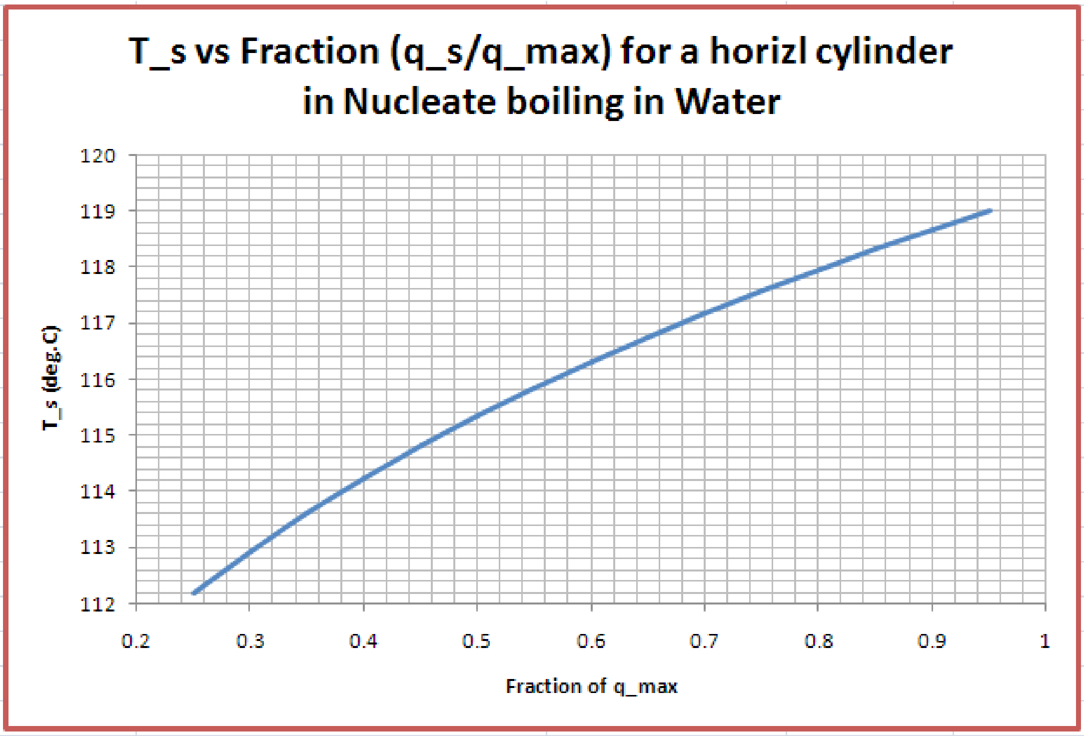
7. Now, click on the Command Button to execute the program. The Table gets filled up immediately:

F272 | f_x 119.004461124321

Fraction	q_nucleate(W/m^2)	T_s(deg.C)
0.25	247319.553	112.179
0.3	296783.464	112.942
0.35	346247.374	113.624
0.4	395711.285	114.244
0.45	445175.196	114.814
0.5	494639.106	115.344
0.55	544103.017	115.839
0.6	593566.927	116.305
0.65	643030.838	116.746
0.7	692494.749	117.165
0.75	741958.659	117.564
0.8	791422.570	117.946
0.85	840886.481	118.313
0.9	890350.391	118.665
0.95	939814.302	119.004

CommandButton1

8. And, plot the graph of T_s vs Fraction in EXCEL:



Compare these results with those obtained with Mathcad:

Fraction of q_max

$Fraction^T =$

	0
0	0.25
1	0.3
2	0.35
3	0.4
4	0.45
5	0.5
6	0.55
7	0.6
8	0.65
9	0.7
10	0.75
11	0.8
12	0.85
13	0.9

Values of Ts (C)

$\left(\overrightarrow{T_s(q_{max} \cdot Fraction)}\right)^T =$

	0
0	112.179
1	112.942
2	113.624
3	114.244
4	114.814
5	115.344
6	115.839
7	116.305
8	116.746
9	117.165
10	117.564
11	117.946
12	118.313
13	118.665

We find that the results match very well.

===

Prob.3.1.16: A 1 mm dia wire, 150 mm long, is submerged horizontally in water at atm pressure. A steady state voltage of 10 V is applied, and the current flowing is 52.5 A. Find the surface temp of the wire.

EXCEL Solution:

It is convenient to make calculations if we have **VBA Functions for Boiling heat transfer calculations.**

So, let us write a few VBA Functions for Nucleate Boiling flux, Max. flux, Film boiling heat transfer coeff. etc.

But, for Film boiling calculations, we need the vapour properties of superheated water vapour (i.e. steam) at different temps and (mostly) at 1 atm.

So, first, we use the properties of steam at 1 atm given in Incropera (Ref: 3) and write VBA Functions for properties of Steam:

	L	M	N	O	P	Q	R	S
143	Properties of Steam (Ref: Incropera, p.921)							
144								
145	T (K)	rho (kg/m^3)	cp (kJ/kg.K)	mu*10^7 (N.s/m^2)	nu*10^6 (m^2/s)	k*10^3 (W/m.K)	alpha*10^6 (m^2/s)	Pr
146	380	0.5863	2.06	127.1	21.68	24.6	20.4	1.06
147	400	0.5542	2.014	134.4	24.25	26.1	23.4	1.04
148	450	0.4902	1.98	152.5	31.11	29.9	30.8	1.01
149	500	0.4405	1.985	170.4	38.68	33.9	38.8	0.998
150	550	0.4005	1.997	188.4	47.04	37.9	47.4	0.993
151	600	0.3652	2.026	206.7	56.6	42.2	57	0.993
152	650	0.338	2.056	224.7	66.48	46.4	66.8	0.996
153	700	0.314	2.085	242.6	77.26	50.5	77.1	1
154	750	0.2931	2.119	260.4	88.84	54.9	88.4	1
155	800	0.2739	2.152	278.6	101.7	59.2	100	1.01
156	850	0.2579	2.186	296.9	115.1	63.7	113	1.02

Now, write VBA Functions for rho_v, cp_v, mu_v and k_v as functions of Temp (K). Linear interpolation is used to get the properties at the required temp.

For rho_v:

```
Function Steam_rho_T(T As Double) As Double
'gives density of steam (water vap.)(kg/m^3)as a function of T (K) at 1 atm.
'Reads rho values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, rho_1 As Double, rho_2 As Double

If T < 380 Or T > 850 Then

 MsgBox ("T must be between 380 K and 850 K !!")
 End
 End If

For i = 0 To 10

   If Cells(146 + i, 12) = T Then
      Steam_rho_T = Cells(146 + i, 13)
   End If
   If Cells(146 + i, 12) < T And Cells(146 + i + 1, 12) > T Then
      T_1 = Cells(146 + i, 12).Value
      T_2 = Cells(146 + i + 1, 12).Value
      rho_1 = Cells(146 + i, 13).Value
      rho_2 = Cells(146 + i + 1, 13).Value
      Steam_rho_T = (rho_1 + (T - T_1) * (rho_2 - rho_1) / (T_2 - T_1))
   End If

Next i

End Function
```

For cp_v:

```
Function Steam_cp_T(T As Double) As Double
'gives sp. heat of steam (water vap.)(J/kg.K)as a function of T (K) at 1 atm.
'Reads cp values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, cp_1 As Double, cp_2 As Double

If T < 380 Or T > 850 Then

 MsgBox ("T must be between 380 K and 850 K !!")
 End
 End If

For i = 0 To 10

   If Cells(146 + i, 12) = T Then
      Steam_cp_T = Cells(146 + i, 14) * 10 ^ -3
   End If
   If Cells(146 + i, 12) < T And Cells(146 + i + 1, 12) > T Then
      T_1 = Cells(146 + i, 12).Value
      T_2 = Cells(146 + i + 1, 12).Value
      cp_1 = Cells(146 + i, 14).Value
      cp_2 = Cells(146 + i + 1, 14).Value
      Steam_cp_T = (cp_1 + (T - T_1) * (cp_2 - cp_1) / (T_2 - T_1)) * 10 ^ -3
   End If

Next i

End Function
```

For mu_v:

```
Function Steam_mu_T(T As Double) As Double
'gives dyn. visc. of steam (water vap.)(N.s/m^2)as a function of T (K) at 1 atm.
'Reads mu values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, mu_1 As Double, mu_2 As Double

If T < 380 Or T > 850 Then

 MsgBox ("T must be between 380 K and 850 K !!")
 End
 End If

For i = 0 To 10

   If Cells(146 + i, 12) = T Then
      Steam_mu_T = Cells(146 + i, 15) * 10 ^ -7
   End If
   If Cells(146 + i, 12) < T And Cells(146 + i + 1, 12) > T Then
      T_1 = Cells(146 + i, 12).Value
      T_2 = Cells(146 + i + 1, 12).Value
      mu_1 = Cells(146 + i, 15).Value
      mu_2 = Cells(146 + i + 1, 15).Value
      Steam_mu_T = (mu_1 + (T - T_1) * (mu_2 - mu_1) / (T_2 - T_1)) * 10 ^ -7
   End If

Next i

End Function
```

For k_v:

```
Function Steam_k_T(T As Double) As Double
'gives thermal cond. of steam (water vap.)(W/m.K)as a function of T (K) at 1 atm.
'Reads k values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, k_1 As Double, k_2 As Double

If T < 380 Or T > 850 Then

 MsgBox ("T must be between 380 K and 850 K !!")
 End
 End If

For i = 0 To 10

   If Cells(146 + i, 12) = T Then
      Steam_k_T = Cells(146 + i, 17) * 10 ^ -3
   End If
   If Cells(146 + i, 12) < T And Cells(146 + i + 1, 12) > T Then
      T_1 = Cells(146 + i, 12).Value
      T_2 = Cells(146 + i + 1, 12).Value
      k_1 = Cells(146 + i, 17).Value
      k_2 = Cells(146 + i + 1, 17).Value
      Steam_k_T = (k_1 + (T - T_1) * (k_2 - k_1) / (T_2 - T_1)) * 10 ^ -3
   End If

Next i

End Function
```

Now. have VBA Functions for Boiling heat transfer calculations:

1. **For Nucleate boiling flux:**

```
Function Boiling_water_q_nucleate(T_s As Double, T_sat As Double, C_sf As Double) As Double
'Returns q_nucleate for Water boiling at 1 atm
'Input: T_s (C), T_sat (C), C_sf from Table
'Output: q_nucleate (W/m^2)
'Valid for any geometry
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double
Dim n As Integer
Dim AA As Double, BB As Double, CC As Double

Dim rho_l As Double, rho_v As Double, k_l As Double, mu_l As Double
Dim Pr_l As Double
Dim cp_l As Double, h_fg As Double, sigma As Double

g = 9.81 'm/s^2....accn due to gravity
n = 1

'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
k_l = SatH2O_kf_T(T_sat + 273.15)
mu_l = SatH2O_muf_T(T_sat + 273.15)
cp_l = SatH2O_cpf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)
Pr_l = SatH2O_Prf_T(T_sat + 273.15)


AA = mu_l * h_fg
BB = (g * (rho_l - rho_v) / sigma) ^ (1 / 2)
CC = (cp_l * (T_s - T_sat) / (C_sf * h_fg * Pr_l ^ n)) ^ 3

Boiling_water_q_nucleate = AA * BB * CC


End Function
```

---

2. **For Max. flux on a horizontal surface:**

```
Function Boiling_water_HorizlSurface_q_max(T_sat As Double) As Double
'Returns q_maxfor Water boiling at 1 atm, on a large, flat surface
'Input: T_s (C), T_sat (C), C_sf from Table
'Output: q_max(W/m^2)
'Valid for large, flat surface
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double

Dim AA As Double, BB As Double

Dim rho_l As Double, rho_v As Double, k_l As Double, mu_l As Double
Dim Pr_l As Double
Dim cp_l As Double, h_fg As Double, sigma As Double

g = 9.81 'm/s^2....accn due to gravity


'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
k_l = SatH2O_kf_T(T_sat + 273.15)
mu_l = SatH2O_muf_T(T_sat + 273.15)
cp_l = SatH2O_cpf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)
Pr_l = SatH2O_Prf_T(T_sat + 273.15)


 AA = 0.149 * h_fg
 BB = (sigma * g * rho_v ^ 2 * (rho_l - rho_v)) ^ (1 / 4)

  Boiling_water_HorizlSurface_q_max = AA * BB


 End Function
```

3. **For Max. flux on a horizontal cylinder:**

```
Function Boiling_water_HorizlCylinder_q_max(T_sat As Double, Rad As Double) As Double
'Returns q_max for Water boiling at 1 atm, on a horizl cylinder
'Input: T_sat (C), Radius (m)
'Output: q_max(W/m^2)
'Valid for horizl cyl
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double, R_prime As Double, q_max_F As Double

Dim AA As Double

Dim rho_l As Double, rho_v As Double, k_l As Double, mu_l As Double
Dim Pr_l As Double
Dim cp_l As Double, h_fg As Double, sigma As Double

g = 9.81 'm/s^2....accn due to gravity


'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
k_l = SatH2O_kf_T(T_sat + 273.15)
mu_l = SatH2O_muf_T(T_sat + 273.15)
cp_l = SatH2O_cpf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)
Pr_l = SatH2O_Prf_T(T_sat + 273.15)


R_prime = Rad * (g * (rho_l - rho_v) / sigma) ^ 0.5

q_max_F = 0.131 * (rho_v) ^ 0.5 * h_fg * (sigma * g * (rho_l - rho_v)) ^ (1 / 4)

AA = 0.89 + 2.27 * Exp(-3.44 * R_prime ^ 0.5)

If R_prime > 3.47 Then

   Boiling_water_HorizlCylinder_q_max = 0.894 * q_max_F

End If

If (R_prime >= 0.15) And (R_prime <= 3.47) Then

   Boiling_water_HorizlCylinder_q_max = q_max_F * AA

End If


End Function
```

4. **For Film boiling on a horizontal surface-heat tr. coeff. h_film:**

```
Function Boiling_water_HorizlSurface_h_film(T_s As Double, T_sat As Double) As Double
'Returns h_film (W/m^2.C)for film boiling with water at 1 atm, on a Horizl surface
'Input: T_s, T_sat (C)
'Valid for Horizl surface
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double

Dim Lambda As Double, C_0 As Double, h_fg_prime As Double

Dim AA As Double, BB As Double

Dim rho_l As Double, rho_v As Double, k_v As Double, mu_v As Double
Dim T_f As Double
Dim cp_v As Double, h_fg As Double, sigma As Double

If (T_s - T_sat) <= 30 Then

  MsgBox ("Use Nucleate Boiling correlations since (T_s - T_sat) <= 30 C !!")

  End

End If

g = 9.81 'm/s^2....accn due to gravity

T_f = (T_s + T_sat) / 2

'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)

'For props of vapour:

rho_v = Steam_rho_T(T_f + 273.15)
cp_v = Steam_cp_T(T_f + 273.15)
k_v = Steam_k_T(T_f + 273.15)
mu_v = Steam_mu_T(T_f + 273.15)

Lambda = 2 * Application.Pi() * (sigma / (g * (rho_l - rho_v))) ^ 0.5

C_0 = 0.59

h_fg_prime = h_fg + 0.4 * cp_v * (T_s - T_sat)

AA = (h_fg_prime * g * rho_v * (rho_l - rho_v) * k_v ^ 3)

BB = mu_v * (T_s - T_sat) * Lambda

 Boiling_water_HorizlSurface_h_film = C_0 * (AA / BB) ^ (1 / 4)

End Function
```

5. **For Film boiling on a horizontal cylinder-heat tr. coeff. h_film:**

```
Function Boiling_water_HorizlCyl_h_film(T_s As Double, T_sat As Double, D As Double) As Double
'Returns h_film (W/m^2.C)for film boiling with water at 1 atm, on a Horizl cyl
'Input: T_s, T_sat (C), Dia D (m)
'Valid for Horizl cyl
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double


Dim C_0 As Double, h_fg_prime As Double

Dim AA As Double, BB As Double

Dim rho_l As Double, rho_v As Double, k_v As Double, mu_v As Double
Dim T_f As Double
Dim cp_v As Double, h_fg As Double, sigma As Double

If (T_s - T_sat) <= 30 Then

  MsgBox ("Use Nucleate Boiling correlations since (T_s - T_sat) <= 30 C !!")

  End

End If

g = 9.81 'm/s^2....accn due to gravity

T_f = (T_s + T_sat) / 2


'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)

'For props of vapour:

rho_v = Steam_rho_T(T_f + 273.15)
cp_v = Steam_cp_T(T_f + 273.15)
k_v = Steam_k_T(T_f + 273.15)
mu_v = Steam_mu_T(T_f + 273.15)


C_0 = 0.62

h_fg_prime = h_fg + 0.4 * cp_v * (T_s - T_sat)

AA = (h_fg_prime * g * rho_v * (rho_l - rho_v) * k_v ^ 3)

BB = mu_v * (T_s - T_sat) * D

 Boiling_water_HorizlCyl_h_film = C_0 * (AA / BB) ^ (1 / 4)

End Function
```

Now, let us solve the problem: Let us state the problem again:

Prob.3.1.16: A 1 mm dia nickel wire, 150 mm long, is submerged horizontally in water at atm pressure. A steady state voltage of 10 V is applied, and the current flowing is 52.5 A. Find the surface temp of the wire.

EXCEL Solution:

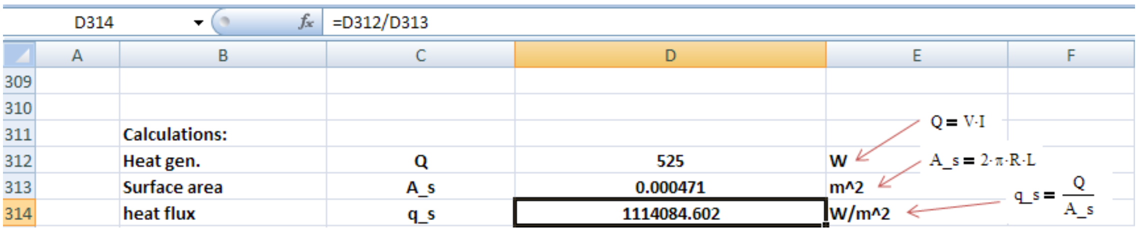
Here, Voltage and current are given. Therefore, Total Power, Q = (V . I) is calculated. Then, (Q/Surface area) of wire gives the surface heat flux. This should be equal to the Nucleate boiling heat flux, assuming that boiling is in the Nucleate boiling regime. Goal Seek is used to find the value of T_s.

1. Set up the Excel worksheet, enter data:

D302 | f_x | 120

	A	B	C	D	E
300					
301		**Data:**	**Fluid =**	**Water**	
302		**Surface temp...assumed**	**T_s**	**120**	C
303		**Sat. temp.**	**T_sat**	**100.0**	C
304		**Radius of cyl.**	**Rad**	**0.0005**	m
305		Water-nickel combination	**C_sf**	**0.006**	From Table
306		Length of wire	**L**	**0.15**	m
307		Voltage	**V**	**10.000**	V
308		Current	**I**	**52.5**	A

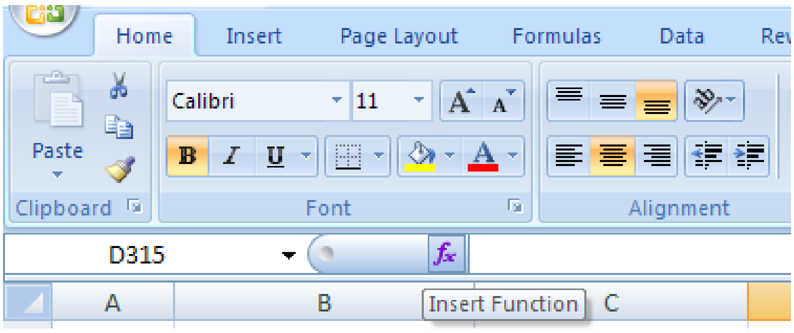
2. Calculate the surface heat flux from the given values of V, I etc.:



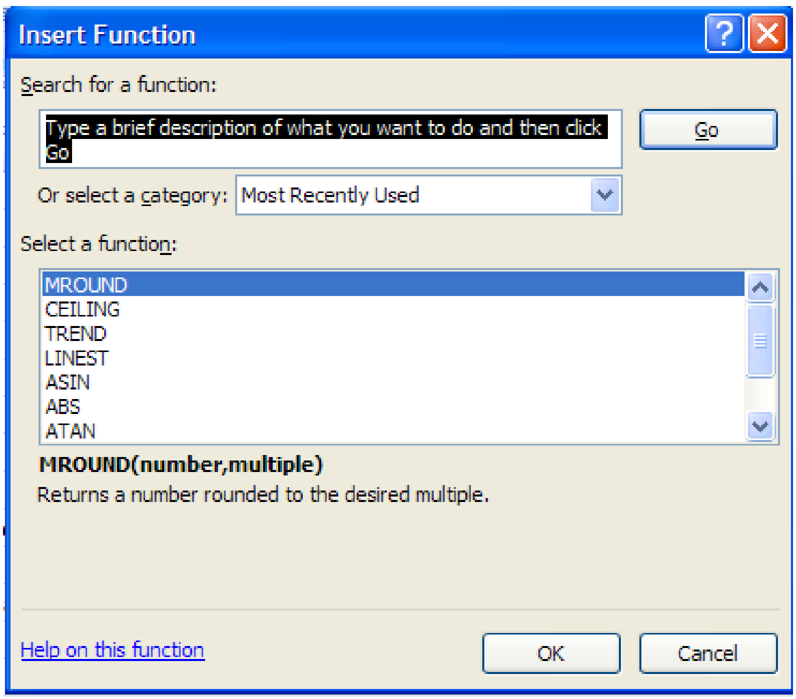
3. Now, **q_nucleate is calculated using the VBA Function for Nucleate boiling flux, written earlier**.

To insert the VBA Function for q_nucleate in cell D315, we do the following:

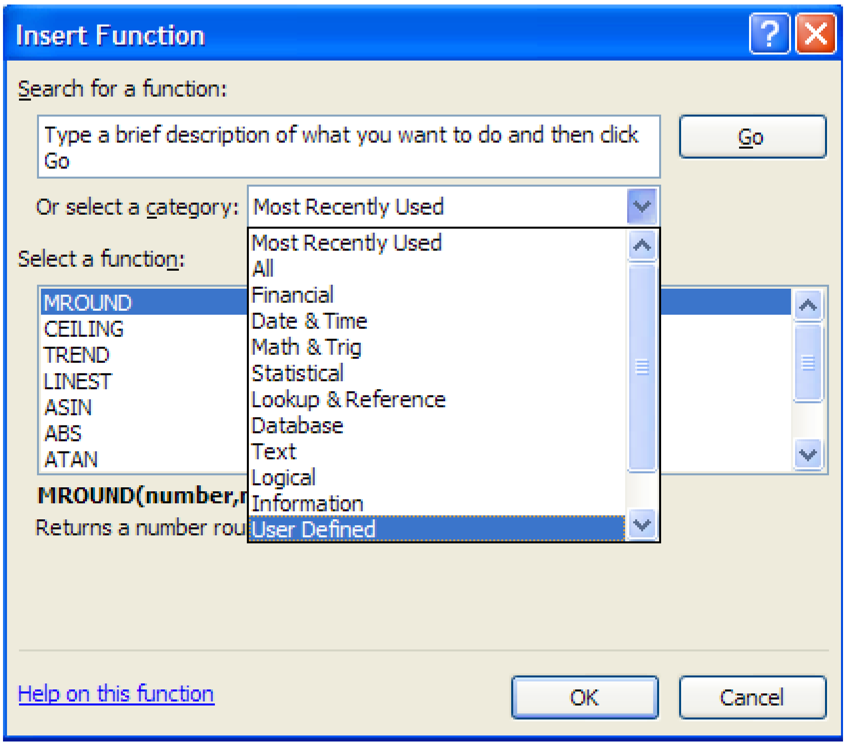
Select cell D315. Then locate the 'Insert Function' symbol as shown below:



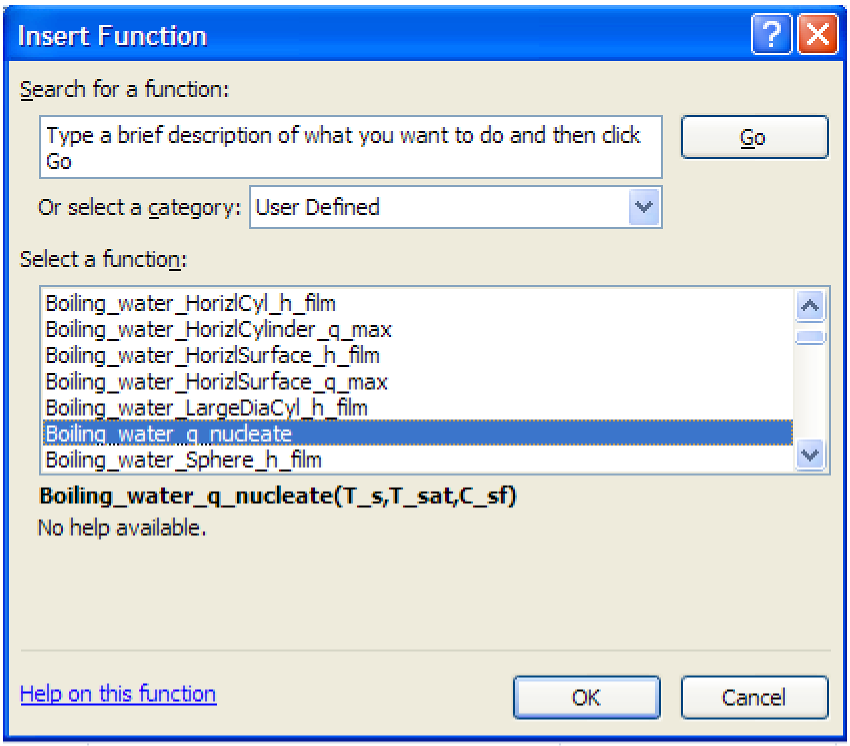
Click on Insert Function symbol. We get:



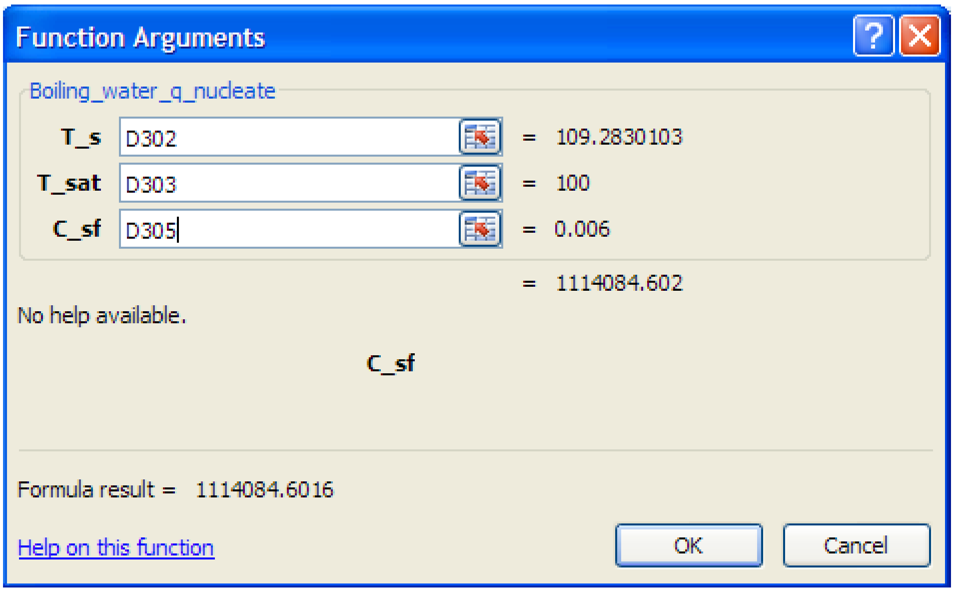
Under Category: select 'User Defined':



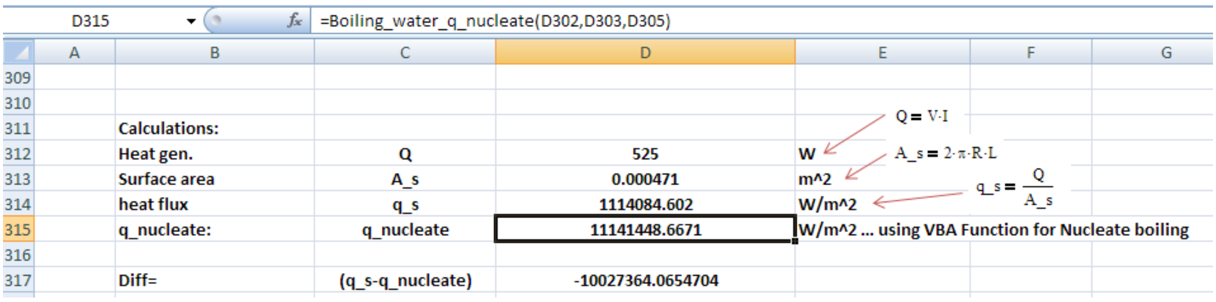
Click on 'User Defined'. Several built-in Functions appear. Choose 'Boiling_Water_q_nucleate':



Click OK. We get the following screen. Fill it up as shown:



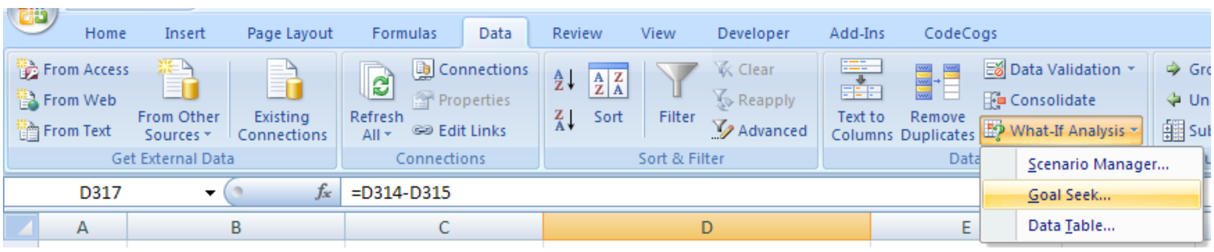
Click OK. The Function is inserted in cell D315:



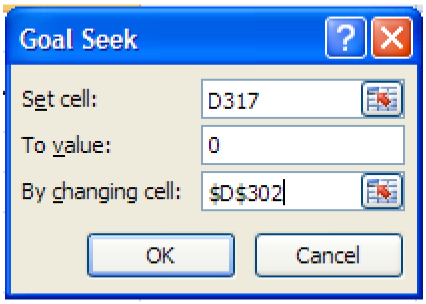
Then, in cell D317, we have the difference = (q_s – q_nucleate), which should be equal to zero. So, use Goal Seek to make cell D317 equal to zero by changing cell D302 (i.e. T_s):

4. Following is the procedure:

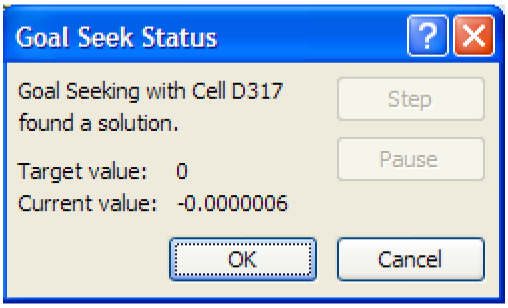
Go to Data – WhatIf Analysis – Goal Seek:



Click on Goal Seek. Fill up the screen that appears as follows:



Click OK. We get:



Goal seek has found a solution. Click OK. We get:

	A	B	C	D	E	F	G
300							
301		Data:	Fluid =	Water			
302		Surface temp...assumed	T_s	109.2830103	C		
303		Sat. temp.	T_sat	100.0	C		
304		Radius of cyl.	Rad	0.0005	m		
305		Water-nickel combination	C_sf	0.006	From Table		
306		Length of wire	L	0.15	m		
307		Voltage	V	10.000	V		
308		Current	I	52.5	A		
309							
310						Q = V·I	
311		Calculations:					
312		Heat gen.	Q	525	W	A_s = 2·π·R·L	
313		Surface area	A_s	0.000471	m^2	q_s = Q/A_s	
314		heat flux	q_s	1114084.602	W/m^2		
315		q_nucleate:	q_nucleate	1114084.6016	W/m^2 ... using VBA Function for Nucleate boiling		
316							
317		Diff=	(q_s-q_nucleate)	-0.0000006			

Thus: T_s = 109.283 C …. Ans.

===

Prob.3.1.17: In a laboratory experiment, a 1 mm dia, 30 cm long nickel wire is submerged horizontally in water at 1 atm, and burn-out occurs when a current of 193 A is passed. What is the voltage at burn-out?

EXCEL Solution:

Here, we first assume the voltage and calculate the surface heat flux. Then we use the VBA Function to get burn-out (or, Max.) flux for a cylinder and use Goal Seek to find the voltage such that the two heat fluxes are equal:

Following are the steps:

1. Set up the EXCEL worksheet, enter data:

	A	B	C	D	E
324		Data:	Fluid =	Water	
325					
326		Sat. temp.	T_sat	100.0	C
327		Radius of cyl.	Rad	0.0005	m
328					
329		Length of wire	L	0.3	m
330		Voltage ... assumed	V	10.000	V
331		Current	I	193	A

2. Calculate the surface heat flux from given data. Also, calculate the burn-out (or, Max.) heat flux from the VBA Function written earlier:

D338 =Boiling_water_HorizlCylinder_q_max(D326,D327)

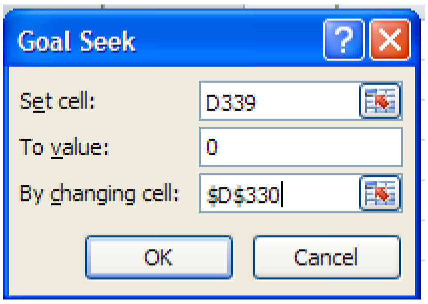
	A	B	C	D	E	F	G
333							
334		Calculations:			$Q = V \cdot I$		
335		Heat gen.	Q	1930	W	$A\_s = 2 \cdot \pi \cdot R \cdot L$	
336		Surface area	A_s	0.000942	m^2	$q\_s = \frac{Q}{A\_s}$	
337		heat flux	q_s	2047793.601	W/m^2		
338		Max. heat flux:	q_max	1524949.916	W/m^2...from VBA Function for Max. heat flux		
339		Diff =	(q_s - q_max)	522843.685	W?m^2		
340							

In the above, in cell D338, q_max is calculated using the VBA Function for q_max for a horizontal cylinder. See the previous problem for the procedure to insert the VBA Function. The eqn can be seen in the Formula bar.

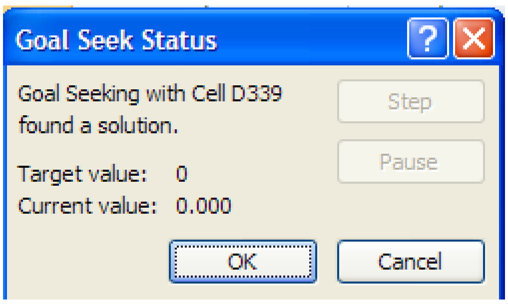
3. Now, in cell D339, we have the difference: (q_s – q_max), which should be equal to zero. So, apply Goal Seek to make cell D339 equal to zero by changing cell D330 (i.e. vlue of voltage, V):

For procedure of Goal Seek, see problem 3.1.16.

We get:



Click OK. We get:



And, the result is:

D339 f_x =D337-D338

	A	B	C	D	E
324		Data:	Fluid =	Water	
325					
326		Sat. temp.	T_sat	100.0	C
327		Radius of cyl.	Rad	0.0005	m
328					
329		Length of wire	L	0.3	m
330		Voltage ... assumed	V	7.447	V
331		Current	I	193	A
332					
333					
334		Calculations:			
335		Heat gen.	Q	1437.231436	W
336		Surface area	A_s	0.000942	m^2
337		heat flux	q_s	1524949.916	W/m^2
338		Max. heat flux:	q_max	1524949.916	W/m^2...from VBA Function for Max. heat flux
339		Diff =	(q_s - q_max)	0.000	W?m^2

$Q = V \cdot I$

$A\_s = 2 \cdot \pi \cdot R \cdot L$

$q\_s = \frac{Q}{A\_s}$

Thus: the voltage at burn-out is: 7.447 V….Ans.

==

Prob.3.1.18: A steel bar, 20 mm in diameter and 200 mm long, with an emissivity of 0.9, is removed from a furnace at 455 C and suddenly submerged in a water bath under atmospheric pressure. Estimate the initial heat transfer rate from the bar.

EXCEL Solution:

It is obviously heat transfer in the Film boiling region since $\Delta T_e > 30$ C.

We shall use the VBA Function written above to get film boiling heat transfer coeff. for a horizontal cylinder.

Following are the steps:

1. Set up the EXCEL worksheet, enter data:

	A	B	C	D	E
345		Data:	Fluid =	Water	
346		Surface temp	T_s	455	C
347		Sat. temp.	T_sat	100.0	C
348		Dia of cylinder	D	0.0200	m
349		Length of cyl	L	0.2	m
350		emissivity	epsilon	0.9	
351		Stefan Boltzmann const.	sigma	5.67E-08	W/m^2.K^4
352					

2. Find the film boiling heat transfer coeff. h_film using the VBA Function. Then, calculate the Q_boiling and also the Q_radn, and add them up. Formulas used are also shown, in the following worksheet, for clarity:

D357 =Boiling_water_HorizlCyl_h_film(D346,D347,D348)

	A	B	C	D	E
345		Data:	Fluid =	Water	
346		Surface temp	T_s	455	C
347		Sat. temp.	T_sat	100.0	C
348		Dia of cylinder	D	0.0200	m
349		Length of cyl	L	0.2	m
350		emissivity	epsilon	0.9	
351		Stefan Boltzmann const.	sigma	5.67E-08	W/m^2.K^4
355		Calculations:			
357		film heat tr coeff.	h_film	150.3956	W/m^2.C
358		boiling heat tr. rate	Q_b	670.924	W
359		radn heat tr. rate	Q_rad	167.7068	W
360		Total heat tr rate:	(Q_b + Q_rad) =	838.631	W....Ans.

$$Q\_b = h\_film \cdot (\pi \cdot D \cdot L) \cdot (T\_s - T\_sat)$$

$$Q\_rad = \sigma \cdot \varepsilon \cdot (\pi \cdot D \cdot L) \cdot \left[(T\_s + 273)^4 - (T\_sat + 273)^4\right]$$

In the above, note in the Formula bar the Function used to calculate h_film for horizontal cylinder.

Thus: Total initial heat transfer rate from the bar = 838.63 W ….. Ans.

===

Prob.3.1.19: Water at 5 bar flows inside a vertical tube of 2.5 cm dia under flow boiling conditions. Tube wall temp is maintained at 10 C above the sat. temp. Determine the heat transfer for 1 m length of tube. (b) What will be the heat transfer if the tube is horizontal?

EXCEL Solution:

This is an internal flow boiling problem.

Following is the EXCEL worksheet:

D372 =2.54*D367^3*EXP(D370/1.551)

	B	C	D	E	F	G	H
366	Data:	Fluid =	Water				
367	Temp. difference	DELTAT_e	10	C			
368	ID of tube	D	0.0250	m			
369	Length of tube	L	1	m			
370	Pressure	P	0.5	Mpa			
371	If tube is vertical:				$h = 2.54 \cdot \Delta T_e^{\,3} \cdot \exp\left(\frac{P}{1.551}\right)$		
372	heat tr. coeff.	h	3.51E+03	W/m^2.C			
373	Heat transfer	Q	2753.773818	W/m...Ans.	$Q = h \cdot (\pi \cdot D \cdot L) \cdot \Delta T_e$		
374							
375	If tube is horizontal:						
376		h	20547.60421	W/m^2.C	$h = 2.253 \cdot \Delta T_e^{\,3.96}$	W/m^2.....for 0.2 < P < 0.7 MPa	
377		Q	16138.05061	W/m....Ans.	$Q = h \cdot (\pi \cdot D \cdot L) \cdot \Delta T_e$		

Formulas used are also shown in the worksheet.

Thus:

For vertical tube: h = 3510 W/m^2.C, Q = 2753.8 W/m … Ans.

For horizontal tube: h = 20547.6 W/m^2.C, Q = 16138.1 W/m … Ans.

===

Prob.3.1.20: A 1 mm dia nickel wire, 150 mm long, is submerged horizontally in water at atm pressure. The surface temp of the wire is 110 C. Find the nucleate boiling flux.

(b) If the water is flowing normal to the wire at 3 m/s, what will be the change in heat flux?

(c) What should be the flow velocity to make convective heat flux equal to the boiling heat flux?

EXCEL Solution:

This is Problem is on external flow boiling.

First, we will find out nucleate boiling flux, $q_{boiling}$ using the VBA Function already written.

Then, we will find out the convection flux, q_{conv} using relation for cross flow of water over a cylinder.

And, total heat flux is: $q_{total} = q_{conv} + q_{boiling}$

Following are the steps:

1. Set up the EXCEL worksheet, enter data:

C389 | fx | U_inf

	A	B	C	D	E
383		Data:	Fluid =	Water	
384		Surface temp	T_s	110	C
385		Sat. temp.	T_sat	100.0	C
386		Radius of cyl.	Rad	0.0005	m
387		Water-nickel combination	C_sf	0.006	From Table
388		Length of wire	L	0.15	m
389		Velocity	U_inf	3.000	m/s

2. Now, calculate the nucleate boiling flux using the VBA Function in cell D393. For the method of entering the Function, see Problem 3.1.16. Following is the result:

D393 | fx =Boiling_water_q_nucleate(D384,D385,D387)

	A	B	C	D	E	F	G
383		Data:	Fluid =	Water			
384		Surface temp	T_s	110	C		
385		Sat. temp.	T_sat	100.0	C		
386		Radius of cyl.	Rad	0.0005	m		
387		Water-nickel combination	C_sf	0.006	From Table		
388		Length of wire	L	0.15	m		
389		Velocity	U_inf	3.000	m/s		
390							
391		Calculations:					
392							
393		q_nucleate:	q_nucleate	1392681.0834	W/m^2 ... using VBA Function for Nucleate boiling		

Thus, $q_{boiling}$ = 1392681.08 W/m^2.

3. Next step is to find out the convection flux, q_{conv}. For cross flow over a cylinder, we use **Churchill and Bernstein equation:**

$$Nu_{cyl} = \frac{h \cdot D}{k} = 0.3 + \frac{0.62 \cdot Re^{\frac{1}{2}} \cdot Pr^{\frac{1}{3}}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}} \cdot \left[1 + \left(\frac{Re}{28200}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \quad .....(9.90)$$

Eqn. (9.90) is valid for $100 < Re < 10^7$, and Re.Pr > 0.2 and correlates very well all available data.

Fluid properties are evaluated at 'film temperature', $T_f = (T_s + T_a)/2$ = average of surface and free stream temperatures.

We use properties of liquid at Tf, and assume zero vapour production:

4. Get the Fluid properties by using the VBA Functions written earlier for Sat. water:

D403 =SatH2O_Prf_T((D397+273.15))

	A	B	C	D	E
395		For q_conv			
396					
397		Film temp	T_f	105	C
398		Liq. Props at Tf:			
399		density	rho_L	956.3246531	kg/m^3
400		dyn. Viscosity	mu_L	0.00026518	N.s/m^2
401		th. cond.	k_L	0.68226	W/m.C
402		Reynolds No. assuming no vapour generation	Re_liq	10818.96809	
403		Prandtl No.	Pr_liq	1.6433	

$$Re_{liq} = \frac{(R \cdot 2) \cdot U_{inf} \cdot rho_{liq}}{mu_{liq}}$$

In the above worksheet, Reynolds No. is calculated using properties of liquid.

5. Next, calculate the Nusselts No. for cross flow over a cylinder. In the worksheet shown below, the eqn for Nusselts No. is calculated in parts, for clarity. From Nusselts no., calculate h_conv, and then q_conv, as shown:

D413 =D393+D411

	B	C	D	E
404	To calculate Nusselts No.:			
405		AA	76.10097622	
406		BB	1.085779992	
407		CC	1.419551688	
408	Nusselts No.	Nusselts	99.79462145	
409				
410	conv. heat tr. coeff	h_conv	68085.87843	W/m^2.C
411	conv. Flux	q_conv	680858.7843	W/m^2 ....
412	Therefore:			
413	Total heat flux:	q_tot = q_nucleate+q_conv	2.07354E+06	W/m^2 ....Ans.

$$Nu_{cyl} = 0.3 + \frac{AA \cdot CC}{BB}$$

$$AA = 0.62 \cdot Re_{liq}^{0.5} \cdot Pr_{liq}^{\frac{1}{3}}$$

$$BB = \left[1 + \left(\frac{0.4}{Pr_{liq}}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}$$

$$CC = \left[1 + \left(\frac{Re_{liq}}{28200}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}}$$

$$h_{conv} = \frac{Nusselts \cdot k_{liq}}{(R \cdot 2)}$$

$$q_{conv} = h_{conv} \cdot (T_s - T_{sat})$$

Thus:

Nucleate boiling flux, qboiling = 1392681.08 W/m^2.

Conv. heat flux = q_conv = 680858.78 W/m^2

Total heat flux = q_total = 2.07354E06 W/m^2 … Ans.

---

6. **What should be the flow velocity to make convective heat flux equal to the boiling heat flux?**

We see from the above calculations that nucleate boiling heat flux is independent of velocity.

Convective heat flux is, of course, dependent on velocity.

To find the velocity which will make q_conv equal to q_boiling, we enter (q_conv – q_boiling) in cell D416.

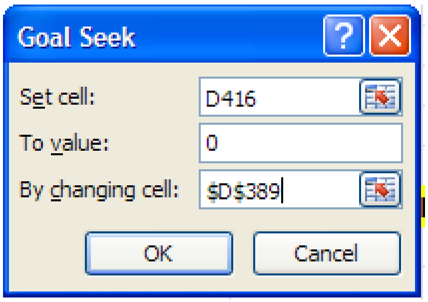
D416 fx =D411-D393

	B	C	D	E
411	conv. Flux	q_conv	680858.7843	W/m^2 ....
412	Therefore:			
413	Total heat flux:	q_tot = q_nucleate+q_conv	2.07354E+06	W/m^2 ....Ans.
414				
415				
416	Diff=	(q_conv - q_boiling) =	-711822.2991	
417				

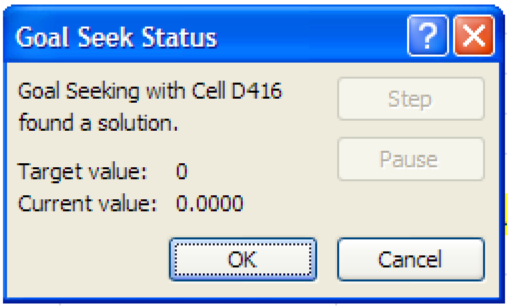
And, apply Goal Seek to make cell D416 zero by changing cell D389 (i.e. value of velocity, U_inf).

For procedure of Goal Seek, see problem 3.1.16.

We get:



Click OK. We get:



Again, click OK.

And, the result is:

U_inf = 8.181 m/s…..Ans.

===

Prob.3.1.21: Estimate the flow velocity that would be necessary to produce a value of h for forced convection through a smooth, 6.5 mm dia brass tube comparable with that which could be obtained by pool boiling with ΔT_e = 15 C, and P = 6.9 bar, and water as the fluid. Take T_{sat} = 164 C, and h_{fg} = 2.068E06 J/kg at 6.9 bar.

EXCEL Solution:

First, find the Nucleate boiling flux for brass-water combination (C_{sf} = 0.006) for the given T_s, T_sat.

From the flux, find out h_boiling.

Then, assume a flow velocity (U_inf) and find h_conv using Dittus – Boelter eqn for Nusselts No. with the constant = 0.019 (instead of 0.023).

Next, apply Goal Seek to make both the h_conv and h_boiling equal, by changing velocity, U_inf.

Following are the steps:

1. Set up the worksheet, enter data:

F453

	B	C	D	E
429				
430	**Data:**	**Fluid =**	**Water**	
431	**Surface temp**	**T_s**	**179**	C
432	**Sat. temp.**	**T_sat**	**164.0**	C
433	**Radius of cyl.**	**Dia**	**0.0065**	m
434	**Water-brass combination**	**C_sf**	**0.006**	From Table
435				
436	**Velocity .... Assumed**	**U_inf**	**3.000**	m/s
437				

2. First, calculate q_nucleate using the VBA Function for nucleate boiling. Then, h_boiling = q_nucleate / ΔT.

Now, get properties of water at bulk mean temp $T_f = T_{sat} + \Delta T/2 = 171.5$ C.

Following worksheet shows these calculations:

D443 =Boiling_water_q_nucleate(D431,D432,D434)

	A	B	C	D	E	F	G
442							
443		q_nucleate:	q_nucleate	18511560.8215	W/m^2 ... using VBA Function for Nucleate boiling		
444		boiling. heat tr coeff	h_boiling	1234104.055	W/m^2.C	$h\_boiling = q\_nucleate / \Delta T$	
445							
446		Film temp	T_f	171.5	C		
447		Liq. Props at Tf:					
448		density	rho_L	895.8345931	kg/m^3		
449		dyn. Viscosity	mu_L	0.000157583	N.s/m^2		
450		th. cond.	k_L	0.6799075	W/m.C		
451		Reynolds No. assuming no vapour generation	Re_liq	110854.7876	$Re = D * U\_inf * rho\_liq / mu\_liq$		
452		Prandtl No.	Pr_liq	1.019075			

The Function for q_nucleate, entered in cell D443 can be seen in the Formula bar.

For convection calculations, we are taking properties of liquid only, and assume zero vapour production.

3. Now, find Reynolds No. = D * U_inf * rho / mu. Then, apply Dittus _ Boelter eqn (with constant = 0.019 instead of 0.023) to get Nusselts No. i.e.

$$Nusselts = 0.019 * \mathrm{Re}\hat{}0.8 * \mathrm{Pr}\hat{}0.4$$

And, next, find h_conv from:

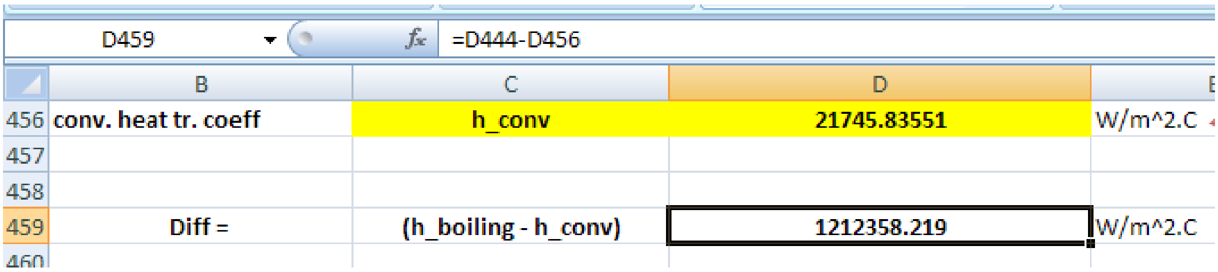
$$h\_conv = Nusselts * k\_liq / D$$

Following worksheet shows these calculations:

D456 | fx =D454*D450/D433

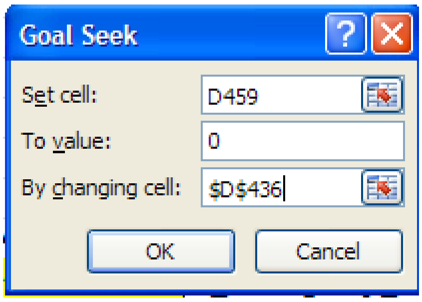
	B	C	D	E	F	G
453	To calculate Nusselts No.:					
454		Nusselts	207.8929	← $Nusselts = 0.019 * \mathrm{Re}\hat{}0.8 * \mathrm{Pr}\hat{}0.4$		
455						
456	conv. heat tr. coeff	h_conv	21745.83551	W/m^2.C ← $h\_conv = Nusselts * k\_liq / D$		

4. Now, all the above calculations were with the assumed value of 3 m/s for the velocity, U_inf. Now, enter (h_boiling – h_conv) in cell D459 and apply Goal Seek to make this cell equal to zero by changing cell D436 (i.e. value of U_inf).

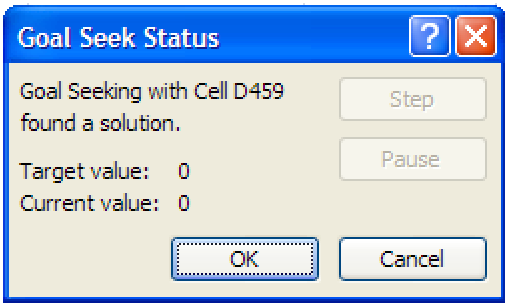


For procedure of Goal Seek, see problem 3.1.16.

We get:



Click OK. We get:



Again, click OK.

And, the result is:

U_inf = 467.295 m/s…..Ans.

i.e. quite a high value of velocity is required to get this heat flux in forced convection.

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Prob.3.1.22: Water at 1 atm, with a mean velocity of 1.5 m/s and a mean temp of 95 C flows through a 15 mm dia brass tube, whose surface is at 110 C. Estimate the heat transfer rate per unit length. (Ref. 3)

EXCEL Solution:

Here, combine the separate effects of forced convection and nucleate boiling.

First, find the Nucleate boiling flux for brass-water combination (C_{sf} = 0.006) for the given T_s, T_sat.

Then, find h_conv using Dittus-Boelter eqn for Nusselts No. with the constant = 0.019 (instead of 0.023), and then find out q_conv.

Following are the steps:

1. Set up the worksheet, enter data:

D472 | fx | 1.5

	B	C	D	E
466	Data:	Fluid =	Water	
467	Surface temp	T_s	110	C
468	Sat. temp.	T_sat	100.0	C
469	Dia of cyl.	Dia	0.0150	m
470	Water-brass combination	C_sf	0.006	From Table
471				
472	Velocity	U_inf	1.500	m/s
473				

2. First, calculate q_nucleate using the VBA Function for nucleate boiling. Now, get properties of water at bulk mean temp T_f = 95 C.

Following worksheet shows these calculations:

D479 | fx | =Boiling_water_q_nucleate(D467,D468,D470)

	B	C	D	E	F	G
476						
477	Calculations:					
478						
479	q_nucleate:	q_nucleate	1392681.0834	W/m^2 ... using VBA Function for Nucleate boiling		
480						
481						
482	Mean bulk temp	T_f	95	C		
483	Liq. Props at Tf:					
484	density	rho_L	961.6401735	kg/m^3		
485	dyn. Viscosity	mu_L	0.00029529	N.s/m^2		
486	th. cond.	k_L	0.67826	W/m.C		
487	Reynolds No. assuming no vapour generation	Re_liq	73273.40548	← $Re = D * U\_inf * rho\_liq / mu\_liq$		
488	Prandtl No.	Pr_liq	1.8407			

The Function for q_nucleate, entered in cell D479 can be seen in the Formula bar.

For convection calculations, we are taking properties of liquid only, and assume zero vapour production.

1. Now, find Reynolds No. = D * U_inf * rho / mu. Then, apply Dittus _ Boelter eqn (with constant = 0.019 instead of 0.023) to get Nusselts No. i.e.

$$Nusselts = 0.019 * \mathrm{Re}\text{^}0.8 * \mathrm{Pr}\text{^}0.4$$

And, next, find h_conv from:

$$h\_conv = Nusselts * k\_liq / D$$

Nd, the convective heat flux from:

$$\boxed{q\_conv = h\_conv * (T\_s - T\_f)}$$

Then, Q_total *for unit length* is calculated as:

$$\boxed{Q\_tot = (q\_boiling + q\_conv) * (\pi * D)}$$

Following worksheet shows these calculations:

D495 =(D479+D493)*(PI()*D469)

	C	D	E
488	Pr_liq	1.8407	
489			Nusselts = 0.019 * Re^0.8 * Pr^0.4
490	Nusselts	189.1054	h _ conv = Nusselts * k _ liq / D
491			
492	h_conv	8550.841444	W/m^2.C
493	q_conv	128262.6217	W/m^2 q _ conv = h _ conv * (T _ s − T _ f)
494			Q _ tot = (q _ boiling + q _ conv) * (π * D)
495	Q_tot	71672.78355	W/m....Ans.

Thus: Total heat transfer from the tube = Q_tot = 71672.8 W/m …. Ans.

===

3.2 Condensation:

Formulas used:

Film condensation and flow regimes: (Ref. 1)

Consider film condensation of a vapour at saturation temperature T_{sat} on the surface of a cooled vertical plate, maintained at a temperature T_s (< T_{sat}). See Fig. 11.7.

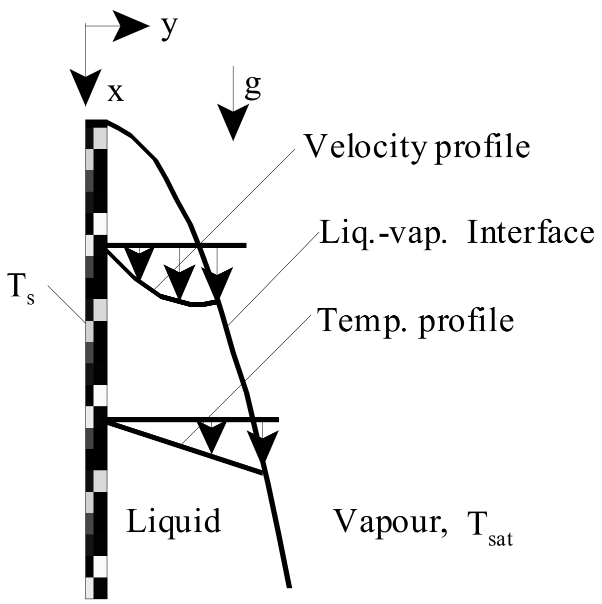


Fig. 11.7 Film condensation on a vertical plate

Vapour condenses on the top of the plate and flows down as a film. Thickness of the film (δ) is zero at the top of the plate (i.e. at x = 0 in the coordinate system shown) and increases as we travel down the plate (i.e. as x increases) due to additional condensation of vapour.

Initially, the liquid film flow is **laminar**; after some distance it will become **wavy** and later, it may even turn **turbulent**. *These different flow regimes are identified according to a* ***'film Reynolds number',*** *defined as follows:*

$$Re_f = \frac{D_h \cdot \rho_L \cdot V_L}{\mu_L} = \frac{4 \cdot A_c \cdot \rho_L \cdot V_L}{P \cdot \mu_L} = \frac{4 \cdot \rho_L \cdot V_L \cdot \delta}{\mu_L} = \frac{4 \cdot m}{P \cdot \mu_L} \quad .....(11.32)$$

where

D_h = 4 A_c/P = 4.δ = hydraulic dia. of condensate flow, m

P = wetted perimeter of condensate, m

A_c = P. δ = area of cross-section of flow at the lowest part of flow, m^2

ρ_L = density of liquid, kg/m^3

μ_L = viscosity of liquid, kg/m.s

V_L = average velocity of condensate at the lowest part of flow, m/s

ρ_L A V_L = m = mass flow rate of condensate at the lowest part of flow, kg/s

For the common geometries of a vertical plate, vertical cylinder and a horizontal cylinder, **hydraulic diameter Dh is equal to 4 times the thickness of the condensate, δ, at the location where the hydraulic diameter is to be evaluated.**

Again, considering eqn. (11.32), for a vertical plate, wetted perimeter, P = B, the breadth; therefore, (m/P) is the mass flow rate per unit breadth. If we denote (m/P) by m', we can write for the vertical plate:

$$Re_f = \frac{4 \cdot m'}{\mu_L} \quad ....(11.32,a)$$

Rohsenow (1956) suggested that sub-cooling of the liquid can be taken into account by replacing h_{fg} by a **'modified latent heat of vapourization'**, h'_{fg}, defined as:

$$h'_{fg} = h_{fg} + 0.68 \cdot C_{pL} \cdot (T_{sat} - T_s) \qquad .....(11.33)$$

where C_{pL} is the sp. heat of liquid at the average film temperature.

Similarly, if a superheated vapour at a temperature, T_v, enters a condenser and condenses, the superheated vapour has to be cooled to T_{sat} first, and then condensed at T_{sat}, and then sub-cooled to some temperature between T_s and T_{sat}. Then. Modified latent heat of vapourization is:

$$h'_{fg} = h_{fg} + 0.68 \cdot C_{pL} \cdot (T_{sat} - T_s) + C_{pV} \cdot (T_V - T_{sat}) \qquad .....(11.34)$$

where C_{pV} is the sp. heat of vapour at the *average* temperature of $(T_V + T_{sat})/2$.

Then, rate of heat transfer in condensation becomes:

$$Q_{conden} = h \cdot A \cdot (T_{sat} - T_s) = m \cdot h'_{fg} \qquad ....(11.35)$$

where A is the surface area on which condensation occurs.

Then, from eqn. (11.35) and (11.32), we can write:

$$Re_f = \frac{4 \cdot Q_{conden}}{P \cdot \mu_L \cdot h'_{fg}} = \frac{4 \cdot A \cdot h \cdot (T_{sat} - T_s)}{P \cdot \mu_L \cdot h'_{fg}} \qquad ....(11.36)$$

When either Q_{conden} or h is known, it is convenient to use eqn. (11.36) to determine Re_f.

Now, different flow regimes are identified according to the value of Ref as follows:

$Re_f \le 30$ ….Liquid film is smooth and wave-free, i.e. **fully laminar**.

$450 < Re_f < 1800$ ….Liquid film has ripples or waves and the flow is **wavy-laminar**.

$Re_f > 1800$ ….Liquid film is **fully turbulent**.

Heat transfer correlations vary depending upon the flow regime.

Nusselt's theory for Laminar film condensation on Vertical Plates:

Velocity profile:

$$u(y) = \frac{g \cdot (\rho_L - \rho_V) \cdot \left(\delta \cdot y - \frac{y^2}{2}\right)}{\mu_L}$$

i.e. $$u(y) = \frac{g \cdot (\rho_L - \rho_V) \cdot \delta^2}{\mu_L} \cdot \left[\frac{y}{\delta} - \frac{1}{2} \cdot \left(\frac{y}{\delta}\right)^2\right] \qquad ......(11.37)$$

And, the mean flow velocity of the liquid at a section is given by:

$$u_m = \frac{g \cdot (\rho_L - \rho_V) \cdot \delta^2}{3 \cdot \mu_L} \qquad .....(11.38)$$

Mass flow rate of condensate through any x-position is given by:

$$m = \frac{\rho_L \cdot (\rho_L - \rho_V) \cdot g \cdot b \cdot \delta^3}{3 \cdot \mu_L} \qquad ......(11.39)$$

The liquid film thickness as a function of position x is given by:

$$\delta(x) = \left[\frac{4 \cdot k_L \cdot \mu_L \cdot (T_{sat} - T_s) \cdot x}{\rho_L \cdot (\rho_L - \rho_V) \cdot g \cdot h_{fg}}\right]^{\frac{1}{4}} \quad .....(11.43)$$

Local heat transfer coeff. is given by:

$$h_x = \frac{k}{\delta} \quad ....(11.44)$$

Substituting the value of δ from eqn. (11.43) in eqn. (11.44):

$$h_x = \left[\frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h_{fg}}{4 \cdot \mu_L \cdot x \cdot (T_{sat} - T_s)}\right]^{\frac{1}{4}} \quad .....(11.45)$$

At x = L, i.e. at the lower end of the plate, local heat transfer coeff. is:

$$h_L = \left[\frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h_{fg}}{4 \cdot \mu_L \cdot L \cdot (T_{sat} - T_s)}\right]^{\frac{1}{4}} \quad .....(11.46)$$

Average value of heat transfer coeff. over the entire height of the plate:

$$h_{avg} = \frac{1}{L} \cdot \int_0^L h_x \, dx$$

We get:

$$h_{avg} = \frac{4}{3} \cdot h_L \quad ....(11.47)$$

In the above, h_L is the local heat transfer coeff. at x = L, i.e. at the lower end of the plate.

We have, for average heat transfer coeff. for laminar film condensation on a vertical plate:

$$h_{avg} = 0.943 \cdot \left[\frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot L \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}}$$ W/(m2.C)...for 0 < Re_f < 30......(11.49)

where

$$h'_{fg} = h_{fg} + 0.68 \cdot C_{pL} \cdot (T_{sat} - T_s)$$

In the above eqn. all the liquid properties should be evaluated at the film temperature,

Tf = (Tsat + Ts)/2 and hfg and ρV should be evaluated at Tsat.

Now, let us define a dimensionless number called **'Condensation number'**, (Co) [or, 'modified Nusselt number'] as follows:

$$Co = \frac{h_{avg}}{k_L} \cdot \left[\frac{\mu_L^2}{\rho_L \cdot (\rho_L - \rho_V) \cdot g} \right]^{\frac{1}{3}}$$ .....(11.50, a)

Since , $\rho_L >> \rho_V$, condensation number can be simplified as:

$$Co = \frac{h_{avg}}{k_L} \cdot \left(\frac{\mu_L^2}{\rho_L^2 \cdot g} \right)^{\frac{1}{3}} = \frac{h_{avg}}{k_L} \cdot \left(\frac{\nu_L^2}{g} \right)^{\frac{1}{3}}$$ ....(11.50, b)

Then, Rohsenow (1985) has shown that above derived relation for heat transfer coeff. for condensation on a vertical plate for the laminar regimes of condensate flow, can be recast as follows:

a) **Laminar flow, (Ref ≤ 30):**

$$Co = 1.47 \cdot Re_f^{\frac{-1}{3}}$$ ..laminar....(11.51)

b) **In the laminar – wavy region, (30 < Ref < 1800):**

Kutatelazde recommends following correlation:

$$Co = \frac{Re_f}{1.08 \cdot Re_f^{1.22} - 5.2} \quad ....laminar\text{-}wavy.....(11.52)$$

c) **For turbulent region, (Ref > 1800):**

Labuntsov recommends following correlation for turbulent film condensation:

$$Co = \frac{Re_f}{8750 + 58 \cdot \left(Re_f^{0.75} - 253\right) \cdot Pr_L^{-0.5}} \quad ...turb.....(11.53)$$

Eqns. (11.51), (11.52) and (11.53) are depicted graphically in Fig. (11.9) below:

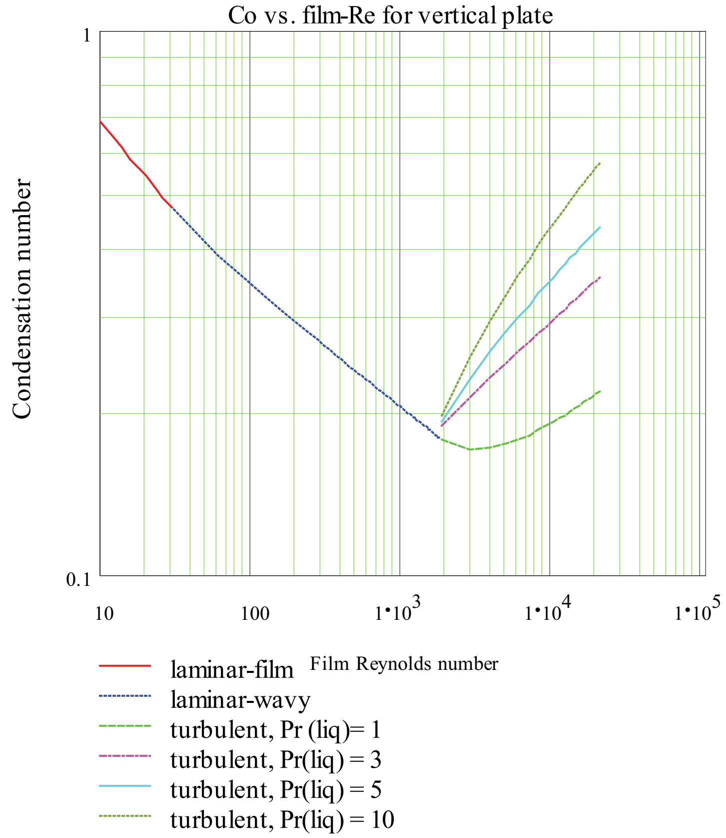


Fig. 11.9 Condensation number vs. film Reynolds number for a vertical plate

Above correlations for condensation on a vertical plate are applicable to condensation inside or outside vertical tubes also, if the tube diameter is not too small.

Calculation formulas for all the three regions of film condensation on a vertical plate (or cylinder) are given below (from Ref. 2, Cengel). Here, h_{vert} is the average heat transfer coeff over the entire height (L) of the vertical plate.

$delta_L$ is the thickness of the film at the bottom of the plate, i.e. at x = L.

For Laminar film: (i.e. 0 < Re <= 30):

$$delta_L = \left[\frac{4\cdot mu_L\cdot k_L\cdot(T_{sat} - T_s)\cdot L}{g\cdot rho_L\cdot(rho_L - rho_V)\cdot h_{fg\_prime}}\right]^{\frac{1}{4}}$$

$$Re = \frac{4\cdot g\cdot rho_L\cdot(rho_L - rho_V)\cdot delta_L^{\,3}}{3\cdot mu_L^{\,2}}$$

$$h_{vert} = 1.47\cdot Re^{\frac{-1}{3}}\cdot k_L\cdot\left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}} \quad \text{if } 0 < Re \le 30$$

For Laminar-wavy film: (i.e. 30 < Re <= 1800):

$$h_{vert} = \frac{Re\cdot k_L}{1.08\cdot Re^{1.22} - 5.2}\cdot\left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}}$$

$$Re_f = \left[4.81 + \frac{3.7\cdot L\cdot k_L\cdot(T_{sat} - T_s)}{mu_L\cdot h_{fg\_prime}}\cdot\left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}}\right]^{0.82}$$

For turbulent film: (i.e. Re > 1800):

$$h_{vert} = \frac{Re\cdot k_L}{8750 + 58\cdot Pr_L^{-0.5}\cdot(Re^{0.75} - 253)}\cdot\left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}}$$

$$Re_f = \left[\frac{0.069\cdot L\cdot k_L\cdot Pr_L^{0.5}\cdot(T_{sat} - T_s)}{mu_L\cdot h_{fg\_prime}}\cdot\left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}} - 151\cdot Pr_L^{0.5} + 253\right]^{\frac{4}{3}}$$

Film condensation on inclined plates, vertical tubes, horizontal tubes and spheres, and horizontal tube banks:

If the plate is inclined at an angle of θ to the vertical, ($\theta \le 60$ deg.), replacing g by g.cos(θ) in eqn. (11.49) gives satisfactory results for laminar condensation on the upper surface of the inclined plate. i.e.

$$h_{inclined} = 0.943 \cdot \left[\frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot \cos(\theta) \cdot h'_{fg}}{\mu_L \cdot L \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}} \quad W/(m^2.C)\text{...for } 0 < Re_f < 30\text{......(11.55)}$$

We can also write:

$$h_{inclined} = h_{vert} \cdot (\cos(\theta))^{\frac{1}{4}} \quad \text{....laminar.....(11.56)}$$

Vertical tubes:

Eqn. (11.49) for laminar condensation on vertical plates can also be used to determine heat transfer coeff. for laminar condensation on the outer or inner surface of a vertical tube, if the tube diameter is large compared to the thickness of the liquid film i.e.

if D >> δ.

Horizontal tubes and spheres:

Horizontal tube-laminar film condensation:

For laminar film condensation on horizontal tubes and spheres, Nusselt type of analysis gives relations similar to eqn. (11.49), except that L is replaced by diameter D and the value of the numerical constant is different. We get:

$$h_{horiz} = 0.729 \cdot \left[\frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot D \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}}$$ W/(m2.C)...for 0 < Re_f < 30......(11.57)

Horizontal tube-forced convection condensation:

Eqn. (11.57) is for the case of a quiescent vapour condensing on a horizonal tube. However, for condensers used in practice, a vapour may be forced through a condenser while being condensed. For the case of a cylinder of diameter D exposed to cross flow of a vapour with a free stream velocity of U, following correlation due to Shekriladze and Gomelauri (1966), may be applied:

$$\frac{h_{horiz} \cdot D}{k} = 0.64 \cdot Re_D^{\frac{1}{2}} \cdot \left[1 + \left(1 + \frac{1.69 \cdot g \cdot h'_{fg} \cdot \mu_L \cdot D}{U^2 \cdot k_L \cdot (T_{sat} - T_s)} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}}$$ .. for Re_D < 106....(11.57,a)

where $Re_D = \frac{\rho_L \cdot U \cdot D}{\mu_L}$

Sphere-laminar film condensation:

$$h_{sphere} = 0.815 \cdot \left[\frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot D \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}}$$ W/(m2.C)...for 0 < Re_f < 30......(11.58)

It is interesting **to compare the laminar condensation on vertical and horizontal tubes.** From eqns. (11.49) and (11.57), we can write:

$$\frac{h_{vert}}{h_{horiz}} = \frac{0.943}{0.729} \cdot \left(\frac{D}{L} \right)^{\frac{1}{4}} = 1.294 \left(\frac{D}{L} \right)^{\frac{1}{4}}$$ ....(11.59)

For h_{vert} to be equal to h_{horiz}, we should have:

$$L = (1.294)^4 \cdot D$$

i.e.

$$L = 2.8 \cdot D$$

i.e. for L > 2.8.D, heat transfer coeff. will be higher for a horizontal tube. It is a fact that most of the tubes used in practice have lengths such that L > 2.8.D. Therefore, tubes used in a steam condenser are generally arranged in a horizontal orientation.

Horizontal tube banks:

Average heat transfer coeff. for film condensation on a vertical tier containing N tubes is obtained by substituting (N.D) in place of D in eqn. (11.57) for a single horizontal tube. i.e.

$$h_{horiz\_Ntubes} = 0.729 \cdot \left[\frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot (N \cdot D) \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}} \quad \text{W/(m}^2\text{.C)...for } 0 < Re_f < 30 \text{......(11.60)}$$

Clearly, this is related to the value of heat transfer coeff. for a single horizontal tube as follows:

$$h_{horiz\_Ntubes} = \frac{1}{N^{\frac{1}{4}}} \cdot h_{horiz\_1tube} \quad \text{.....(11.61)}$$

Chen (1961) has suggested the following modified form of eqn.(11.57) for condensation on a vertical tube bank, to take into account the condensation occurring on the sub-cooled film between two adjacent tubes:

$$h_{horiz\_Ntubes} = 0.725 \cdot \left[\frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot (N \cdot D) \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}} \cdot \left[1 + 0.2 \cdot \frac{C_{pL} \cdot (T_{sat} - T_s) \cdot (N - 1)}{h_{fg}} \right] \quad \text{...(11.61)}$$

Note that the second square brackets on the RHS, is a correction factor to eqn. (11.60); also note that term inside this square bracket is h_{fg} and not h'_{fg}. Eqn. (11.61) is valid for:

$$\frac{C_{pL} \cdot (T_{sat} - T_s)}{h_{fg}} \le 2 \quad \text{and,} \quad Pr_L \ge 1$$

And,

$$\frac{C_{pL}\cdot\left(T_{sat}-T_{s}\right)}{h_{fg}} = Ja = Jacob\_number$$

==

Prob.3.2.1. Saturated steam at atmospheric pressure condenses on a vertical plate (size: 30 cm × 30 cm) maintained at 60 C. Determine heat transfer rate and the mass of steam condensed per hour.

(b) If the plate is tilted at an angle of 30 deg. to the vertical, what is the value of condensation rate?

Mathcad Solution:

In Mathcad we have already written Functions for properties of Sat. water and also for Steam, as functions of temperature.

So, now, in the same worksheet, **let us write Functions for Film condensation of water (i.e. steam) on various geometries, using the equations given above.**

Mathcad Function to find h_vert etc. for Film condensation of steam on a vertical plate:

Input: Ts, Tsat (C), L, b (m)

Output: delta_L, h (W/m^2.C), Re_film, Q (W), m_cond (kg/s) in a Matrix

Note: Take liquid properties at Tf = (Tsat + Ts)/2, and h_fg and vap. properties at Tsat.

Following are the steps:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Tf = (Tsat + Ts)/2 is calculated

Line 3 to 10: Various properties of liquid and vapour are calculated using the property Functions for Sat. water already written

Line 11: hfg_prime is calculated

Line 12: value of g is entered

Line 13: delta_L, the film thickness at a distance L from top, is calculated

Line 14: Re, the 'film Reynold's No.' is calculated

Line 15: If Re < 30, it is pure laminar film condensation, and h_vert (i.e. average heat tr. coeff.) is calculated as per the formula shown

Line 16, 17, 18: If 30 < Re < =1800, it is 'laminar-wavy' film, and now, the h_vert and the new Re_f are calculated as per the calculation formulas

Line 19, 20, 21: If Re > 1800, it is 'turbulent' film, and now, h_vert and the new Re_f are calculated again as per the calculation formulas

Line 22: heat transfer, Q is calculated as: Q = h_vert * (L * b) * (Tsat – Ts)

Line 23: mass of steam condensed is calculated

Line 24: AA is defined as a Matrix of 2 rows and 5 columns, first row being the column headings and the second row giving values of delta_L, h_vert, Re_f, Q and m_condensed.

Line 25: returns this Matrix as the output of the Function.

See the Function below:

FilmCondensation_Steam_VertPlate$(T_s, T_{sat}, L, b) :=$

return "Ts must be less than Tsat ! " if $T_s - T_{sat} \geq 0$

$$T_f \leftarrow \frac{T_s + T_{sat}}{2}$$

$$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_f + 273.15)}$$

$$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$$

$$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$$

$$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_f + 273.15)$$

$$k_L \leftarrow k\_f\_H2O(TempK, H2Ok\_f, T_f + 273.15)$$

$$cp_L \leftarrow cp\_f\_H2O(TempK, H2Ocp\_f, T_f + 273.15)$$

$$Pr_L \leftarrow Pr\_f\_H2O(TempK, H2OPr\_f, T_f + 273.15)$$

$$\nu_L \leftarrow \frac{mu_L}{rho_L}$$

$$h_{fg\_prime} \leftarrow h_{fg} + 0.68 \cdot cp_L \cdot (T_{sat} - T_s)$$

$$g \leftarrow 9.81$$

$$delta_L \leftarrow \left[\frac{4 \cdot mu_L \cdot k_L \cdot (T_{sat} - T_s) \cdot L}{g \cdot rho_L \cdot (rho_L - rho_V) \cdot h_{fg\_prime}}\right]^{\frac{1}{4}}$$

$$Re \leftarrow \frac{4 \cdot g \cdot rho_L \cdot (rho_L - rho_V) \cdot delta_L^{\,3}}{3 \cdot mu_L^{\,2}}$$

$$h_{vert} \leftarrow 1.47 \cdot Re^{\frac{-1}{3}} \cdot k_L \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}} \quad \text{if } 0 < Re \leq 30$$

if $30 < Re \leq 1800$

$$h_{vert} \leftarrow \frac{Re \cdot k_L}{1.08 \cdot Re^{1.22} - 5.2} \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}}$$

$$Re_f \leftarrow \left[4.81 + \frac{3.7 \cdot L \cdot k_L \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}}\right]^{0.82}$$

if $Re > 1800$

$$h_{vert} \leftarrow \frac{Re \cdot k_L}{8750 + 58 \cdot Pr_L^{\,-0.5} \cdot (Re^{0.75} - 253)} \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}}$$

$$Re_f \leftarrow \left[\frac{0.069 \cdot L \cdot k_L \cdot Pr_L^{\,0.5} \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}} - 151 \cdot Pr_L^{\,0.5} + 253\right]^{\frac{4}{3}}$$

$$Q \leftarrow h_{vert} \cdot (L \cdot b) \cdot (T_{sat} - T_s)$$

$$m_{condensed} \leftarrow \frac{Q}{h_{fg\_prime}}$$

$$AA \leftarrow \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^{}2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ delta_L & h_{vert} & Re_f & Q & m_{condensed} \end{pmatrix}$$

AA

Now, let us use this Function to get results for the above problem:

Data:

$T_s := 60 \quad T_{sat} := 100 \quad L := 0.3 \quad b := 0.3$

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^{}2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 1.506 \times 10^{-4} & 7.28 \times 10^{3} & 404.868 & 2.621 \times 10^{4} & 0.011 \end{pmatrix}$$

Immediately, we see that:

heat transfer rate, Q = 26210 W … Ans.

steam condensed = 0.011 kg/s = 39.6 kg/h … Ans.

In addition, note the value of thickness of film at the bottom of the plate (i.e. at x = L), and h_vert and Re_f. Since Re_f is between 30 and 1800, it is 'laminar-wavy' region.

(b) If the plate is tilted at an angle of 30 deg. to the vertical, what is the value of condensation rate?

Now, eqns for vertical plate are used, but h_inclined = h_vert * (cos (θ))^(1/4) where θ (deg.) is the inclination of the plate to the vertical.

Following is the Mathcad Function for an Inclined plate, inclined at θ degrees to vertical:

Mathcad Function to find h_vert for Film condensation of steam on an Inclined plate, inclined at theta deg to the vertical:

Input: Ts, Tsat (C), L, b (m), theta (deg.)

Output: h_film (W/m^2.C)

Note: Take liquid properties at Tf = (Tsat + Ts)/2, and h_fg and vap. properties at Tsat.

```
FilmCondensation_Steam_InclinedVPlate_h(Ts, Tsat, L, b, theta) :=
    | return "Ts must be less than Tsat ! "   if Ts − Tsat ≥ 0
    | AA ← FilmCondensation_Steam_VertPlate(Ts, Tsat, L, b)
    | h_vert ← AA_(1,1)
    | theta_rad ← theta·π / 180
    | h_inclined ← h_vert·(cos(theta_rad))^(1/4)
    | h_inclined
```

In the above program, we have:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Mathcad Function written above for a vertical plate is invoked, and the resulting Matrix is assigned to AA

Line 3: h_vert is reads off from the Matrix. Remember that result of the Function is a 2 × 5 Matrix. In Mathcad, by default, rows and columns are *numbered starting from zero* (not 1 , which is usual). So, note that ***h_vet is the element AA is the element in the first row, first column as per this notation.***

Line 4: theta is converted to radians since in Mathcad arguments to trigonometric functions should be in Radians.

Line 5: h_inclined is calculated

Line 6: value of h_inclined is returned as the output of this Mathcad Function

---

Now, applying the above Function for this problem:

When the plate is inclined at 30 deg. to vertical:

$T_s := 60$ C $T_{sat} := 100$ C $L := 0.3$ m $b := 0.3$ m theta := 30 deg.

$\text{FilmCondensation\_Steam\_InclinedVPlate\_h}(T_s, T_{sat}, L, b, \text{theta}) = 7.023 \times 10^3$ W/m^2.C

Therefore: $Q := 7023 \cdot (0.3 \cdot 0.3) \cdot (T_{sat} - T_s)$

i.e. $Q = 2.528 \times 10^4$ W

and, $m_{cond} := \frac{Q}{2257 \cdot 10^3}$

i.e. $m_{cond} = 0.0112$ kg/s

==

Prob.3.2.2. Saturated steam at 80 C condenses as a film on a vertical plate maintained at 70 C. Calculate the average heat transfer coeff. and the rate of condensation. [VTU – M.Tech. – June/July 2009]

Mathcad Solution:

Apply the Function written above directly:

$T_s := 70$ C $T_{sat} := 80$ C $L := 1$ m $b := 1$ m

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 1.463 \times 10^{-4} & 7.305 \times 10^3 & 323.82 & 7.305 \times 10^4 & 0.031 \end{pmatrix}$$

Note: Since the size of plate is not given, we have assumed it to be 1 m × 1 m.

Thus, h_avg = 7305 W/m^2.C, and m_cond = 0.031 kg/s per m^2 area …. Ans.

==

Prob.3.2.3. A vertical plate, 500 mm high and 200 mm wide is to be used to condense sat. steam at 1 atm. (a) At what surface temp must the plate be maintained to achieve a condensation rate of 25 kg/h?

(b) compute and plot the surface temp as a function of condensation rate for 15 < m_cond < 50 kg/h

(Ref: 3)

Mathcad Solution:

We shall use the Mathcad Function already written for a vertical plate, and apply 'Solve block' of Mathcad to find Ts to get the desired condensation rate:

Following is the worksheet:

First, assume a value for Ts and do the calculations using the Mathcad Function written earlier for a vertical plate:

Data:

$T_s := 60$ C.... assumed value

$T_{sat} := 100$ C $L := 0.5$ m $b := 0.2$ m

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^{}2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 1.711 \times 10^{-4} & 6.682 \times 10^{3} & 614.859 & 2.673 \times 10^{4} & 0.011 \end{pmatrix}$$

Now, m_cond is the element (1,4) in the Matrix above. (Remember: numbering of rows and columns starts from zero in Mathcad).

So, let us apply the 'Solve Block' of Mathcad to get the value of Ts such that m_cond will be 25 kg/h = (25/3600) kg/s:

$m_{cond} := 25$ kg/h .... required as per data

Given

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b)_{1,4} = \frac{m_{cond}}{3600}$$

$$Ts(m_{cond}) := \text{Find}(T_s)$$

Note that we have written the result of Solve Block, viz. Ts as a function of M_cond so that we can easily draw the plot of Ts vs m_cond later:

We get:

Therefore:

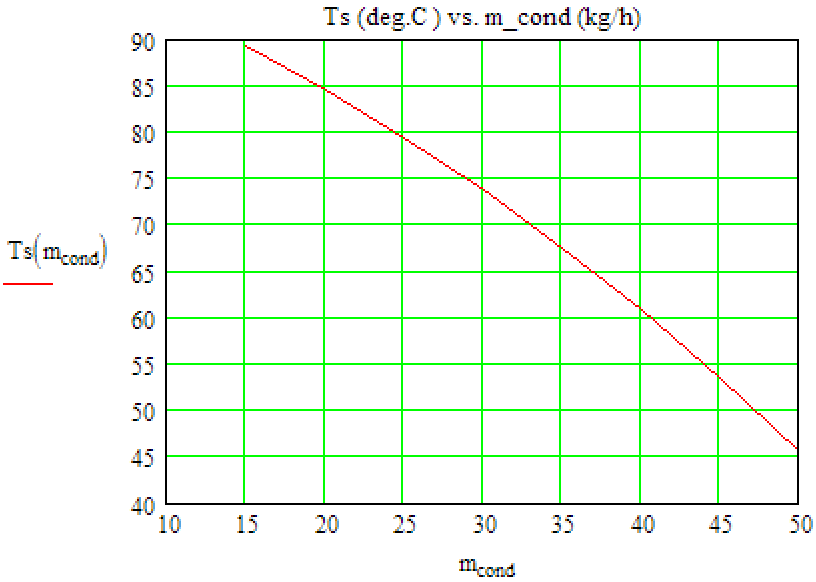
$Ts(m_{cond}) = 79.36$ C....Ans.

i.e. Value of surface temp required to get a condensation rate of 25 kg/h is 79.36 deg. C … Ans.

Now, plot Ts vs m_cond:

$m_{cond} := 15, 20 .. 50$ ....define m_cond as a range variable from 15 to 50 kg/h

m_{cond} =	$Ts(m_{cond})$ =
15	89.278
20	84.55
25	79.36
30	73.71
35	67.555
40	60.825
45	53.408
50	45.424



===

Prob.3.2.4. A vertical plate, 2.5 m high, maintained at a uniform temp of 54 C, is exposed to sat. steam at atm. pressure.

a) Estimate the condensation and heat transfer rates per unit width of the plate
b) If the plate height were halved, would turbulent flow still exist?
c) For 54 < Ts < 90 C, plot the condensation rate as a function of plate temp for the two plate heights of parts (a) and (b). (Ref: 3)

Mathcad Solution:

We shall use the Mathcad Function already written for a vertical plate.

Following is the worksheet:

Data:

$T_s := 54$ C....

$T_{sat} := 100$ C $\quad L := 2.5$ m $\quad b := 1$ m

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, 2.5, b) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 2.665 \times 10^{-4} & 4.925 \times 10^{3} & 2.433 \times 10^{3} & 5.664 \times 10^{5} & 0.237 \end{pmatrix}$$

We observe that:

Re_f = 2433 > 1800…Therefore, it is turb. flow.

Heat transfer, Q = 5.664E05 W ….Ans.

Condensation rate, m_cond = 0.237 kg/s …. Ans.

(b) When the vertical height is halved, i.e. L = 1.25 m, we have:

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, 1.25, b) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 2.241 \times 10^{-4} & 5.524 \times 10^{3} & 1.379 \times 10^{3} & 3.176 \times 10^{5} & 0.133 \end{pmatrix}$$

We see that:

Re_f = 1379 . i.e. 30 < Re_f < 1800 … Therefore, it is *not turb. film*, but *wavy laminar film*…..Ans.

(c) Plot the condensation rate as a function of plate temp, for plate heights L = 2.5 m and L = 1.25 m:

For L = 2.5 m:

Note that in the output of the Mathcad Function, m_cond is element (1,4) i.e. element in the first row, 4th column. *Remember that numbering of rows and columns starts from zero in Mathcad, by default.*

$T_s := 54, 60..90$ C .... define a range variable for Ts

For this range of Ts, m_cond is given as:

$T_s =$	$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b)_{1,4}$
54	0.262
60	0.231
66	0.2
72	0.167
78	0.139
84	0.109
90	0.075

Now, for L = 1.25 m:

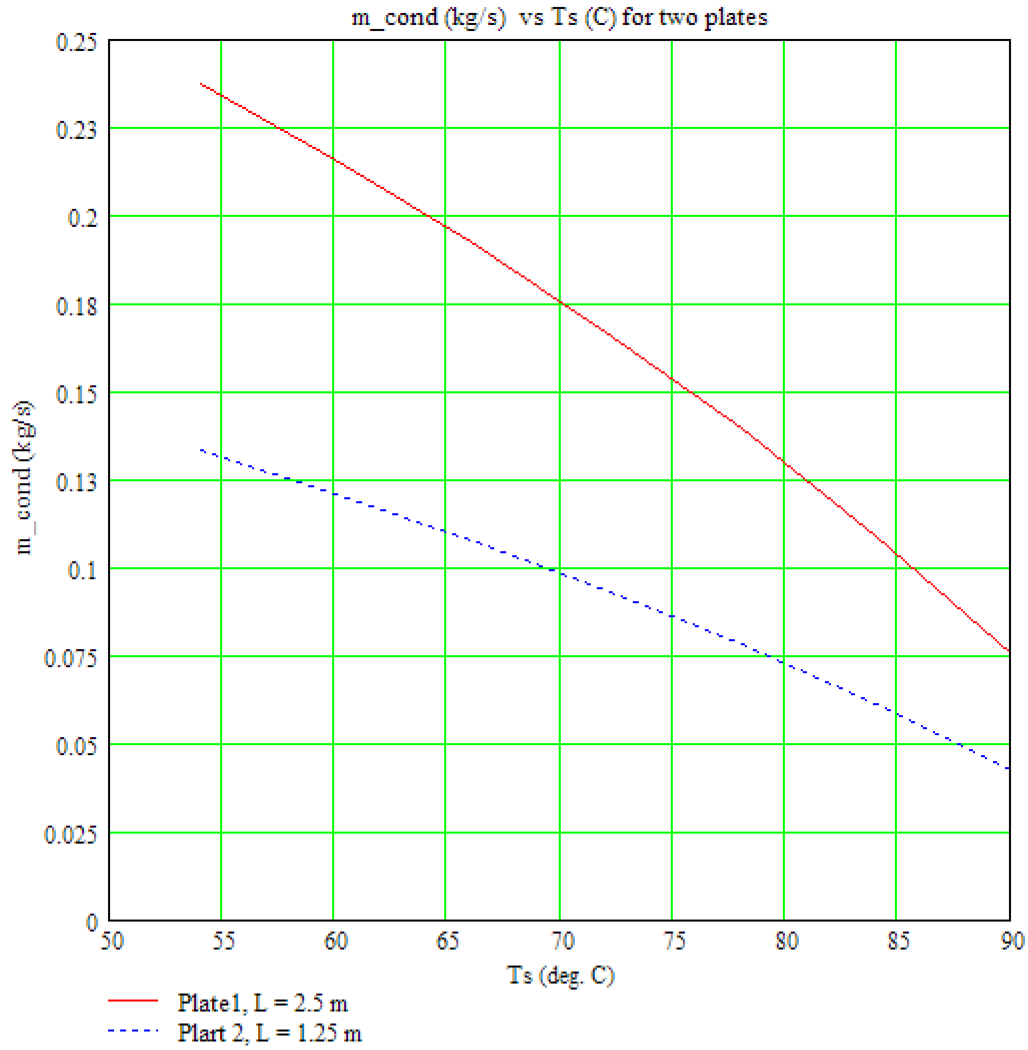
Take the same variation of Ts as earlier, i.e.

$T_{s2} := 54, 60..90$ C .... define a range variable for Ts

And, the corresponding values of m_cond are:

$T_{s2} =$	$\text{FilmCondensation\_Steam\_VertPlate}(T_{s2}, T_{sat}, 1.25, b)_{1,4}$
54	0.133
60	0.121
66	0.108
72	0.094
78	0.078
84	0.061
90	0.042

Now, plot the variation of m_cond against Ts for both the plates, on the same graph:



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Mathcad Function to find h_vert etc. for Film condensation of steam on a vertical cylinder:

Input: Ts, Tsat (C), L, D (m)

Output: delta_L, h (W/m^2.C), Re_film, Q (W), m_cond (kg/s) in a Matrix

When D >> delta_L, *eqns for vertical plate can be used for vertical cylinder too.*

Let us write a Mathcad Function to calculate various parameters for this case.

$$
\begin{aligned}
&\text{FilmCondensation\_Steam\_VertCyl}(T_s, T_{sat}, L, D) := \\
&\quad \text{return "Ts must be less than Tsat ! " if } T_s - T_{sat} \ge 0 \\
&\quad T_f \leftarrow \frac{T_s + T_{sat}}{2} \\
&\quad rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_f + 273.15)} \\
&\quad rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)} \\
&\quad h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15) \\
&\quad mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_f + 273.15) \\
&\quad k_L \leftarrow k\_f\_H2O(TempK, H2Ok\_f, T_f + 273.15) \\
&\quad cp_L \leftarrow cp\_f\_H2O(TempK, H2Ocp\_f, T_f + 273.15) \\
&\quad Pr_L \leftarrow Pr\_f\_H2O(TempK, H2OPr\_f, T_f + 273.15) \\
&\quad \nu_L \leftarrow \frac{mu_L}{rho_L} \\
&\quad h_{fg\_prime} \leftarrow h_{fg} + 0.68 \cdot cp_L \cdot (T_{sat} - T_s) \\
&\quad g \leftarrow 9.81 \\
&\quad delta_L \leftarrow \left[\frac{4 \cdot mu_L \cdot k_L \cdot (T_{sat} - T_s) \cdot L}{g \cdot rho_L \cdot (rho_L - rho_V) \cdot h_{fg\_prime}}\right]^{\frac{1}{4}} \\
&\quad Re \leftarrow \frac{4 \cdot g \cdot rho_L \cdot (rho_L - rho_V) \cdot delta_L^{\,3}}{3 \cdot mu_L^{\,2}} \\
&\quad h_{vert} \leftarrow 1.47 \cdot Re^{\frac{-1}{3}} \cdot k_L \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}} \text{ if } 0 < Re \le 30 \\
&\quad \text{if } 30 < Re \le 1800 \\
&\quad\quad h_{vert} \leftarrow \frac{Re \cdot k_L}{1.08 \cdot Re^{1.22} - 5.2} \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}} \\
&\quad\quad Re_f \leftarrow \left[4.81 + \frac{3.7 \cdot L \cdot k_L \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}}\right]^{0.82} \\
&\quad \text{if } Re > 1800 \\
&\quad\quad h_{vert} \leftarrow \frac{Re \cdot k_L}{8750 + 58 \cdot Pr_L^{\,-0.5} \cdot (Re^{0.75} - 253)} \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}} \\
&\quad\quad Re_f \leftarrow \left[\frac{0.069 \cdot L \cdot k_L \cdot Pr_L^{\,0.5} \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}} - 151 \cdot Pr_L^{\,0.5} + 253\right]^{\frac{4}{3}} \\
&\quad Q \leftarrow h_{vert} \cdot (L \cdot \pi \cdot D) \cdot (T_{sat} - T_s) \\
&\quad m_{condensed} \leftarrow \frac{Q}{h_{fg\_prime}} \\
&\quad AA \leftarrow \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^{}2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ delta_L & h_{vert} & Re_f & Q & m_{condensed} \end{pmatrix} \\
&\quad AA
\end{aligned}
$$

Note: Above program for vertical cylinder is similar to the one for vertical plate written earlier, except that now, heat transfer area is As = (π.D.L). Then heat transferred, Q and m_cond are calculated as earlier. Study the program shown above.

Prob.3.2.5. Consider a vertical tube, 1 m high, 80 mm dia, maintained at a uniform temp of 50 C, exposed to sat. steam at atm. pressure. Find out the heat transfer and steam condensation rate.

Mathcad Solution:

Let us use the Mathcad Function for condensation on a vertical cylinder, written above:

Data:

$T_s := 50$ C $T_{sat} := 100$ C L := 1 m D := 0.08 m

$$\text{FilmCondensation\_Steam\_VertCyl}(T_s, T_{sat}, L, D) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 2.1742 \times 10^{-4} & 5.6045 \times 10^{3} & 1.1828 \times 10^{3} & 7.0428 \times 10^{4} & 0.0294 \end{pmatrix}$$

We see that:

Re_f = 1182.8 i.e. 30 < Re_f < 1800, so it is 'laminar-wavy' film region.

Heat transfer rate, Q = 70428 W … Ans.

Condensation rate, m_cond = 0.0294 kg/s … Ans.

Plot m_cond against Ts for 20 < Ts < 50 C:

$T_s := 20, 25 .. 50$ C ... define a range variable for Ts

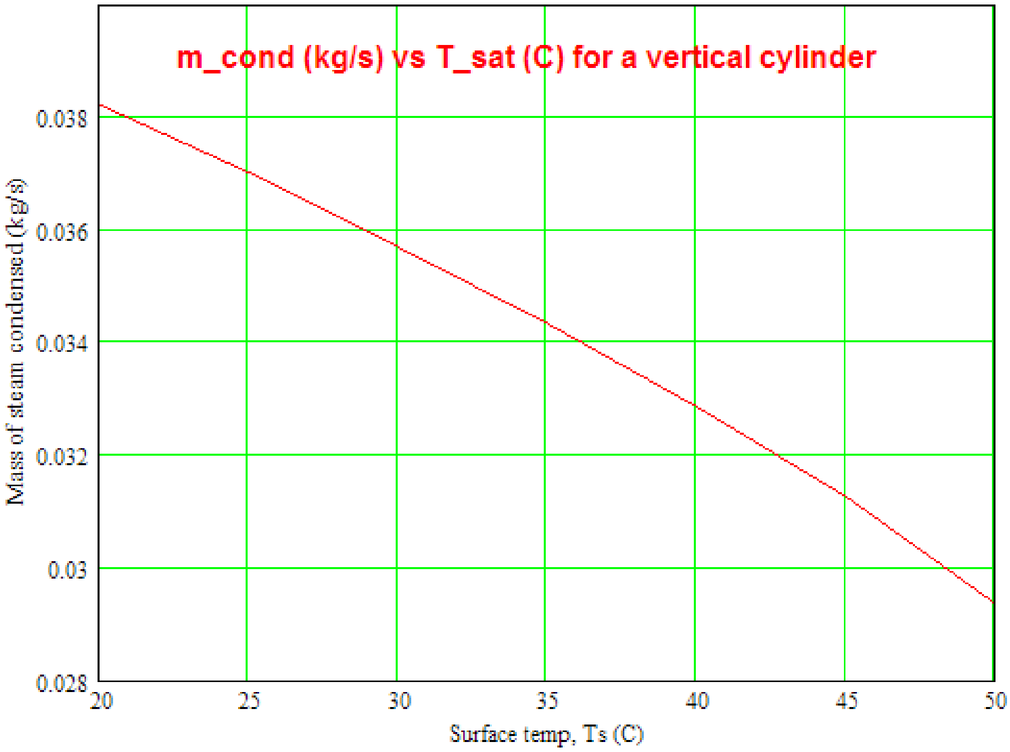
Note that m_cond is element (1,4) in the output Matrix of the above Function.

Remember that numbering of rows and columns starts from zero in Mathcad, by default.

Then, we have:

$T_s =$	$FilmCondensation\_Steam\_VertCyl(T_s, T_{sat}, L, D)_{1,4}$
20	0.038
25	0.037
30	0.036
35	0.034
40	0.033
45	0.031
50	0.029

And, plot the results:



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Prob.3.2.6. Dry, sat. steam at a pressure of 2.45 bar condenses on the surface of a vertical tube of 40 mm dia and height 1 m. Tube surface temp is 117 C. Estimate the thickness of the condensate film and local heat transfer coeff. at a distance of 0.2 m from the upper end of the tube. [VTU – M.Tech. – Dec. 2010]

Mathcad Solution:

At 2.45 bar, sat. temp. of water is: Tsat = 126.75 deg.C. Ts is given as 117 C.

Let us use the Mathcad Function for condensation on a vertical cylinder, written above:

We get:

Data:

$T_s := 117$ C $\quad T_{sat} := 126.75$ C $\quad L := 0.2$ m $\quad D := 0.04$ m

$$FilmCondensation\_Steam\_VertCyl(T_s, T_{sat}, L, D) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 8.929 \times 10^{-5} & 1.1612 \times 10^{4} & 175.9457 & 2.8456 \times 10^{3} & 1.2867 \times 10^{-3} \end{pmatrix}$$

Thus:

Thickness of film at x = 0.2 m = delta_L = 0.0893 mm…..Ans.

Avg. heat transfer coeff = 11341 W/m^2.C

Therefore, local heat transfer coeff is obtained from: h_avg = (4/3).h_x

i.e. h_x = h_avg.(3/4) = 8506 W/m^2.C ….Ans.

==

Prob.3.2.7. A horizontal tube, 3 cm in dia has its surface temp maintained at 30 C. Steam at 7.38 kPa pressure condenses over it. Determine the rate of heat transfer and the rate of condensation per unit length of the tube.

Mathcad Solution:

Let us write a Mathcad Function for condensation of steam on horizontal pipe, using the equation given in the beginning of the Chapter:

Mathcad Function to find h_horizl, Q and m for Film condensation of steam on a horizontal cylinder:

Input: Ts, Tsat (C), D (m)

Output: h (W/m^2.C), Q (W), m_condensed (kg/s)

Note: Take liquid properties at Tf = (Tsat + Ts)/2, and h_fg and vap. properties at Tsat.

$$\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L) :=$$

$$\begin{aligned}
&\text{return "Ts must be less than Tsat ! "} \quad \text{if } T_s - T_{sat} \ge 0\\
&T_f \leftarrow \frac{T_s + T_{sat}}{2}\\
&rho_L \leftarrow \frac{1}{\text{vf_H2O}(\text{TempK}, \text{H2Ov_f}, T_f + 273.15)}\\
&rho_V \leftarrow \frac{1}{\text{vg_H2O}(\text{TempK}, \text{H2Ov_g}, T_{sat} + 273.15)}\\
&h_{fg} \leftarrow \text{h_fg_H2O}(\text{TempK}, \text{H2Oh_fg}, T_{sat} + 273.15)\\
&mu_L \leftarrow \text{mu_f_H2O}(\text{TempK}, \text{H2Omu_f}, T_f + 273.15)\\
&k_L \leftarrow \text{k_f_H2O}(\text{TempK}, \text{H2Ok_f}, T_f + 273.15)\\
&cp_L \leftarrow \text{cp_f_H2O}(\text{TempK}, \text{H2Ocp_f}, T_f + 273.15)\\
&h_{fg_prime} \leftarrow h_{fg} + 0.68 \cdot cp_L \cdot (T_{sat} - T_s)\\
&g \leftarrow 9.81\\
&h_{horizl} \leftarrow 0.729 \cdot \left[\frac{g \cdot rho_L \cdot (rho_L - rho_V) \cdot h_{fg_prime} \cdot k_L^3}{mu_L \cdot (T_{sat} - T_s) \cdot D}\right]^{\frac{1}{4}}\\
&A_s \leftarrow \pi \cdot D \cdot L\\
&Q \leftarrow h_{horizl} \cdot A_s \cdot (T_{sat} - T_s)\\
&m_{cond} \leftarrow \frac{Q}{h_{fg_prime}}\\
&\begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) "} & \text{"m_cond (kg/s)"} \\ h_{horizl} & Q & m_{cond} \end{pmatrix}
\end{aligned}$$

In the above program:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Tf = (Tsat + Ts)/2 is calculated

Line 3 to 8: Various properties of liquid and vapour are calculated using the property Functions for Sat. water already written.

Line 9: Modified heat of evaporation, h_{fg}_prime is calculated here

Line 10: value of g is entered

Line 11: Average heat tr. coeff. h_horizl is calculated

Line 12: Surface area As is calculated

Line 13: Heat transferred, Q is calculated

Line 14: Mass of steam condensed, m_cond is calculatedas: m_cond = (Q/ hfg_prime)

Line 15: Output of the Function is a (2 × 5) Matrix. Its first row contains headings, and second row contains values of h_horizl (W/m^2.C), Q (W)and m_cond (kg/s) respectively.

Now, let us solve the above problem using this Function for horizl cylinder:

At 7.38 kPa, the sat. temp of water is: Tsat = 40 C, and Ts is given as 30 C.

Following is the Mathcad worksheet:

Data:

$T_s := 30$ C $T_{sat} := 40$ C $L := 1$ m $D := 0.03$ m

$$\mathrm{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ 9.308 \times 10^3 & 8.773 \times 10^3 & 3.603 \times 10^{-3} \end{pmatrix}$$

Thus:

Heat transfer coeff. = h_horizl = 9308 W/m^2.C …. Ans.

Heat transferred, Q = 8773 W …. Ans.

Steam condensed = m_cond = 0.003603 kg/s … Ans.

===

Prob.3.2.8. A horizontal tube, 1 m long has its surface temp maintained at 70 C. Sat. steam at 1 atm pressure condenses over it. (a) What is the diameter required to achieve a condensation rate of 125 kg/h? (b) Plot the condensation rate as a function of surface temp for Ts between 70 and 90 C and for diameters of 125, 150 and 175 mm.(Ref. 3)

Mathcad Solution:

First, we shall assume a value for dia, D and then use the Mathcad Function for condensation od steam over horizl cylinders, written above. Then, we will use the 'Solve Block' of Mathcad to get the required dia to achieve 125 kg/h of condensation rate.

Following is the Mathcad worksheet:

Data:

$T_s := 70$ C $T_{sat} := 100$ C $L := 1$ m

$D := 0.03$ **m.....Assumed value**

$$\mathrm{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ 8.8816 \times 10^3 & 2.5112 \times 10^4 & 0.0107 \end{pmatrix}$$

We see that with assumed value of D = 0.03 m, we have m_cond = 0.0107 kg/s

But, we need m_cond = 125 kg/h.

Let us use 'Solve Block' of Mathcad:

Note that in the output Matrix, m_cond is element (1,2) of the Matrix.

Remember that numbering of rows and columns starts from zero in Mathcad, by default.

$m_{cond} := 125$ kg/h ... from data

Given

$$\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L)_{1,2} = \frac{125}{3600}$$

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

$D = 0.144$ m.... dia required to get 125 kg/h condensation.....Ans.

Plot m_cond as a function of Ts for various diameters:

$T_s := 70, 72..90$ C ... define Ts as a range variable

For D = 0.125 m:

$T_s =$	$\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, 0.125, L)_{1,2}$
70	0.031
72	0.03
74	0.028
76	0.027
78	0.025
80	0.024
82	0.022
84	0.02
86	0.018
88	0.016
90	0.014

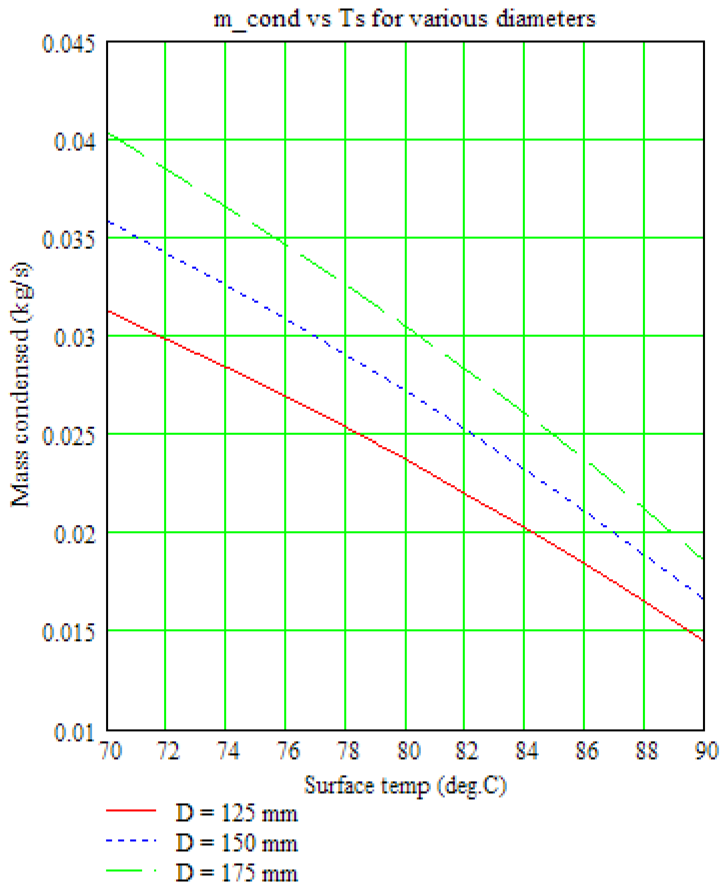
For D = 0.150 m:

T_s =	$FilmCondensation\_Steam\_HorizlCyl\_hQm(T_s, T_{sat}, 0.15, L)_{1,2}$
70	0.036
72	0.034
74	0.033
76	0.031
78	0.029
80	0.027
82	0.025
84	0.023
86	0.021
88	0.019
90	0.017

For D = 0.175 m:

T_s =	$FilmCondensation\_Steam\_HorizlCyl\_hQm(T_s, T_{sat}, 0.175, L)_{1,2}$
70	0.04
72	0.038
74	0.037
76	0.035
78	0.033
80	0.03
82	0.028
84	0.026
86	0.024
88	0.021
90	0.019

Plot the results:



==

Prob.3.2.9. A horizontal tube, 1 m long has its surface temp maintained at 34 C. Sat. steam at 0.2 bar condenses over it. Determine the heat transfer rate and condensation rate.

Mathcad Solution:

At 0.2 bar, we have: T_{sat} = 60 C.

Use the Mathcad Function for a horizl cylinder.

Following is the Mathcad worksheet:

Data:

$T_s := 34$ C $\quad T_{sat} := 60$ C $\quad L := 1$ m $\quad D := 0.05$ m.

$$\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ 6.9336 \times 10^3 & 2.8317 \times 10^4 & 0.0116 \end{pmatrix}$$

Thus:

Heat transfer rate, Q = 28.317 kW/m …. Ans.

Condensation rate, mcond = 0.0116 kg/s …. Ans.

==

Above problem was on condensation on a single, horizontal tube.

But, of **more practical interest** is the condensation on a vertical tier of horizontal tubes.

We come across such a case in heat exchangers, particularly **in steam condensers.**

Let us write a Mathcad Function for condensation on a vertical tier of horizontal tubes:

Condensation on a Tube bank: N horizontal tubes in a vertical tier:

Mathcad Function to find h_horizl, Q, and m for Film condensation of steam on a vertical tier of N horizontal cylinders:

Input: Ts, Tsat (C), D (m), N

Output: h (W/m^2.C), het transferred per Tier, Q_Tier (W/Tier), m_cond (kg/s) per Tier

Note: Take liquid properties at Tf = (Tsat + Ts)/2, and h_fg and vap. properties at Tsat.

FilmCondensation_Steam_VertTierCyl_hQm$(T_s, T_{sat}, D, L, N) :=$

return "Ts must be less than Tsat ! " if $T_s - T_{sat} \geq 0$

$$T_f \leftarrow \frac{T_s + T_{sat}}{2}$$

$$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_f + 273.15)}$$

$$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$$

$$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$$

$$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_f + 273.15)$$

$$k_L \leftarrow k\_f\_H2O(TempK, H2Ok\_f, T_f + 273.15)$$

$$cp_L \leftarrow cp\_f\_H2O(TempK, H2Ocp\_f, T_f + 273.15)$$

$$h_{fg\_prime} \leftarrow h_{fg} + 0.68 \cdot cp_L \cdot (T_{sat} - T_s)$$

$$g \leftarrow 9.81$$

$$h_{horizl\_N} \leftarrow 0.729 \cdot \left[\frac{g \cdot rho_L \cdot (rho_L - rho_V) \cdot h_{fg\_prime} \cdot k_L^{3}}{mu_L \cdot (T_{sat} - T_s) \cdot D \cdot N}\right]^{\frac{1}{4}}$$

$$A_s \leftarrow N \cdot \pi D \cdot L$$

$$Q_{Tier} \leftarrow h_{horizl\_N} \cdot A_s \cdot (T_{sat} - T_s)$$

$$m_{cond} \leftarrow \frac{Q_{Tier}}{h_{fg\_prime}}$$

$$\begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) per Tier"} & \text{"m\_cond (kg/s) per Tier"} \\ h_{horizl\_N} & Q_{Tier} & m_{cond} \end{pmatrix}$$

In the above program:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Tf = (Tsat + Ts)/2 is calculated

Line 3 to 8: Various properties of liquid and vapour are calculated using the property Functions for Sat. water already written.

Line 9: Modified heat of evaporation, h_{fg}_prime is calculated here

Line 10: value of g is entered

Line 11: Average heat tr. coeff. for the tier, h_horizl_N is calculated; note that this eqn is similar to that for a single horizl tube, except that now, D is replaced by (N.D)

Line 12: Surface area As is calculated for the tier (i.e. for N tubes in the tier)

Line 13: Heat transferred for the tier, QTier is calculated

Line 14: Mass of steam condensed for the N tubes of the tier, m_cond is calculatedas: m_cond =

(QTier/ hfg_prime)

Line 15: h, Q and m_cond are returned in a 2 × 3 Matrix. First row of the matrix gives column headings and the second row gives numerical values of h, Q and m_cond respectively.

Prob.3.2.10. Consider a heat exchanger with 20 tubes in a vertical column. Each tube has a dia of 1.5 cm, and is 1 m long. Sat. steam at 50 C condenses on the tubes, which are maintained at a surface temp of 20 C. Determine the average heat transfer coeff and rate of condensation of steam.

Mathcad Solution:

Use the Mathcad Function written above.

The worksheet is shown below:

Data:

$T_s := 20$ C $T_{sat} := 50$ C $L := 1$ m $D := 0.015$ m. $N := 20$

$$\mathrm{FilmCondensation\_Steam\_VertTierCyl\_hQm}(T_s, T_{sat}, D, L, N) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) per Tier"} & \text{"m\_cond (kg/s) per Tier"} \\ 3.99054 \times 10^3 & 1.1283 \times 10^5 & 0.04572 \end{pmatrix}$$

Thus:

Avg. heat transfer coeff. h = 3.99 kW/m^2.C … Ans.

Heat transfer, Q = 112.83 kW/Tier …. Ans.

Steam condensed, m_cond = 0.04572 kg/s = 164.592 kg/h …. Ans.

==

Prob.3.2.11. Condenser of a steam Power plant operates at 4.25 kPa. There are 100 horizontal tubes arranged in a 10 × 10 square array. Each tube is 8 m long, 3 cm in dia. Tube surface is at 20 C. Determine: (a) Rate of heat transfer (b) Rate of condensation of steam (Ref. 2)

Mathcad Solution:

At 4.25 kPa pressure, we have: Tsat = 30 C.

Using the Mathcad Function for N horizontal tubes in a vertical Tier, we get:

Data:

$T_s := 20$ C $T_{sat} := 30$ C $L := 8$ m $D := 0.03$ m. $N := 10$

$$FilmCondensation\_Steam\_VertTierCyl\_hQm(T_s, T_{sat}, D, L, N) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) per Tier"} & \text{"m\_cond (kg/s) per Tier"} \\ 4.89688 \times 10^3 & 3.69216 \times 10^5 & 0.15016 \end{pmatrix}$$

In the above worksheet, we got Q and m_cond per Tier.

But, there are 10 Tiers. So, multiplying the above values by 10, we get:

Heat transferred, Q = 3692.16 kW …. Ans.

Steam condensed, m_cond = 1.5016 kg/s = 5406 kg/h …. Ans.

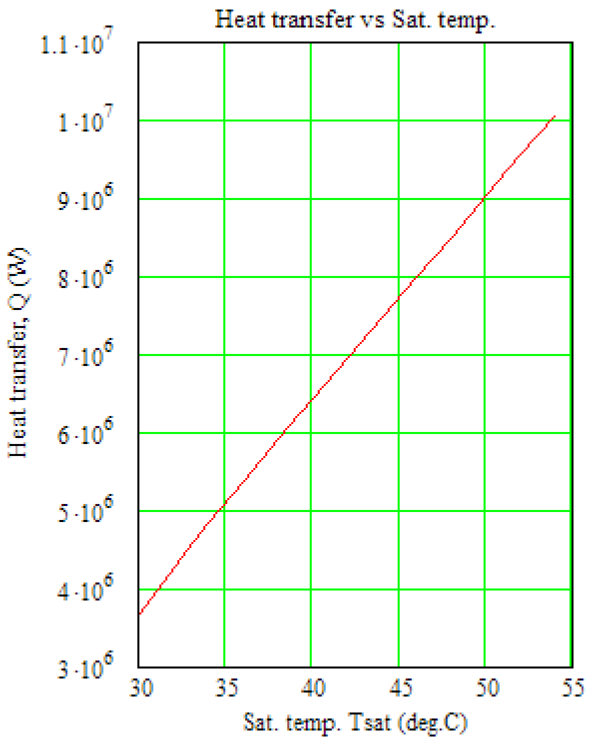
Now, if Tsat varies from 30 C to 54 C (corresponding to sat. pressure of 4.246 kPa to 15.02 kPa respectively), plot Q and mcond against Tsat:

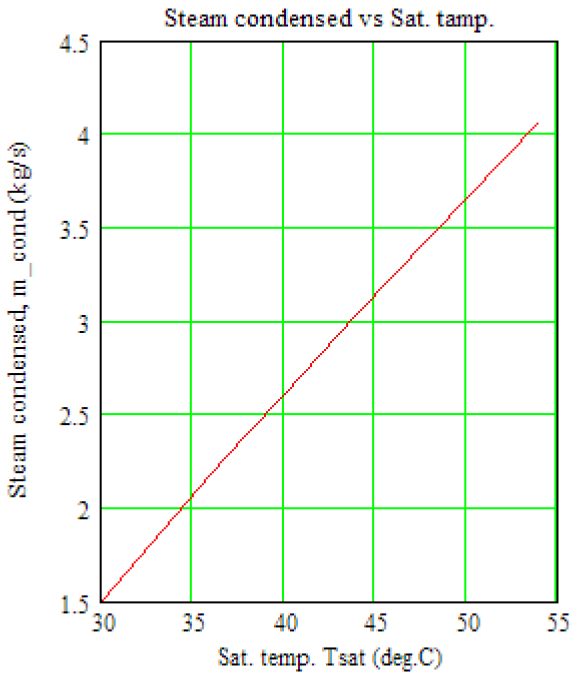
$T_{sat} := 30, 32 .. 54$ C.....define a range variable for Tsat

$T_{sat} =$	$FilmCondensation\_Steam\_VertTierCyl\_hQm(T_s, T_{sat}, D, L, N)_{1,1} \cdot 10$ ....Q for 10 Tiers
30	$3.692 \cdot 10^6$
32	$4.265 \cdot 10^6$
34	$4.825 \cdot 10^6$
36	$5.369 \cdot 10^6$
38	$5.904 \cdot 10^6$
40	$6.434 \cdot 10^6$
42	$6.96 \cdot 10^6$
44	$7.482 \cdot 10^6$
46	$7.998 \cdot 10^6$
48	$8.512 \cdot 10^6$
50	$9.026 \cdot 10^6$
52	$9.54 \cdot 10^6$
54	$1.005 \cdot 10^7$

T_{sat} =	$\text{FilmCondensation\_Steam\_VertTierCyl\_hQm}(T_s, T_{sat}, D, L, N)_{1,2} \cdot 10$ ..m_cond..for 10 Tiers
30	1.502
32	1.734
34	1.961
36	2.181
38	2.398
40	2.612
42	2.824
44	3.035
46	3.243
48	3.451
50	3.658
52	3.865
54	4.071

And, Plot the results:





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Prob.3.2.12. A square array of 400 tubes, 15 mm OD is used to condense steam at atm. pressure. The tube walls are maintained at 88 C by a coolant flowing through the tubes. Calculate the amount of steam condensed per hour per unit length of tubes. [VTU – M.Tech. – Dec. 2009–Jan. 2010]

Mathcad Solution:

There are totally 400 tubes, in a square array.

Therefore, we have: 20 tubes per Tier, and there are 20 Tiers.

Using the Mathcad Function already written, we get:

Data:

$T_s := 88$ C $\quad T_{sat} := 100$ C $\quad L := 1$ m $\quad D := 0.015$ m. $\quad N := 20$

$$\text{FilmCondensation\_Steam\_VertTierCyl\_hQm}(T_s, T_{sat}, D, L, N) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) per Tier"} & \text{"m\_cond (kg/s) per Tier"} \\ 6.42254 \times 10^3 & 7.26372 \times 10^4 & 0.0317 \end{pmatrix}$$

Thus:

Steam condensed = m_cond = 0.0317 kg/s =

$0.0317 \cdot 3600 = 114.12$ **kg/h...Ans.**

==

Prob.3.2.13. Sat. steam at 1.5 bar condenses inside a 75 mm dia horizontal pipe whose surface is maintained at 100 C. Assuming low vapour velocities and film condensation, estimate the heat transfer coeff. and the condensation rate per unit length of the pipe.

Mathcad Solution:

Let us first write a Mathcad Function for film condensation inside horizontal pipe using the equations given at the beginning of the Chapter.

Film condensation inside horizl tubes: Chato's relation:

For low vapour velocities, i.e. Re_vap < 35000: Input: Ts, Tsat (C), D (m), L (m)

Input: Ts, Tsat (C), D (m), L (m)

Output: h_internal (W/m^2.C), Q (W) and m_cond (kg/s)

$$\text{FilmCondensation\_Steam\_InsideHorizlCyl\_hQm}(T_s, T_{sat}, D, L) :=$$

$$\text{return "Ts must be less than Tsat ! " if } T_s - T_{sat} \geq 0$$
$$T_f \leftarrow \frac{T_s + T_{sat}}{2}$$
$$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_f + 273.15)}$$
$$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$$
$$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$$
$$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_f + 273.15)$$
$$k_L \leftarrow k\_f\_H2O(TempK, H2Ok\_f, T_f + 273.15)$$
$$cp_L \leftarrow cp\_f\_H2O(TempK, H2Ocp\_f, T_f + 273.15)$$
$$g \leftarrow 9.81$$
$$h_{fg\_star} \leftarrow h_{fg} + \frac{3}{8} \cdot cp_L \cdot (T_{sat} - T_s)$$
$$h_{internal} \leftarrow 0.555 \cdot \left[\frac{g \cdot rho_L \cdot (rho_L - rho_V) \cdot k_L^{3}}{mu_L \cdot (T_{sat} - T_s) \cdot D} \cdot h_{fg\_star}\right]^{\frac{1}{4}}$$
$$A_s \leftarrow \pi \cdot D \cdot L$$
$$Q \leftarrow h_{internal} \cdot A_s \cdot (T_{sat} - T_s)$$
$$m_{cond} \leftarrow \frac{Q}{h_{fg\_star}}$$
$$\begin{pmatrix} \text{" h (W/m^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ h_{internal} & Q & m_{cond} \end{pmatrix}$$

In the above program:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Tf = (Tsat + Ts)/2 is calculated

Line 3 to 8: Various properties of liquid and vapour are calculated using the property Functions for Sat. water already written.

Line 9: value of g is entered

Line 10: Modified heat of evaporation, h_{fg}_star is calculated here

Line 11: Average heat tr. coeff., h_internal is calculated

Line 12: Surface area As is calculated for the tier (i.e. for N tubes in the tier)

Line 13: Heat transferred, Q is calculated

Line 14: Mass of steam condensed inside the tube, m_cond is calculatedas: m_cond =

(Q/ hfg_star)

Line 15: h, Q and m_cond are returned in a 2 × 3 Matrix. First row of the matrix gives column headings and the second row gives numerical values of h, Q and m_cond respectively.

Now, let us solve the above problem.

Note that corresponding to a pressure of 1.5 bar, for water: T_{sat} = 111.35 C.

Following is the Mathcad worksheet, wherein the above Mathcad Function is invoked:

Data:

$T_s := 100$ C $\quad T_{sat} := 111.35$ C $\quad D := 0.075$ m $\quad L := 1$ m

$$\text{FilmCondensation\_Steam\_InsideHorizlCyl\_hQm}(T_s, T_{sat}, D, L) = \begin{pmatrix} \text{" h (W/m^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ 7.21 \times 10^{3} & 1.928 \times 10^{4} & 8.591 \times 10^{-3} \end{pmatrix}$$

Thus:

Heat transfer coeff, h = 7210 W/m^2.C ….. Ans.

Condensation rate = 0.008591 kg/s = 30.928 kg/h …. Ans.

(b) What is the length of tube required for a condensation rate of 50 kg/h?

Plot m_cond against L for m_cond varying from 10 to 70 kg/h:

We will use the 'Solve Block' of Mathcad to easily calculate the value of L required to get m_cond = 50 kg/h:

$m_{cond} := 50$ kg/h

Given

$$\text{FilmCondensation\_Steam\_InsideHorizlCyl\_hQm}(T_s, T_{sat}, D, L)_{1,2} = \frac{m_{cond}}{3600}$$

$L(m_{cond}) := \text{Find}(L)$

i.e. $L(m_{cond}) = 1.617$ **m….length of tube required to get a condensation rate of 50 kg/h …. Ans.**

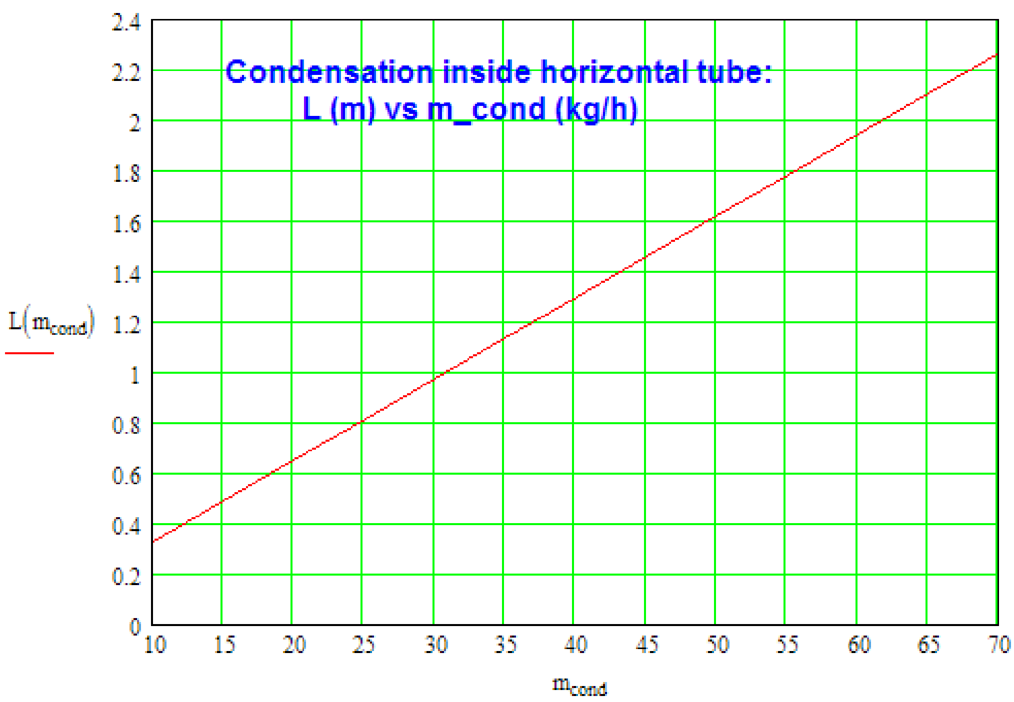
Note: In the above, L is written as function of mcond. It is useful to draw the plot of L against mcond, as shown below:

To plot the results:

Use the function L (m_{cond}) to get values of L for different values of m_{cond}:

$m_{cond} := 10, 15 .. 70$ kg/h.....define a range variable for m_cond

m_{cond} =	$L(m_{cond})$ =
10	0.323
15	0.485
20	0.647
25	0.808
30	0.97
35	1.132
40	1.293
45	1.455
50	1.617
55	1.778
60	1.94
65	2.102
70	2.263



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EES Procedures for Condensation heat transfer:

EES has the advantage that it has built-in Functions for properties of a large number of Fluids and materials.

So, it is very convenient to write Functions/Procedures for complicated equations, particularly if properties have to be calculated many times.

We present below a few Procedures for condensation of steam on a few geometries:

```
$UnitSystem SI Pa C J

PROCEDURE condensation_VP_Fluid(Fluid$,T_sat, T_s, b, L: delta_l, h_avg, Re_f, Q, m_condensed)

"Condensation of any Fluid at T_sat on a vertical Plate (VP) held at T_s:"

"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ ='Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22' etc. etc."
```

```
"Calculates h_avg for laminar, wavy and turbulent film condensation
based on value of Re_f"

"Note: positive x direction is from top of plate downwards; y dirn is from left to right"
"x is the distance from top, b is the breadth of plate perpendicular to paper"

g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"

h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s) "modified h_fg….takes care of nonlinear temp distribn
and liq film subcooling"
delta_l:= ((4 * k_l * mu_l * (T_sat – T_s) * L)/(rho_l * (rho_l – rho_v) * g * h_fg_prime))^(1/4) "[m]….
thickness of b. l. at a
distance L from top"

Re:= (4 * g * rho_l * (rho_l – rho_v) * delta_l^3)/(3 * mu_l^2) "…film Reynolds No."

If (Re> 0) and (Re<= 30) Then "laminar film"

   h_avg:= 1.47 * k_l * Re^(-1/3) * (g/nu_l^2)^(1/3)

Else
```

```
If (Re> 30) and (Re<= 1800) Then "wavy-laminar flow in film"

    h_avg:= ((Re* k_l)/(1.08 *Re^1.22 – 5.2)) * (g/nu_l^2)^(1/3)

    Re_f:= (4.81 + (3.7 * L * k_l * (T_sat – T_s) / (mu_l * h_fg_prime)) *(g / nu_l^2)^(1/3))^0.82

Else

If (Re > 1800) Then "turb. flow in film"

    h_avg:= ((Re * k_l)/(8750 + 58 * Pr_l^(-0.5) * (Re^0.75 – 253))) * (g/nu_l^2)^(1/3)

    Re_f:= (( 0.069* L * k_l * Pr_l^0.5 * (T_sat – T_s) / (mu_l * h_fg_prime)) * (g / nu_l^2)^(1/3) – 151
    * Pr_l^0.5 + 253)^(4/3)

EndIf
EndIf
EndIf

Q:= h_avg *(b * L) * (T_sat – T_s) "W"

m_condensed:= Q/h_fg_prime "kg/s"

END

"-----------------------------------------------------------------------------------------------------------------------------"

"Condensation on Vertical cylinder (VC):"

PROCEDURE condensation_VC_Fluid(Fluid$,T_sat, T_s, D, L: delta_l, h_avg, Q, mass_condensed)

"Condensation of any Fluid at T_sat on a vertical cyl held at T_s:"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ = 'Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22' etc. etc."

g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2
```

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"

h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s)"modified h_fg….takes care of nonlinear temp distribn and liq film subcooling"
delta_l:= ((4 * k_l * mu_l * (T_sat – T_s) * L)/(rho_l * (rho_l – rho_v) * g * h_fg_prime))^(1/4) "[m]…. thickness of b. l. at a
distance L from top"

```
Re:= (4 * g * rho_l * (rho_l – rho_v) * delta_l^3)/(3 * mu_l^2) "…film Reynolds No."

If (Re > 0) and (Re <= 30) Then "laminar film"

    h_avg:= 1.47 * k_l * Re^(-1/3) * (g/nu_l^2)^(1/3)

Else

 If (Re > 30) and (Re <= 1800) Then "wavy-laminar flow in film"

    h_avg:= ((Re * k_l)/(1.08 *Re^1.22 – 5.2)) * (g/nu_l^2)^(1/3)

    Re_f:= (4.81 + (3.7 * L * k_l * (T_sat – T_s) / (mu_l * h_fg_prime)) *(g / nu_l^2)^(1/3))^0.82

Else

 If (Re > 1800) Then "turb. flow in film"

    h_avg:= ((Re * k_l)/(8750 + 58 * Pr_l^(-0.5) * (Re^0.75 – 253))) * (g/nu_l^2)^(1/3)

    Re_f:= ((0.069* L * k_l * Pr_l^0.5 * (T_sat – T_s) / (mu_l * h_fg_prime)) * (g / nu_l^2)^(1/3) – 151
    * Pr_l^0.5 + 253)^(4/3)

EndIf
EndIf
EndIf

Q = h_avg * (pi * D *L)*(T_sat – T_s) "W"

mass_condensed = Q/h_fg_prime "kg/s"

END

"-------------------------------------------------------------------------------------------------------------------"

PROCEDURE condensation_HC_Fluid(Fluid$,T_sat, T_s, D, L: h_avg, Q, mass_condensed)

"Condensation of any Fluid at T_sat on a horizontal cyl at T_s:"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ ='Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22'
etc. etc."
```

```
g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"

h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s) "modified h_fg….takes care of nonlinear temp distribn and liq film subcooling"
h_avg:= 0.729 * ((g * rho_l *(rho_l – rho_v) * h_fg_prime * k_l^3)/(mu_l * (T_sat – T_s) * D))^(1/4) "[W/m^2-C] …. avg heat tr coeff over L"
Q = h_avg * (pi * D *L)*(T_sat – T_s) "W"
mass_condensed = Q/h_fg_prime "kg/s"
END

"-------------------------------------------------------------------------------------------------------------------------------"

"Condensation on a Tube bank: N Horizontal Tubes in a vertical tier"

PROCEDURE condensation_HTBank_Fluid(Fluid$,T_sat, T_s, D, L, N, N_total: h_avg, Q, mass_condensed)

"Condensation of any Fluid at T_sat on a Bank of horizl tubes:"
"Condensation on a Tube bank: N horizontal tubes in a vertical tier"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ ='Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22' etc. etc."
```

```
"N horizontal tubes in a vertical tier:"
"N_toal is the total no. of tubes in the tube bank"

g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"

h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s) "modified h_fg….takes care of nonlinear temp distribn and liq film subcooling"
h_avg:= 0.729 * ((g * rho_l *(rho_l – rho_v) * h_fg_prime * k_l^3)/(mu_l * (T_sat – T_s) * N* D))^(1/4) "[W/m^2-C] …. avg heat tr coeff over L"
Q = h_avg * (N_total *pi * D *L)*(T_sat – T_s) "W"
mass_condensed = Q/h_fg_prime "kg/s"
END

"-----------------------------------------------------------------------------------------------------------------------------"

"Condensation on a Sphere:"

PROCEDURE condensation_Sphere_Fluid(Fluid$,T_sat, T_s, D: h_avg, Q, mass_condensed)

"Condensation of any Fluid at T_sat on a Sphere maintained at T_s:"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ = 'Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22' etc. etc."
```

```
g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"
```

```
h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s) "modified h_fg....takes care of nonlinear temp distribn and liq film subcooling"
h_avg:= 0.826 * ((g * rho_l *(rho_l – rho_v) * h_fg_prime * k_l^3)/(mu_l * (T_sat – T_s) * D))^(1/4)
"[W/m^2-C] .... avg heat tr coeff over the sphere"
Q = h_avg * (pi * D^2)*(T_sat – T_s) "W"
mass_condensed = Q/h_fg_prime "kg/s"
END

"=================================================================="

$UnitSystem SI Pa C J

PROCEDURE condensation_InsideHCyl(Fluid$,T_sat, T_s, D, L, U_v: h_avg, Q, mass_condensed)

"Condensation of any Fluid at T_sat inside a Horizontal Cyl at T_s:"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ = 'Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22' etc. etc."

g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
mu_v:=Viscosity(Fluid$,T=T_sat,x=1) "[kg/m-s]"

h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"
```

```
h_fg_prime:= h_fg + (3/8) * cp_l * (T_sat – T_s) "modified h_fg….takes care of nonlinear temp distribn and liq film subcooling"

Re_vap:= rho_v * U_v * D/mu_v "..Vapour Reynolds No…must be < 35000!!"

If (Re_vap <= 35000) Then

h_avg:= 0.555 * ((g * rho_l *(rho_l – rho_v) * h_fg_prime * k_l^3)/(mu_l * (T_sat – T_s) * D))^(1/4) "[W/m^2-C] …. avg internal heat tr coeff over L"

Else

If (Re_vap > 35000) Then

    CALL ERROR('Re_vap must be <= 35000. Now, Re_vap = XXXA6',Re_vap)

    EndIf

EndIf

Q:= h_avg * (pi * D * L)*(T_sat – T_s) "W"

mass_condensed:= Q/h_fg_prime "kg/s"

END

"==================================================================="
```

Now, let us solve a few problems using these EES Procedures:

Prob. 3.2.14. Sat. steam at atm pressure condenses on a 2 m high, 3 m wide vertical plate maintained at 80 C. Determine the avg heat transfer coeff., rate of heat transfer and the rate of condensation.

(b) If the plate is inclined to vertical at 30 deg. what will be these value s?

(c) For the case (a) draw the variation of condensation rate against Ts for 50 < Ts < 90 C.

EES Solution:

T_sat = 100 C since pressure is 1 atm.

Use the EES Procedure written above.

We have:

"Data:"

T_sat = 100 [C]
T_s = 80 [C]
b = 3 [m]
L = 2 [m]

Fluid$ = 'Steam_IAPWS'

CALL condensation_VP_Fluid(Fluid$,T_sat, T_s, b, L: delta_l, h_avg, Re_f, Q, m_condensed)

Results:

Main | condensation_VP_Fluid

Unit Settings: SI C Pa J mass deg

b = 3 [m]	δ_l = 0.0002002 [m]	Fluid$ = 'Steam_IAPWS'
h_{avg} = 6207 [W/m²-C]	L = 2 [m]	$m_{condensed}$ = 0.3219 [kg/s]
Q = 744860 [W]	Re_f = 1291	T_s = 80 [C]
T_{sat} = 100 [C]		

Main | condensation_VP_Fluid

Local variables in Procedure condensation_VP_Fluid (1 call, 0.02 sec)

b=3 [m]	cp_l =4205 [J/kg-C]	δ_l =0.0002002 [m]
Fluid$='Steam_IAPWS'	g=9.81 [m/s^2]	h_{avg} =6207 [W/m^2-C]
h_f =419169 [J/kg]	h_{fg} =2.256E+06 [J/kg]	$h_{fg'}$ =2.314E+06 [J/kg]
h_g=2.676E+06 [J/kg]	k_l =0.6752 [W/m-C]	L=2 [m]
μ_l =0.0003144 [kg/m-s]	$m_{condensed}$=0.3219 [kg/s]	ν_l =3.257E-07 [m^2/s]
Pr_f=1.958	Q =744860 [W]	Re =989.1
Re_f=1291	ρ_l =965.3 [kg/m^3]	ρ_v=0.5981 [kg/m^3]
T_f=90 [C]	T_s=80 [C]	T_{sat} =100 [C]

Thus:

h_avg = 6207 W/m^2-C….ans.

Q = 744860 W…ns.

m_cond = 0.3219 kg/s…..Ans.

(b) If the plate is tilted at 30 deg. to vertical, heat tr. coeff. for that case is:

h_inclined = h_vert * (cos(30))^(1/4).

Modify the program above as shown below:

"Data:"

T_sat = 100 [C]
T_s = 80 [C]
b = 3 [m]
L = 2 [m]

Fluid$ = 'Steam_IAPWS'

CALL condensation_VP_Fluid(Fluid$,T_sat, T_s, b, L: delta_l, h_avg, Re_f, Q, m_condensed)

"For part (b)…plate inclined at 30 deg to vertical:"

h_fg_prime2 = 2.314E06 [J/kg] "…This is the same as h_fg_prime in part (a), copied from there"

theta = 30 [deg]

h_inclined = h_avg * (cos (theta))^(1/4)

Q_inclined = h_inclined * (L * b) * (T_sat – T_s)

m_cond_inclined = Q_inclined /h_fg_prime2

So, we get:

Main | condensation_VP_Fluid

Unit Settings: SI C Pa J mass deg

b = 3 [m]	δ_l = 0.0002002 [m]	Fluid$ = 'Steam_IAPWS'
h_{avg} = 6207 [W/m^2-C]	$h_{fg,prime2}$ = 2.314E+06 [J/kg]	$h_{inclined}$ = 5988 [W/m^2-C]
L = 2 [m]	$m_{condensed}$ = 0.3219 [kg/s]	$m_{cond,inclined}$ = 0.3105 [kg/s]
Q = 744860 [W]	$Q_{inclined}$ = 718551 [W]	Re_f = 1291
θ = 30 [deg]	T_s = 80 [C]	T_{sat} = 100 [C]

Main | condensation_VP_Fluid

Local variables in Procedure condensation_VP_Fluid (1 call, 0.02 sec)

b=3 [m]	cp_l =4205 [J/kg-C]	δ_l =0.0002002 [m]
Fluid$='Steam_IAPWS'	g=9.81 [m/s^2]	h_{avg} =6207 [W/m^2-C]
h_f =419169 [J/kg]	h_{fg} =2.256E+06 [J/kg]	$h_{fg'}$ =2.314E+06 [J/kg]
h_g=2.676E+06 [J/kg]	k_l =0.6752 [W/m-C]	L=2 [m]
μ_l =0.0003144 [kg/m-s]	$m_{condensed}$=0.3219 [kg/s]	ν_l =3.257E-07 [m^2/s]
Pr_l=1.958	Q =744860 [W]	Re =989.1
Re_f=1291	ρ_l =965.3 [kg/m^3]	ρ_v=0.5981 [kg/m^3]
T_f=90 [C]	T_s=80 [C]	T_{sat} =100 [C]

So,

h_inclined = 5988 W/m^2-C….ans.

Q_inclined = 718551 W…ns.

m_cond = 0.3105 kg/s…..Ans.

P lot m_cond vs Ts for case (a), with 50 < Ts < 90 C:

First, construct the Parametric Table:

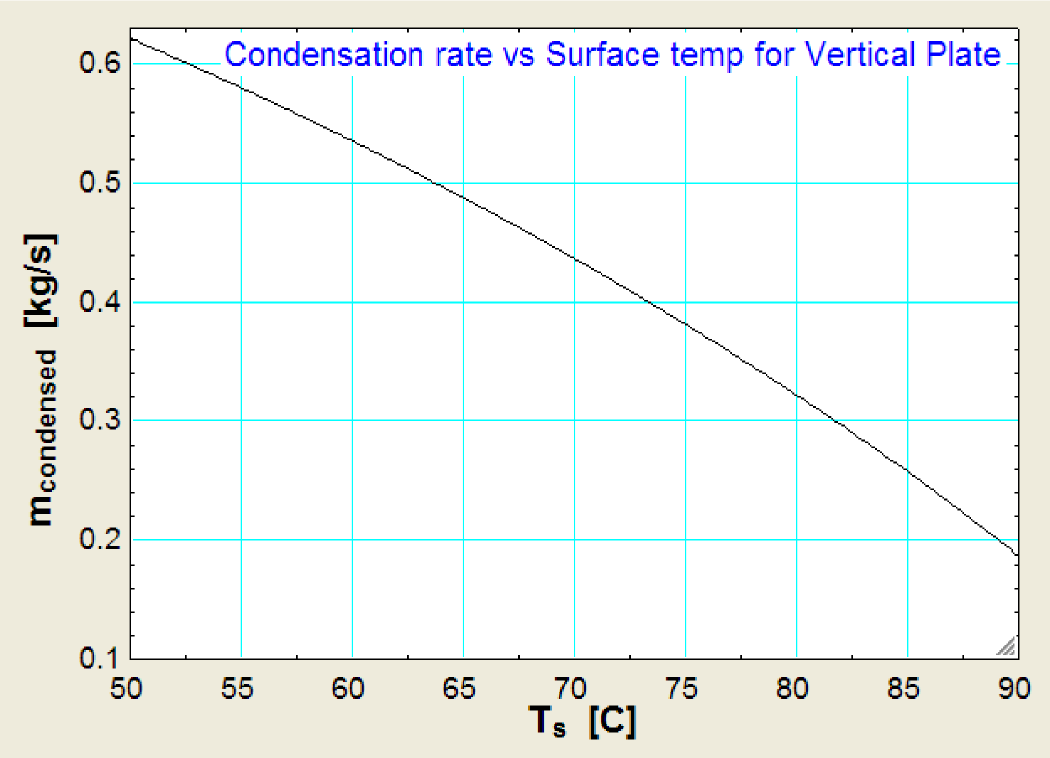
Parametric Table

Table 1

1..9	T_s [C]	h_{avg} [W/m2-C]	Q [W]	$m_{condensed}$ [kg/s]
Run 1	50	4968	1.490E+06	0.6213
Run 2	55	5121	1.383E+06	0.5798
Run 3	60	5287	1.269E+06	0.5353
Run 4	65	5471	1.149E+06	0.4876
Run 5	70	5678	1.022E+06	0.4363
Run 6	75	5918	887635	0.3813
Run 7	80	6207	744860	0.3219
Run 8	85	6579	592094	0.2575
Run 9	90	7109	426522	0.1867

Note that in the same Table, we have obtained the values of h_avg and Q also for various values of Ts.

Now, plot the results:



==

Prob. 3.2.15. Refrigerant-12 (R12) condenses on a vertical plate (size: 1 m × 1 m) at 40 C. Plate is held at 20 C. Determine the value of heat transfer coeff and the condensation rate.

EES Solution:

Use the EES procedure for vertical plate as in the previous problem.

For Fluid$ take Fluid$ = 'R12'

Following is the program:

"Data:"

T_sat = 40 [C]
T_s = 20 [C]
b = 1 [m]
L = 1 [m]

Fluid$ = 'R12'

CALL condensation_VP_Fluid(Fluid$,T_sat, T_s, b, L: delta_l, h_avg, Re_f, Q, m_condensed)

Press F2 and we get:

Main | condensation_VP_Fluid

Unit Settings: SI C Pa J mass deg

b = 1 [m]	δ_l = 0.0001503 [m]	Fluid$ = 'R12'
h_{avg} = 882.4 [W/m^2-C]	L = 1 [m]	$m_{condensed}$ = 0.1245 [kg/s]
Q = 17648 [W]	Re_f = 2205	T_s = 20 [C]
T_{sat} = 40 [C]		

Main | condensation_VP_Fluid

Local variables in Procedure condensation_VP_Fluid (1 call, 0.05 sec)

b=1 [m]	cp_l =969.4 [J/kg-C]	δ_l =0.0001503 [m]
Fluid$='R12'	g=9.81 [m/s^2]	h_{avg} =882.4 [W/m^2-C]
h_f =74571 [J/kg]	h_{fg} =128625 [J/kg]	$h_{fg'}$ =141809 [J/kg]
h_g=203196 [J/kg]	k_l =0.06732 [W/m-C]	L=1 [m]
μ_l =0.0002109 [kg/m-s]	$m_{condensed}$=0.1245 [kg/s]	ν_l =1.632E-07 [m^2/s]
Pr_l=3.037	Q =17648 [W]	Re =1597
Re_f=2205	ρ_l =1292 [kg/m^3]	ρ_v=55.01 [kg/m^3]
T_f=30 [C]	T_s=20 [C]	T_{sat} =40 [C]

Thus:

h_avg = 882.4 W/m^2-C….Ans.
Q = 17648 W…Ans.
m_cond = 0.1245 kg/s…..Ans.

==

Prob. 3.2.16. Sat. steam at 55 C is to be condensed at a rate of 10 kg/h on the outside of a 3 cm OD vertical tube whose surface is maintained at 45 C. Determine the tube length required.

EES Solution:

Use the EES Procedure written above.

We have:

"Data:"

T_sat = 55 [C]
T_s = 45 [C]

D = 0.03 [m]

Fluid$ = 'Steam_IAPWS'

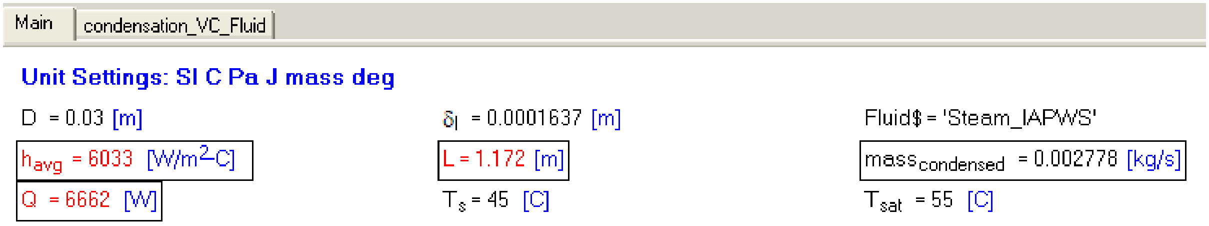
mass_condensed = 10 * convert(kg/h, kg/s)

CALL condensation_VC_Fluid(Fluid$,T_sat, T_s, D, L: delta_l, h_avg, Q, mass_condensed)

Note: In the above CALL to the Procedure, input L is not known; however, output: mass_condensed is known. It is converted to kg/s from kg/h, since all units are required to be in SI and mass rate is kg/s.

Observe the ease with which EES does these calculations of trial and error.

We get, on clicking F2 to solve:



Main | condensation_VC_Fluid

Local variables in Procedure condensation_VC_Fluid (5 calls, 0.02 sec)

cp_l =4182 [J/kg-C]	D =0.03 [m]	δ_l =0.0001637 [m]
Fluid$='Steam_IAPWS'	g=9.81 [m/s^2]	h_{avg} =6033 [W/m^2-C]
h_f =230259 [J/kg]	h_{fg} =2.370E+06 [J/kg]	$h_{fg'}$ =2.398E+06 [J/kg]
h_g=2.600E+06 [J/kg]	k_l =0.6435 [W/m-C]	L=1.172 [m]
$mass_{condensed}$ =0.002778 [kg/s]	μ_l =0.0005468 [kg/m-s]	ν_l =5.535E-07 [m^2/s]
Pr_F3.553	Q =6662 [W]	Re =187.3
Re_f=210.3	ρ_l =988 [kg/m^3]	ρ_v=0.1046 [kg/m^3]
T_f=50 [C]	T_s=45 [C]	T_{sat} =55 [C]

Thus: Length of tube required = L = 1.172 m ….. Ans.

Note that h, Q, mass_cond, and all properties are also immediately available. This becomes very convenient for verification, in case we get any unreasonable results.

(b) Keeping the tube length as 1.172 m just obtained, plot mass condensed against Ts for tube diameters of 2 cm, 3 cm and 4 cm:

Let Ts vary from 25 C to 50 C:

We modify the program as follows:

"Data:"

```
T_sat = 55 [C]
{T_s = 45 [C]}
D = 0.03 [m]
L = 1.172[m]

{mass_condensed = 10 * convert(kg/h, kg/s)}

Fluid$ = 'Steam_IAPWS'

CALL condensation_VC_Fluid(Fluid$,T_sat, T_s, D, L: delta_l, h_avg, Q, mass_condensed)
```

Note that in the above program, Ts is 'commented out' since it is the variable in the Parametric Table.

L is entered as 1.21 m. Then, we call the Procedure to get mass_condensed.

Following are the 3 parametric Tables for D = 2, 3 and 4 cm:

D = 2cm:

Parametric Table

Table 1 - D = 2 cm | Table 2 - D = 3 cm | Table

1..6	T_s [C]	$mass_{condensed}$ [kg/s]
Run 1	25	0.004162
Run 2	30	0.003674
Run 3	35	0.003132
Run 4	40	0.00253
Run 5	45	0.001852
Run 6	50	0.001071

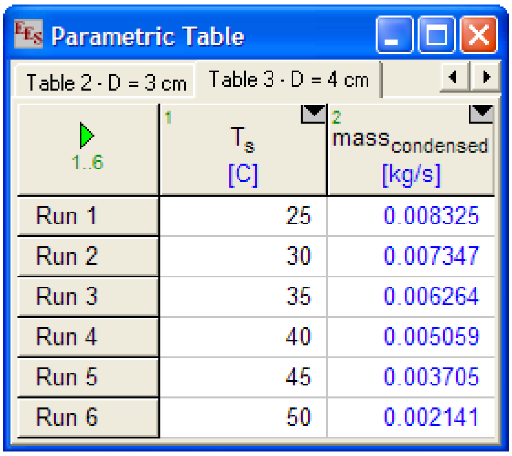
D = 3cm:

Parametric Table

Table 1 - D = 2 cm | Table 2 - D = 3 cm | Table

1..6	T_s [C]	$mass_{condensed}$ [kg/s]
Run 1	25	0.006243
Run 2	30	0.00551
Run 3	35	0.004698
Run 4	40	0.003794
Run 5	45	0.002779
Run 6	50	0.001606

D = 4 cm:

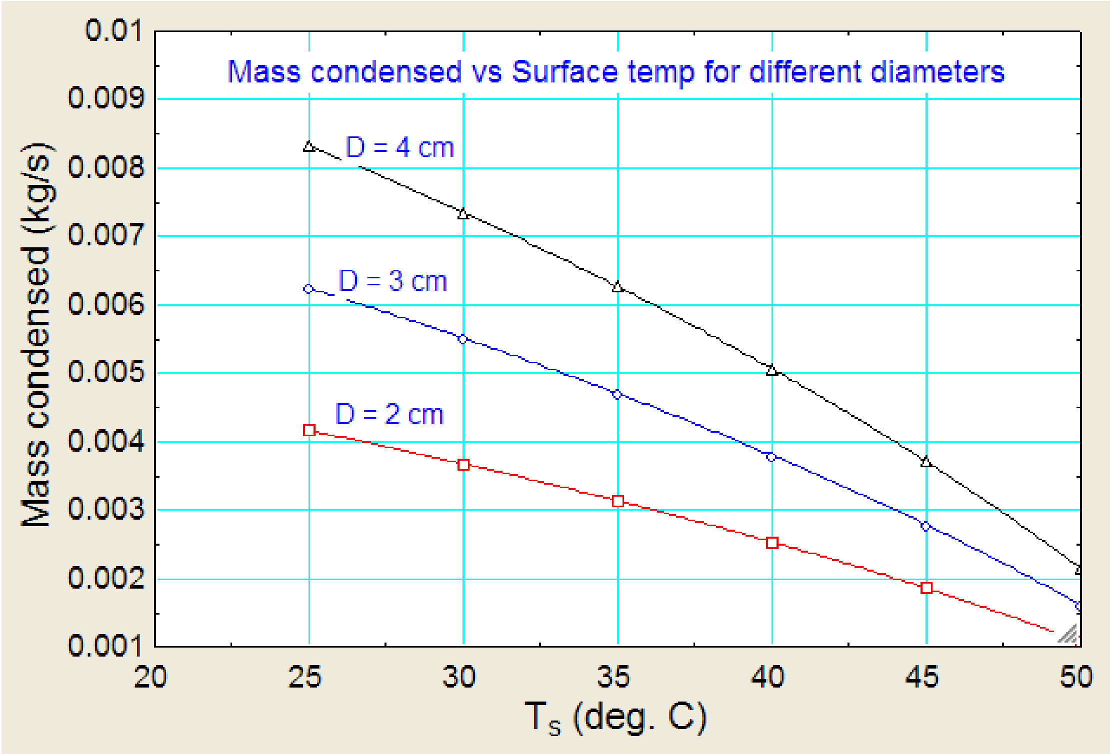


Parametric Table

Table 2 - D = 3 cm | Table 3 - D = 4 cm

1..6	T_s [C]	$mass_{condensed}$ [kg/s]
Run 1	25	0.008325
Run 2	30	0.007347
Run 3	35	0.006264
Run 4	40	0.005059
Run 5	45	0.003705
Run 6	50	0.002141

Now, plot them on the same plot:



==

Prob.3.2.17. A horizontal tube, 1 m long has its surface temp maintained at 70 C. Sat. steam at 1 atm pressure condenses over it. (a) What is the diameter required to achieve a condensation rate of 125 kg/h? (b) Plot the condensation rate as a function of surface temp for Ts between 70 and 90 C and for diameters of 125, 150 and 175 mm. (Ref. 3)

EES Solution:

This is the same as Prob. 3.2.8, which was solved with Mathcad.

Now, we shall solve it with EES, using the Procedure for a horizontal cylinder written above.

Following is the EES program with a call to the Procedure:

"Data:"

T_sat = 100 [C]
T_s = 70 [C]
L = 1[m]

Fluid$ = 'Steam_IAPWS'

mass_condensed = 125 * convert(kg/h, kg/s)

CALL condensation_HC_Fluid(Fluid$,T_sat, T_s, D, L: h_avg, Q, mass_condensed)

Note that, in the above program, one of the inputs, viz. D is not known; however, one of the outputs i.e. mass_condensed is given. It is converted here from kg/h to kg/s since SI units are to be used throughout.

It is interesting to see the ease with which this is solved with EES:

Click F2 to solve:

We get:

Main | condensation_HC_Fluid

Unit Settings: SI C Pa J mass deg

D = 0.1441 [m]	Fluid$ = 'Steam_IAPWS'	h_{avg} = 5988 [W/m^2-C]
L = 1 [m]	$mass_{condensed}$ = 0.03472 [kg/s]	Q = 81324 [W]
T_s = 70 [C]	T_{sat} = 100 [C]	

Main | condensation_HC_Fluid

Local variables in Procedure condensation_HC_Fluid (12 calls, 0.03 sec)

cp_l =4201 [J/kg-C]	D =0.1441 [m]	Fluid$='Steam_IAPWS'
g=9.81 [m/s^2]	h_{avg} =5988 [W/m^2-C]	h_f =419169 [J/kg]
h_{fg} =2.256E+06 [J/kg]	h_{fg}' =2.342E+06 [J/kg]	h_g=2.676E+06 [J/kg]
k_l =0.6728 [W/m-C]	L=1 [m]	$mass_{condensed}$ =0.03472 [kg/s]
μ_l =0.0003333 [kg/m-s]	ν_l =3.441E-07 [m^2/s]	Pr_F=2.081
Q =81324 [W]	ρ_l =968.6 [kg/m^3]	ρ_v=0.5981 [kg/m^3]
T_f=85 [C]	T_s=70 [C]	T_{sat} =100

Thus:

Dia of tube to get a condensation rate of 125 kg/h (i.e. 0.03472 kg/s) is = D = 0.1441 m …Ans.

Note: This matches with the result we got with Mathcad earlier.

To plot mass_cond vs Ts for = 125, 150 and 175 mm:

Compute the Parametric Tables for these three diameters:

Modify the earlier program as follows:

"Data:"

T_sat = 100 [C]
{T_s = 70 [C]}
L = 1[m]
D = 0.125 [m]

Fluid$ = 'Steam_IAPWS'

CALL condensation_HC_Fluid(Fluid$,T_sat, T_s, D, L: h_avg, Q, mass_condensed)

In the above, D is entered as 0.125 m. Ts is 'commented out' since it is now the variable for the Parametric Table.

We have 3 Parametric Tables for three values of Diameters:

D = 125 mm:

Parametric Table

Table 1 - D = 125 mm | Table 2 - D = 150 mm

1..11	T_s [C]	$mass_{condensed}$ [kg/s]
Run 1	70	0.03121
Run 2	72	0.02979
Run 3	74	0.02832
Run 4	76	0.0268
Run 5	78	0.02523
Run 6	80	0.02361
Run 7	82	0.02192
Run 8	84	0.02016
Run 9	86	0.01833
Run 10	88	0.0164
Run 11	90	0.01438

D = 150 mm:

Parametric Table

Table 1 - D = 125 mm | Table 2 - D = 150 mm

1..11	T_s [C]	$mass_{condensed}$ [kg/s]
Run 1	70	0.03578
Run 2	72	0.03415
Run 3	74	0.03247
Run 4	76	0.03073
Run 5	78	0.02893
Run 6	80	0.02706
Run 7	82	0.02513
Run 8	84	0.02312
Run 9	86	0.02101
Run 10	88	0.01881
Run 11	90	0.01648

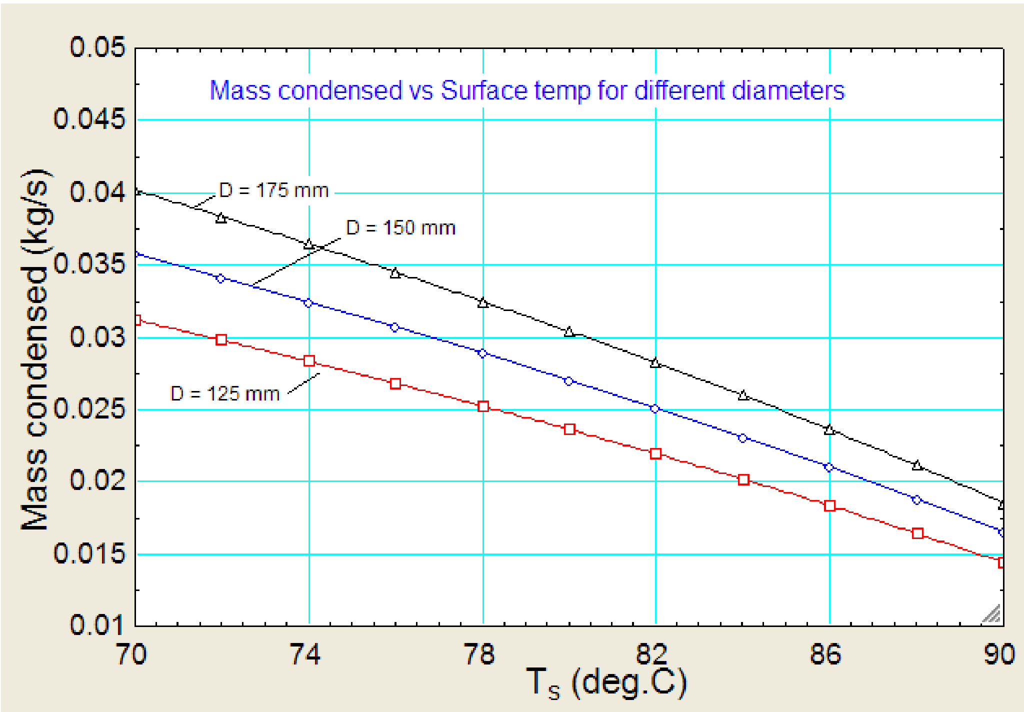
D = 175 mm:

Parametric Table

Table 2 - D = 150 mm | Table 3- D = 175 mm

1..11	T_s [C]	$mass_{condensed}$ [kg/s]
Run 1	70	0.04017
Run 2	72	0.03834
Run 3	74	0.03645
Run 4	76	0.03449
Run 5	78	0.03247
Run 6	80	0.03038
Run 7	82	0.02821
Run 8	84	0.02595
Run 9	86	0.02359
Run 10	88	0.02111
Run 11	90	0.0185

Now, plot the results:



Note: These results match with those obtained with Mathcad in Prob. 3.2.8.

==

Prob. 3.2.18. Sat. NH3 vapour at 10 C condenses on the outside of a 2 cm dia, 5 m long horizontal tube whose surface is maintained at -10 C. Determine: (a) rate of heat transfer (b) rate of condensation. (Ref. 2)

EES Solution:

Use the EES procedure written for condensation of a Fluid on the outside of a horizl cylinder:

"Data:"

T_sat = 10 [C]
T_s = -10 [C]
L =5 [m]
D = 0.02 [m]

Fluid$ = 'Ammonia'

CALL condensation_HC_Fluid(Fluid$,T_sat, T_s, D, L: h_avg, Q, mass_condensed)

Press F2 to solve, and we get:

Main | condensation_HC_Fluid

Unit Settings: SI C Pa J mass deg

D = 0.02 [m]	Fluid$ = 'Ammonia'	h_{avg} = 7807 [W/m^2-C]
L = 5 [m]	$mass_{condensed}$ = 0.03808 [kg/s]	Q = 49050 [W]
T_s = -10 [C]	T_{sat} = 10 [C]	

Main | condensation_HC_Fluid

Local variables in Procedure condensation_HC_Fluid (1 call, 0.03 sec)

cp_l =4615 [J/kg-C]	D =0.02 [m]	Fluid$='Ammonia'
g=9.81 [m/s^2]	h_{avg} =7807 [W/m^2-C]	h_f =246379 [J/kg]
h_{fg} =1.225E+06 [J/kg]	$h_{fg'}$ =1.288E+06 [J/kg]	h_g=1.472E+06 [J/kg]
k_l =0.5594 [W/m-C]	L=5 [m]	$mass_{condensed}$ =0.03808 [kg/s]
μ_l =0.0001702 [kg/m-s]	ν_l =2.666E-07 [m^2/s]	Pr_l=1.405
Q =49050 [W]	ρ_l =638.7 [kg/m^3]	ρ_v=4.885 [kg/m^3]
T_f=0 [C]	T_s=-10 [C]	T_{sat} =10

Thus:

h_avg = 7807 W/m^2-C….Ans.

Q = 49050 W…Ans.

m_cond = 0.03808 kg/s

==

Prob. 3.2.19. A steam condenser consists of a square array of 400 horizontal tubes, each 6 mm in diameter. The tubes are exposed to exhaust steam arriving from the turbine at a pressure of 0.1 bar. If the tube surface temperature is maintained at a temperature of 25 C by circulating cold water through the tubes, determine the heat transfer coefficient and the rate at which the steam is condensed per unit length of tubes for the entire array. Assume laminar film condensation and that there are no condensable gases mixed with steam. (Ref. 1)

EES Solution:

Now, we shall solve this problem using the Procedure for an array of horizontal cylinders in a vertical tier, written above.

Following is the EES program with a call to the Procedure:

```
"Data:"

T_sat = 45.8 [C]"..Tsat for Water at a pressure of 0.1 bar"
T_s = 25 [C]
L = 1[m]
D = 0.006 [m]
N_total = 400
N = 20 " i.e. N = 400^0.5, since there are 400 tubes in a square array."
Fluid$ = 'Steam_IAPWS'

CALL condensation_HTBank_Fluid(Fluid$,T_sat, T_s, D, L, N, N_total: h_avg, Q, mass_condensed)
```

Click F2 to solve, and we get:

Main | condensation_HTBank_Fluid

Unit Settings: SI C Pa J mass deg

D = 0.006 [m]	Fluid$ = 'Steam_IAPWS'	h_{avg} = 5499 [W/m^2-C]
L = 1 [m]	$mass_{condensed}$ = 0.3518 [kg/s]	N = 20
N_{total} = 400	Q = 862415 [W]	T_s = 25 [C]
T_{sat} = 45.8 [C]		

Main | condensation_HTBank_Fluid

Local variables in Procedure condensation_HTBank_Fluid (1 call, 0.02 sec)

cp_l =4180 [J/kg-C]	D =0.006 [m]	Fluid$='Steam_IAPWS'
g=9.81 [m/s^2]	h_{avg} =5499 [W/m^2-C]	h_f =191782 [J/kg]
h_{fg} =2.392E+06 [J/kg]	$h_{fg'}$ =2.451E+06 [J/kg]	h_g=2.584E+06 [J/kg]
k_l =0.6239 [W/m-C]	L=1 [m]	$mass_{condensed}$ =0.3518 [kg/s]
μ_l =0.0007136 [kg/m-s]	N =20	ν_l =7.180E-07 [m^2/s]
N_{total} =400	Pr=4.781	Q =862415 [W]
ρ_l =993.8 [kg/m^3]	ρ_v=0.06815 [kg/m^3]	T_f=35.4 [C]
T_s=25 [C]	T_{sat} =45.8 [C]	

Thus:

Heat transfer coeff., h_avg = 5499 W/m^2-C….Ans.

Total heat transfer for the array, Q = 862415 W ….Ans.

Mass condensed for the entire array = 0.3518 kg/s = 1266 kg/h … Ans.

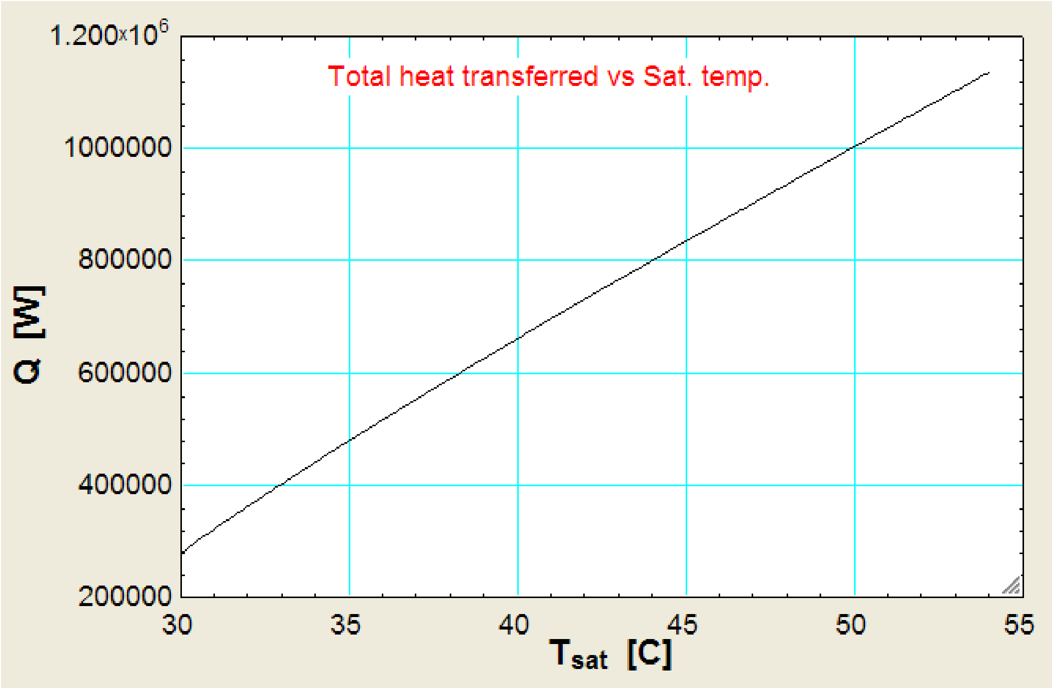
Now, if Tsat varies from 30 C to 54 C (corresponding to sat. pressure of 4.246 kPa to 15.02 kPa respectively), plot Q and mcond against Tsat:

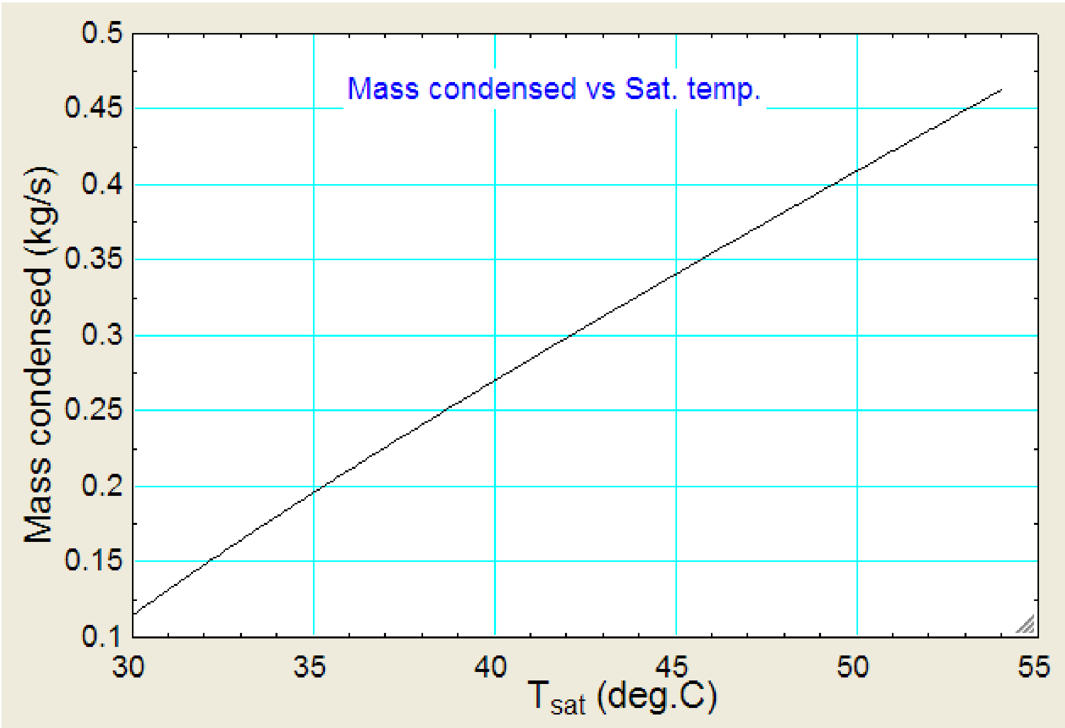
First, compute the Parametric Table:

Table 1

1..13	T_{sat} [C]	Q [W]	$mass_{condensed}$ [kg/s]
Run 1	30	279962	0.1145
Run 2	32	363016	0.1485
Run 3	34	441539	0.1805
Run 4	36	516976	0.2113
Run 5	38	590170	0.2411
Run 6	40	661665	0.2702
Run 7	42	731833	0.2988
Run 8	44	800946	0.3269
Run 9	46	869207	0.3546
Run 10	48	936771	0.382
Run 11	50	1.004E+06	0.4092
Run 12	52	1.070E+06	0.4362
Run 13	54	1.136E+06	0.4629

Now, plot the results:





===

Prob. 3.2.20. Refrigerant 12 (R12) at 35 C is to be condensed at the rate of 10000 kg/h on a square array of 25 × 25 tubes, each tube of 12 mm OD, maintained at 25 C. Calculate the length of each tube required.

EES Solution:

Use the EES procedure for a Tube bank:

"Data:"

T_sat = 35 [C]
T_s = 25 [C]
D = 0.012 [m]
N_total = 625

N = 25 "i.e. N = 400^0.5, since there are 400 tubes in a square array."

mass_condensed = 10000 * convert(kg/h, kg/s)

Fluid$ = 'R12'

CALL condensation_HTBank_Fluid(Fluid$,T_sat, T_s, D, L, N, N_total: h_avg, Q, mass_condensed)

Click on F2 to solve, and we get:

Main | condensation_HTBank_Fluid

Unit Settings: SI C Pa J mass deg

D = 0.012 [m]	Fluid$ = 'R12'	h_{avg} = 738.5 [W/m^2-C]
L = 2.211 [m]	$mass_{condensed}$ = 2.778 [kg/s]	N = 25
N_{total} = 625	Q = 384719 [W]	T_s = 25 [C]
T_{sat} = 35 [C]		

Main | condensation_HTBank_Fluid

Local variables in Procedure condensation_HTBank_Fluid (3 calls, 0.06 sec)

cp_l =969.4 [J/kg-C]	D =0.012 [m]	Fluid$='R12'
g=9.81 [m/s^2]	h_{avg} =738.5 [W/m^2-C]	h_f =69535 [J/kg]
h_{fg} =131907 [J/kg]	$h_{fg'}$ =138499 [J/kg]	h_g=201442 [J/kg]
k_l =0.06732 [W/m-C]	L=2.211 [m]	$mass_{condensed}$ =2.778 [kg/s]
μ_l =0.0002109 [kg/m-s]	N =25	ν_l =1.632E-07 [m^2/s]
N_{total} =625	Pr_l=3.037	Q =384719 [W]
ρ_l =1292 [kg/m^3]	ρ_v=48.43 [kg/m^3]	T_f=30 [C]
T_s=25 [C]	T_{sat} =35 [C]	

==

Prob. 3.2.21. Ammonia at 40 C is condensing inside a horizontal tube of 16 mm ID. Mass velocity of ammonia vapour at inlet is 20 kg/(m².s). Surface of the tube is maintained at a constant temperature of 20 C by circulating cold water. Calculate the fraction of vapour that will condense if the tube is 0.5 m long.(Ref.1)

EES Solution:

This is the case of condensation inside a horizontal tube.

Chato's relation is valid for Re_vap < 35000. See the formulas at the beginning of the Chapter.

See the EES Procedure for condensation inside a horizontal tube for any Fluid, written earlier:

Following is the worksheet:

"Data:"

T_sat = 40 [C
T_s = 20 [C]
L = 0.5 [m]
D = 0.016 [m]

Fluid$ = 'Ammonia'

G = 20 [kg/m^2-s] "….mass velocity of NH3"

A_c = pi * d^2 / 4 "[m^2]…..area of cross-section of tube"

rho_v = Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"

mu_v = Viscosity(Fluid$,T=T_sat,x=1) "[kg/m-s]"

U_v = G /rho_v "[m/s]…velocity of NH3 vap."

{Re_v = G D / mu_v}

CALL condensation_InsideHCyl(Fluid$,T_sat, T_s, D, L, U_v: h_avg, Q, mass_condensed)

mass_in = G * A_c "[kg/s] … mass flow rate of vap at inlet"

Fraction = mass_condensed / mass_in "….Fraction of vapour condensed"

Click F2 to solve, and we get:

Main | condensation_InsideHCyl

Unit Settings: SI C Pa J mass deg

A_c = 0.0002011 [m²]	D = 0.016 [m]	Fluid$ = 'Ammonia'
Fraction = 0.6122	G = 20 [kg/m²-s]	h_{avg} = 5562 [W/m²-C]
L = 0.5 [m]	$mass_{condensed}$ = 0.002462 [kg/s]	$mass_{in}$ = 0.004021 [kg/s]
μ_v = 0.00001033 [kg/m-s]	Q = 2796 [W]	ρ_v = 12.02 [kg/m³]
T_s = 20 [C]	T_{sat} = 40 [C]	U_v = 1.663 [m/s]

Main | condensation_InsideHCyl

Local variables in Procedure condensation_InsideHCyl (1 call, 0.02 sec)

cp_l =4827 [J/kg-C]	D =0.016 [m]	Fluid$='Ammonia'
g=9.81 [m/s²]	h_{avg} =5562 [W/m²-C]	h_f =390639 [J/kg]
h_{fg} =1.099E+06 [J/kg]	$h_{fg'}$ =1.136E+06 [J/kg]	h_g=1.490E+06 [J/kg]
k_l =0.4714 [W/m-C]	L=0.5 [m]	$mass_{condensed}$ =0.002462 [kg/s]
μ_l =0.0001255 [kg/m-s]	μ_v=0.00001033 [kg/m-s]	ν_l =2.109E-07 [m²/s]
Pr_l=1.285	Q =2796 [W]	Re_{vap}=30991
ρ_l =595.3 [kg/m³]	ρ_v=12.02 [kg/m³]	T_f=30 [C]
T_s=20 [C]	T_{sat} =40 [C]	U_v =1.663 [m/s]

Thus:

h_avg = 5562 W/m^2.C ….Ans.

Q = 2796 W …. Ans.

Mass_cond = 0.002462 kg/s …. Ans.

Mass_in = 0.004021 kg/s

Therefore, fraction of Mass condensed:

Fraction = 0.6122 = 61.22 % …. Ans.

==

Prob. 3.2.22. Sat.steam at 1 atm condenses on a 0.5 m high, 0.2 m wide vertical plate maintained at 90 C. Determine: (a) the thickness of film at the bottom of the plate, delta_L, (b) film Reynolds No. Re_f, (c) heat transfer coeff. h_avg, (d) total heat transfer, Q, and (e) the condensation rate.

EXCEL Solution:

Let us solve this problem in EXCEL.

We have already written VBA Functions for the properties of sat. water, air etc. and we shall use the same worksheet.

Following are the steps:

1. Set up the EXCEL worksheet, enter data and name the cells:

T_f =(T_s +T_sat)/2

	A	B	C	D	E	F
209						
210		Data:	Fluid =	Water		
211		Surface temp	T_s	90	C	
212		Sat. temp.	T_sat	100.0	C	$T\_f = (T\_s + T\_sat)/2$
213		Avg. temp	T_f	95.0	C	
214		Height of plate	L	0.5	m	
215		Width of plate	B	0.2	m	
216		Inclination to vertical	theta	0.0	deg.	
217		Accn. due to gravity	g	9.810	m/s^2	

2. Calculate the properties of water, using the VBA Functions already writte. Note that liquid properties are determined at the mean temp, T_f and heat of vapourization h_fg and properties of vapour are determined at the sat. temp T_sat:

h_fg | =SatH2O_hfg_T((T_sat+273.15))

	A	B	C	D	E	F	G
221		Calculations:					
222		Props. of liquid.. at Tf:					
223		density_liq	rho_L	961.6401735	kg/m^3		
224		dyn. Visc_liq	mu_L	0.000295	N.s/m^2		
225		kinem. Visc. of liq	nu_L	3.07069E-07	m^2/s		
226		th. conductivity_liq	k_L	0.67826	W/m.C		
227		sp.heat_liq	cp_L	4212.15	J/kg.K	Using VBA Functions for Props. of Sat. water	
228		Prandtl No._liq	Pr_L	1.8407			
229							
230							
231		Props of vapour: at Tsat:					
232		density_vap	rho_V	0.5956	kg/m^3		
233		sp.heat_vap	cp_V	2029	J/kg.K		
234		th. conductivity_vap	k_V	0.0248	W/m.C		
235		Heat of vaporization	h_fg	2257000	J/kg		
236		Modified h_fg	h_fg_prime	2285642.62	J/kg		
237					$h\_fg\_prime = h\_fg + 0.68 * cp\_L * (T\_sat - T\_s)$		

3. Now, continue the calculations to find thickness of condensate film at the lower end of plate, i.e. at x = L, (delta_L), local heat transfer coeff. h_L at x = L, and the film Reynplds No. (Re), as shown below. Equations used are also shown in the worksheet, for clarity:

delta_L   fx =(4*mu_L*k_L*(T_sat-T_s)*L/(g*rho_L*(rho_L-rho_V)*h_fg_prime))^(1/4)

	B	C	D	E
236	Modified h_fg	h_fg_prime	2285642.62	J/kg
237				
238	thickness of film at dist. L from top of plate	delta_L	0.000117913	m
239	local heat tr coeff	h_L	5752.225	W/m^2.C
240				
241	Reynolds No.	Re	227.273	
242				
243				

$$h\_fg\_prime = h\_fg + 0.68 * cp\_L * (T\_sat - T\_s)$$

$$delta_L = \left[\frac{4\cdot mu_L\cdot k_L\cdot (T_{sat} - T_s)\cdot L}{g\cdot rho_L\cdot (rho_L - rho_V)\cdot h_{fg\_prime}}\right]^{\frac{1}{4}}$$

$$h\_L = \frac{k\_L}{delta\_L}$$

$$Re = \frac{4\cdot g\cdot rho_L\cdot (rho_L - rho_V)\cdot delta_L^{\,3}}{3\cdot mu_L^{\,2}}$$

4. Re calculated above indicates the if the film is laminar, laminar-wavy, or turbulent. Equations for the average heat transfer coeff, h_vert, in three types of flow are given at the beginning of the Chapter and are reproduced below. These values are calculated separately and kept ready, and the appropriate value is chosen depending on value of Re, using an IF Function in EXCEL:

For Laminar film: (i.e. 0 < Re <= 30):

$$h_{vert} = 1.47\cdot Re^{\frac{-1}{3}}\cdot k_L\cdot\left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}} \quad \text{if} \;\; 0 < Re \le 30$$

For Laminar-wavy film: (i.e. 30 < Re <= 1800):

$$h_{vert} = \frac{Re\cdot k_L}{1.08\cdot Re^{1.22} - 5.2}\cdot\left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}}$$

$$Re_f = \left[4.81 + \frac{3.7\cdot L\cdot k_L\cdot (T_{sat} - T_s)}{mu_L\cdot h_{fg\_prime}}\cdot\left(\frac{g}{\nu_L^{\,2}}\right)^{\frac{1}{3}}\right]^{0.82}$$

For turbulent film: (i.e. Re > 1800):

$$h_{vert} = \frac{Re \cdot k_L}{8750 + 58 \cdot Pr_L^{-0.5} \cdot \left(Re^{0.75} - 253\right)} \cdot \left(\frac{g}{\nu_L^{2}}\right)^{\frac{1}{3}}$$

$$Re_f = \left[\frac{0.069 L \cdot k_L \cdot Pr_L^{0.5} \cdot \left(T_{sat} - T_s\right)}{mu_L \cdot h_{fg\_prime}} \cdot \left(\frac{g}{\nu_L^{2}}\right)^{\frac{1}{3}} - 151 \cdot Pr_L^{0.5} + 253\right]^{\frac{4}{3}}$$

---

h_vert | fx | =IF(Re<=30,h_vert_lam,IF(Re<=1800,h_vert_wavy,h_vert_turb))

	B	C	D	E	F	G
244	**Now, depending upon above value of Re, get h_vert and Re_vert:(Ref: Cengel)**				h_vert_lam	7684.163798
245					h_vert_wavy	9010.075542
246	Avg. heat tr. coeff.	h_vert	9010.076	W/m^2.C	Re_vert_wavy	259.5109239
247	Reynolds No.	Re_vert	259.511		h_vert_turb	16606.31957
248	Film flow range:	Film flow is:	Laminar_wavy		Re_vert_turb	289.9080821
249	Heat transfer:	Q	9010.076	W		
250	Condensation rate:	m_cond	0.003942032	kg/s	$Q = h\_vert \cdot (L \cdot B) \cdot (T\_sat - T\_s)$	
251	Condens. rate per hour:	m_cond_per_hour	14.191	kg/h	$m\_cond = \frac{Q}{h\_fg\_prime}$	
252						

In the above, yellow-filled box at the right corner calculates the values of h_vert separately and the cells are 'named'. Then, actual values of h_vert and Re_vert are transferred to cells D246 and D247 using the IF Function. Formula of IF Function entered in cell D246 can be seen in the Formula bar.

5. Thus, the results are:

delta_L = 0.000117913 m…. thickness of condensate film at the bottom of plate (i.e. at x = 0.5 m)

Re_f = 259.511 = Reynolds No. …Laminar wavy region

h_avg = h_vert = 9010.1 W/m^2.C = avg heat transfer coeff

Q = 9010.71 W = heat tr to plate

m_cond = 0.003942 kg/s = 14.191 kg/h ….Ans.

---

6. **If the plate is inclined to vertical at 30 deg. what are the changes in results?**

For an inclined plate, inclined at an angle of **θ** deg. to vertical, we have:

h_inclined = h_vert x (cos(θ))^(1/4)

Following worksheet shows these calculations:

D256 fx =h_vert*(COS(D255))^(1/4)

	B	C	D	E
250	Condensation rate:	m_cond	0.003942032	kg/s
251	Condens. rate per hour:	m_cond_per_hour	14.191	kg/h
252				
253	If the plate is inclined at 'theta' deg. to vertical:			
254	Angle of incln. to vert.	theta	30	deg.
255	theta in radians	theta_rad	0.523598776	radians
256	heat tr coeff.	h_inclined	8691.827	W/m^2.C
257	Heat transfer:	Q_inclined	8691.827	W
258	Condensation rate:	m_cond_incl	0.003803	kg/s
259	Condens. rate per hour:	m_cond_incl_per_hour	13.690	kg/h

In the above worksheet, note that theta was converted from degrees to radians, since EXCEL requires that arguments to Trigonometric Functions such as Sin, Cos etc. should be in radians.

Thus, we get, for the plate inclined at 30 deg to vertical:

h_avg = h_inclined = 8691.83 W/m^2.C = avg heat transfer coeff

Q_inclined = 8691.83 W = heat tr to inclined plate

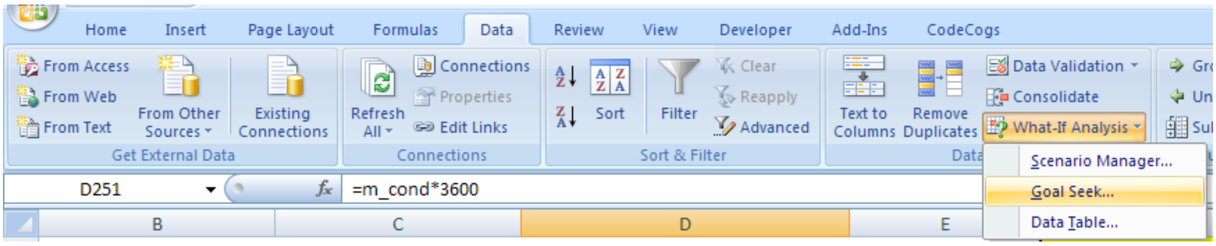
m_cond_incl = 0.003803 kg/s = 13.69 kg/h ….Ans.

---

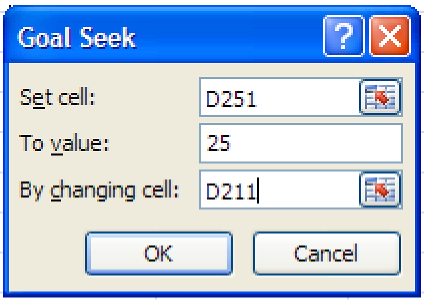
7. **For the vertical plate, what should be the surface temp to achieve a condensation rate of 25 kg/h?**

This is calculated very easily using the Goal Seek in EXCEL. We will apply Goal Seek, to make cell D251 zero, by changing cell D211 (i.e. value of T_s): Following is the procedure:

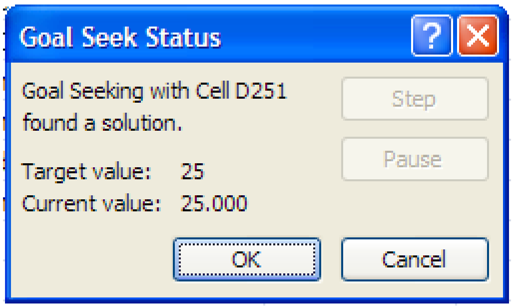
Select cell D251, and go to Data – WhatIf Analysis – Goal Seek:



Click on Goal Seek. We get the following screen. Fill it up as explained above:



Press OK. We get:



i.e. Goal Seek has found a solution. Again click OK and see the value of T_s in cell D211:

210	Data:	Fluid =	Water	
211	Surface temp	T_s	79.3601	C
212	Sat. temp.	T_sat	100.0	C
213	Avg. temp	T_f	89.7	C
214	Height of plate	L	0.5	m
215	Width of plate	B	0.2	m
216	Inclination to vertical	theta	0.0	deg.
217	Accn. due to gravity	g	9.810	m/s^2

$T\_f = (T\_s + T\_sat)/2$

Thus:

Surface temp required to get a cond. rate of 25 kg/h is: T_s = 79.3601 deg. C….Ans.

---

8. **Now, plot the surface temps for different condensation rates (from 15 to 50 kg/h):**

Here, we have to apply Goal Seek to each value of m_cond. So, it is convenient to write a small VBA program:

First, set up a Table as shown below:

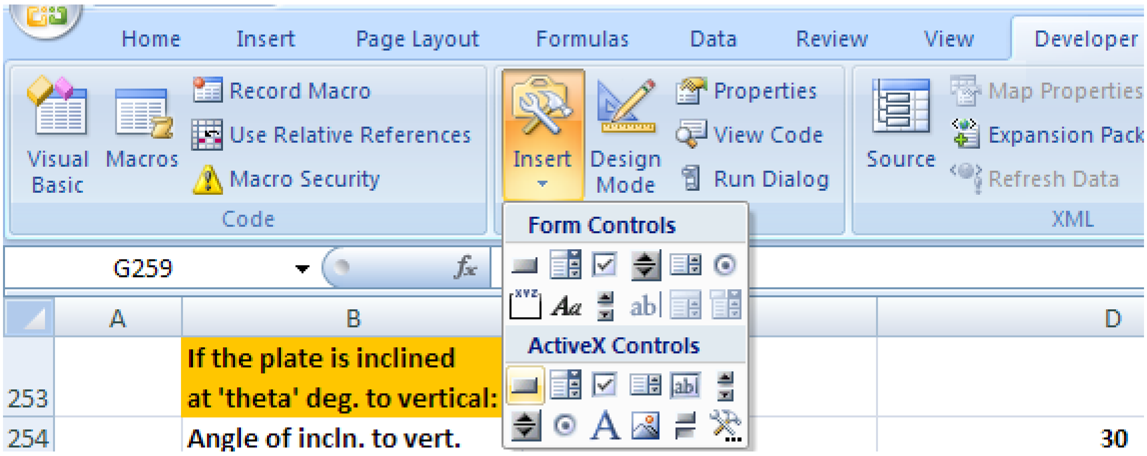
	A	B	C	D	E
262		Plot T_s for m_cond values ranging from 10 kg/h to 50 kg/h:			
263			m_cond-starting value = m_initial	10	kg/h
264			m_cond_final value = m_final	50	...upper limit is 65 kg/h
265			Change these two values between 0 and 65 and click CommandButton1		
266					
267		m_cond (kg/h)	h_vert (W/m^2.C)	Q (W)	T_s (deg.C)
268					
269					
270					
271					
272					
273					
274					
275					
276					

Here, we enter the range of m_cond desired in cells D263 and D264 as shown.

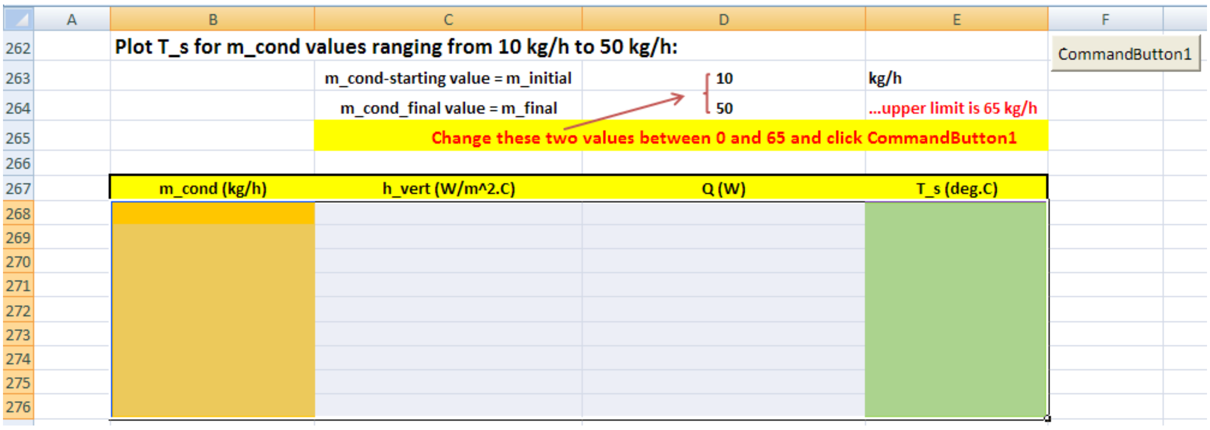
Table has 9 rows; so increment will be: Inc = (final value – initial value) / 8 = 5

Now, we will have a control button to operate our VBA program.

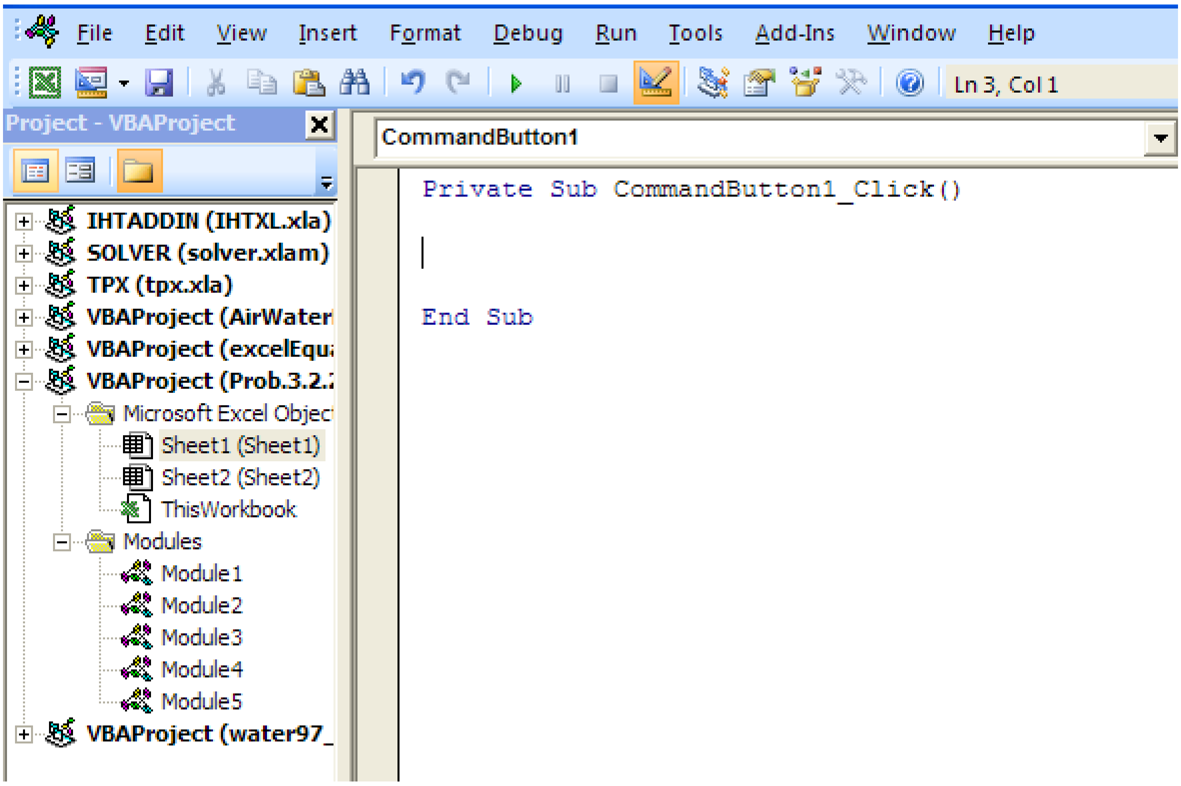
So, go to: Developer – Insert – ActiveX controls:



Click on first, left button under ActiveX Controls, and locate the button at the required place in the worksheet and adjust its size:



Now, in Developer tab, click VisualBasic (extreme left) and we see under Sheet 1, the VBA program for this control button:



Now, modify this program to:

generate the value of m_cond within the desired range and apply Goal Seek, get the values of h, Q and T_s for each case, and write them all at appropriate places in the Table.

Following is the program:

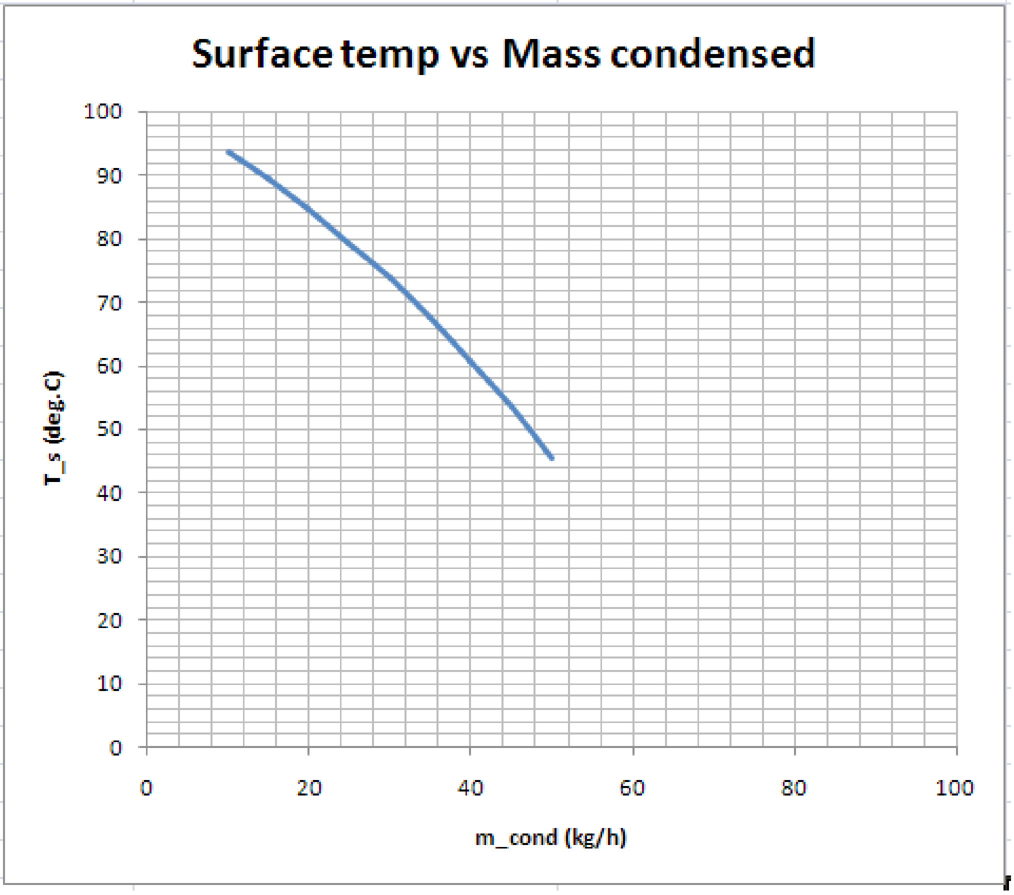
```
CommandButton1                                  Click

Private Sub CommandButton1_Click()

Dim i As Integer
Dim m_initial As Double, m_final As Double, Inc As Double

m_initial = Range("D263")  'starting value for m_cond
m_final = Range("D264")  'starting value for m_cond

Inc = (m_final - m_initial) / 8

For i = 0 To 8

Range("D251").GoalSeek Goal:=m_initial + i * Inc, ChangingCell:=Range("D211")  'This line performs Goal Seek

Cells(268 + i, 2) = m_initial + i * Inc  'Fills the first column of Table, i.e. m_cond values

Cells(268 + i, 3) = Range("D246")  'Fills the second column of Table, i.e. h_vert values

Cells(268 + i, 4) = Range("D249")  'Fills the third column of Table, i.e. Q values

Cells(268 + i, 5) = Range("D211")  'Fills the fourth column of Table, i.e. T_s values

Next i

End Sub
```

In the above program, read the comments given to see what each line does.

Now, click on the CommandButton1 and we get:

	A	B	C	D	E	F
262		Plot T_s for m_cond values ranging from 10 kg/h to 50 kg/h:				CommandButton1
263			m_cond-starting value = m_initial	10	kg/h	
264			m_cond_final value = m_final	50	...upper limit is 65 kg/h	
265			Change these two values between 0 and 65 and click CommandButton1			
266						
267		m_cond (kg/h)	h_vert (W/m^2.C)	Q (W)	T_s (deg.C)	
268		10	9785.894	6320.857	93.541	
269		15	8890.174	9532.118	89.278	
270		20	8275.042	12784.572	84.550	
271		25	7792.478	16083.592	79.360	
272		30	7392.308	19434.487	73.710	
273		35	7040.901	22844.055	67.555	
274		40	6718.590	26320.306	60.825	
275		45	6411.791	29873.807	53.408	
276		50	6139.606	33507.805	45.424	

Now, plot the graph:



9. Now, if we need the T_s values for another range of mass_condensed, we have to just enter the desired values in cells D263 and D264 and click the CommandButton1. ***But, take care to see that upper limit for mass condensed should not go beyond 65 kg/h, since otherwise, T_s value will go below zero and the program will stop.***

For ex: let us have m_cond between 0 and 65 kg/h:

Then, enter the values in D263 and D264 as shown and click CommandButton1. We get:

Plot T_s for m_cond values ranging from 10 kg/h to 50 kg/h:

CommandButton1

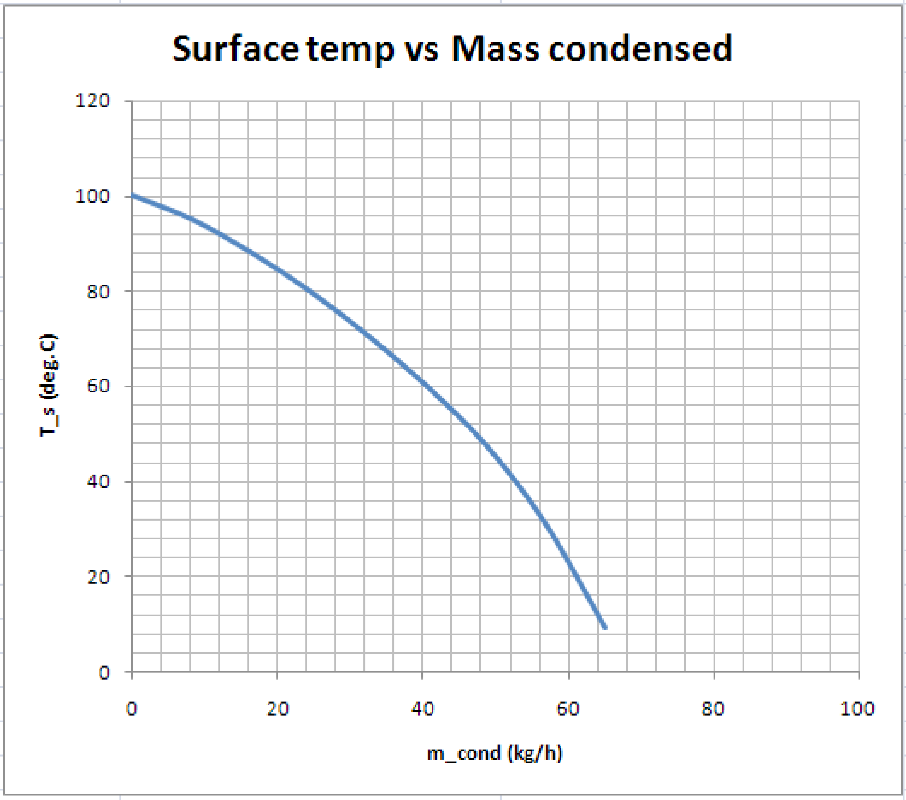
m_cond-starting value = m_initial 0 kg/h

m_cond_final value = m_final 65 ...upper limit is 65 kg/h

Change these two values between 0 and 65 and click CommandButton1

m_cond (kg/h)	h_vert (W/m^2.C)	Q (W)	T_s (deg.C)
0	2093998.422	0.000	100.000
8.125	10262.297	5126.234	95.005
16.25	8717.986	10341.175	88.138
24.375	7847.619	15668.487	80.034
32.5	7210.868	21131.604	70.695
40.625	6678.726	26760.200	59.932
48.75	6205.622	32591.079	47.481
56.875	5630.841	38753.608	31.176
65	5001.528	45414.907	9.198

And, the plot immediately changes as follows:



===

Note: While solving this problem, all the calculations have been done in the worksheet itself. So, values of all steps are seen transparently in the worksheet. For example, as the T_s changes how all values, including properties of Water, change can be seen in the worksheet.

So, this worksheet can be used as Template for all such condensation calculations on a vertical plate.

However, if we don't need all the intermediate values, it is better to write a VBA Function to do the calculations and return the desired final values only. This is demonstrated in the next problem:

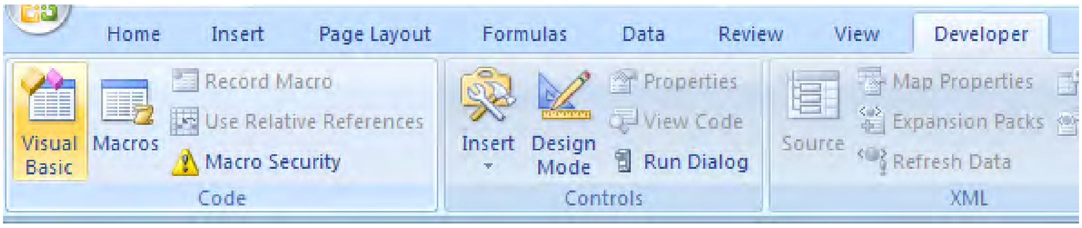
===

Prob. 3.2.23. Solve the above Problem in EXCEL using VBA Function written for the purpose:.

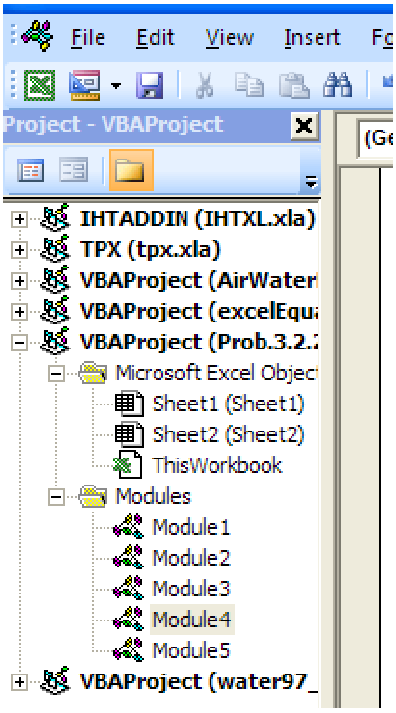
EXCEL Solution:

Let us write a VBA Function to do the calculations:

1. In the above Worksheet, go to: Developer – Visual Basic:



Click on Visual Basic, Select Module4:



And, type the following code:

```
Function Condensation_VPlate_Steam(T_sat As Double, T_s As Double, b As Double, L As Double) As Variant

'Condensation of Steam at T_sat on a Vertical Plate  held at T_s

'Calculates h_avg for laminar, wavy and turbulent film condensation
'based on value of Re_f

'Note: positive x direction is from top of plate downwards; y dirn is from left to right
'x is the distance from top, b is the breadth of plate perpendicular to paper

Dim g As Double, Re As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, delta_l As Double, Re_f As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


'Properties of liquid at Tf:

rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
mu_l = SatH2O_muf_T(T_f + 273.15)
cp_l = SatH2O_cpf_T(T_f + 273.15)
k_l = SatH2O_kf_T(T_f + 273.15)
nu_l = mu_l / rho_l
Pr_l = SatH2O_Prf_T(T_f + 273.15)


'Properties of vapour and h_fg at Tsat:

rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)


'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling"
delta_l = ((4 * k_l * mu_l * (T_sat - T_s) * L) / _
(rho_l * (rho_l - rho_v) * g * h_fg_prime)) ^ (1 / 4) '[m]....thickness of film at a
'distance L from top

Re = (4 * g * rho_l * (rho_l - rho_v) * delta_l ^ 3) / (3 * mu_l ^ 2) '...film Reynolds No.
```

```
If (Re > 0) And (Re <= 30) Then  'laminar film

   h_avg = 1.47 * k_l * Re ^ (-1 / 3) * (g / nu_l ^ 2) ^ (1 / 3)

   Re_f = Re 'Film Reynolds No. for laminar flow

ElseIf (Re > 30) And (Re <= 1800) Then 'wavy - laminar flow in film

      h_avg = ((Re * k_l) / (1.08 * Re ^ 1.22 - 5.2)) * (g / nu_l ^ 2) ^ (1 / 3)

      Re_f = (4.81 + (3.7 * L * k_l * (T_sat - T_s) / (mu_l * h_fg_prime)) * (g / nu_l ^ 2) ^ (1 / 3)) ^ 0.82

ElseIf (Re > 1800) Then    'turb. flow in film

   h_avg = ((Re * k_l) / (8750 + 58 * Pr_l ^ (-0.5) * (Re ^ 0.75 - 253))) * _
   (g / nu_l ^ 2) ^ (1 / 3)

   Re_f = ((0.069 * L * k_l * Pr_l ^ 0.5 * (T_sat - T_s) / (mu_l * h_fg_prime)) * _
   (g / nu_l ^ 2) ^ (1 / 3) - 151 * Pr_l ^ 0.5 + 253) ^ (4 / 3)

End If


 Q = h_avg * (b * L) * (T_sat - T_s) 'W

 m_condensed = Q / h_fg_prime 'kg/s

 Condensation_VPlate_Steam = Application.Transpose(Array(delta_l, Re_f, h_avg, Q, m_condensed))


 End Function
```

Note in the definition of the Function that:

Inputs are: T_sat (Sat. temp.), T_s (Surface temp.), b (Width of vertical plate) and L (height of vertical plate)

Output of Function: is a vertical array containing, in order: delta_L (thickness of condensate at the bottom of plate), Re_f (film Reynolds No.), h_avg (avg. heat tr coeff. h_vert), Q (heat transfer to the plate in Watts) and m_condensed in kg/s

Now, this Function is available like any other built-in Function in EXCEL.

It is located under the **'User Defined' category**.

Using the earlier Worksheet itself, where the data are entered and the cells are named, we have:

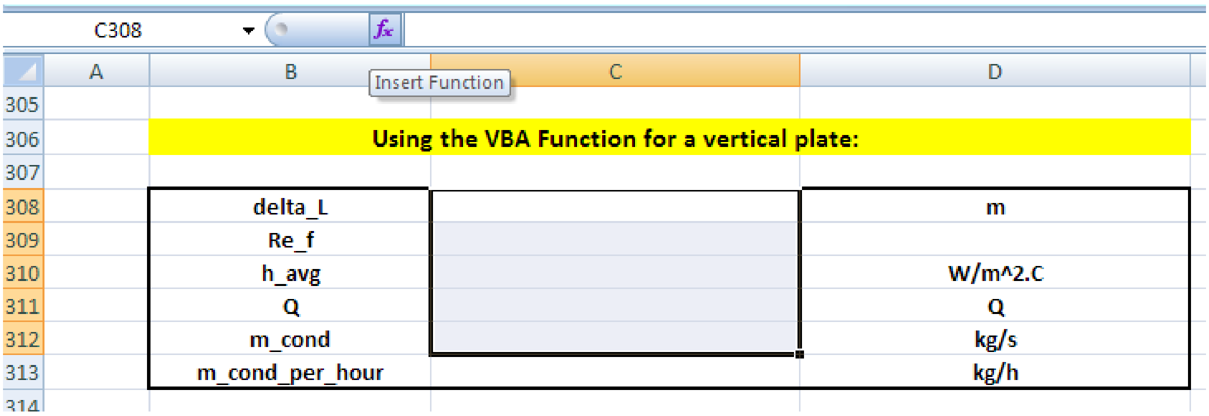
L | fx 0.5

	A	B	C	D	E	F
209						
210		Data:	Fluid =	Water		
211		Surface temp	T_s	45.4235	C	
212		Sat. temp.	T_sat	100.0	C	$T\_f = (T\_s + T\_sat)/2$
213		Avg. temp	T_f	72.7	C	
214		Height of plate	L	0.5	m	
215		Width of plate	B	0.2	m	
216		Inclination to vertical	theta	0.0	deg.	
217		Accn. due to gravity	g	9.810	m/s^2	
218						

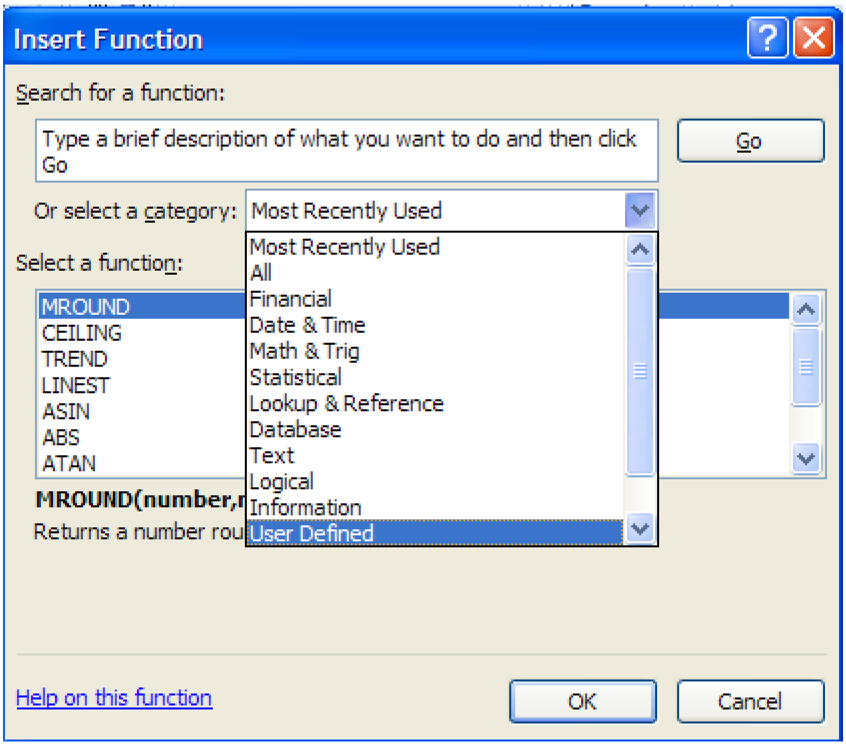
Now, set up the worksheet with 5 consecutive cells in column C (i.e. cells C308 to C312) selected as shown:

	A	B	C	D
305				
306		**Using the VBA Function for a vertical plate:**		
307				
308		delta_L		m
309		Re_f		
310		h_avg		W/m^2.C
311		Q		Q
312		m_cond		kg/s
313		m_cond_per_hour		kg/h
314				

Now, with the range still selected, place the cursor in any cell between C308 and C312, and click on the 'Insert Function' symbol:

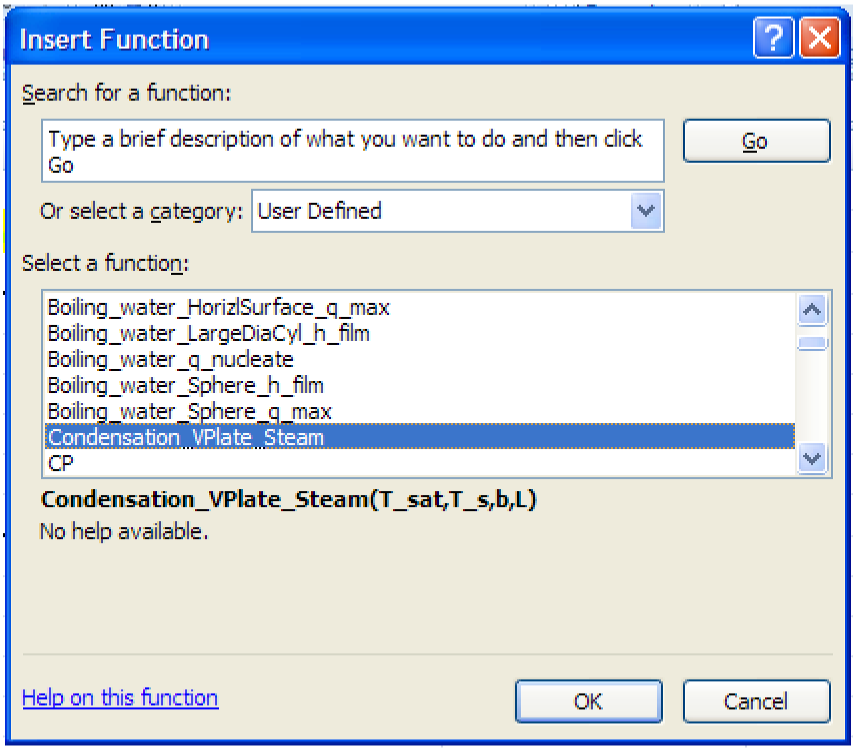


Choose 'User Defined' category:

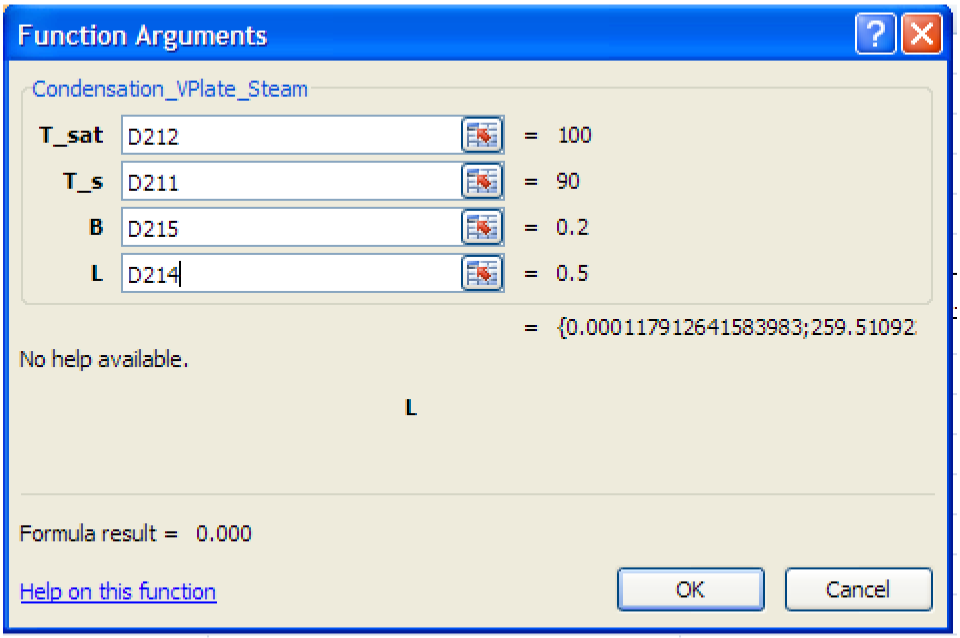


Click OK.

And, in ‘Select a Function’: click on the desired Function as shown:

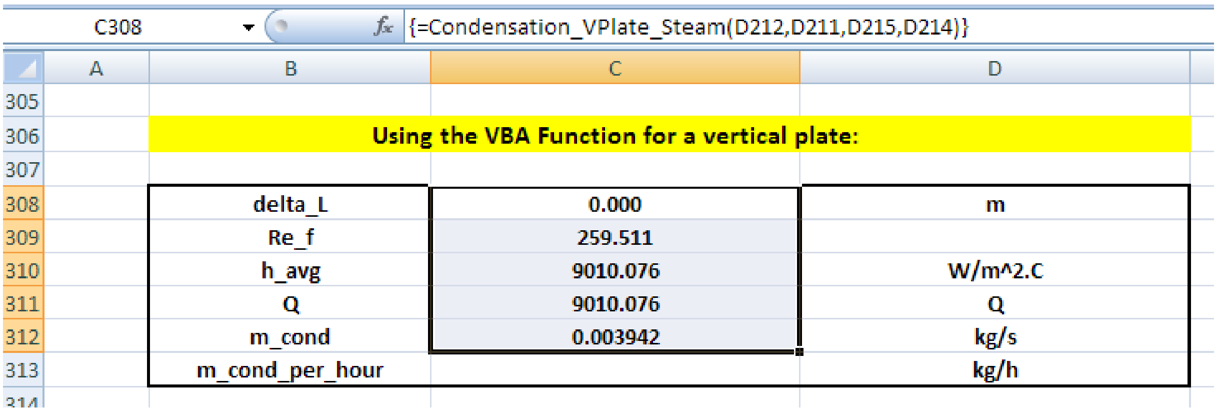


Click OK. We get the following screen. Fill it up as shown:



Important: Now, keeping Ctrl+Shift pressed, click OK, since this is an Array Function (i.e. it returns an Array of values).

We get:



C308 {=Condensation_VPlate_Steam(D212,D211,D215,D214)}

	A	B	C	D
305				
306		Using the VBA Function for a vertical plate:		
307				
308		delta_L	0.000	m
309		Re_f	259.511	
310		h_avg	9010.076	W/m^2.C
311		Q	9010.076	Q
312		m_cond	0.003942	kg/s
313		m_cond_per_hour		kg/h

Observe that all the 5 selected cells are filled with the respective values returned by the Function.

Last cell, ie. m_cond_per_hour may now be calculated as: m_cond_per_hour = m_cond * 3600.

Finally, we have:

C313 =C312*3600

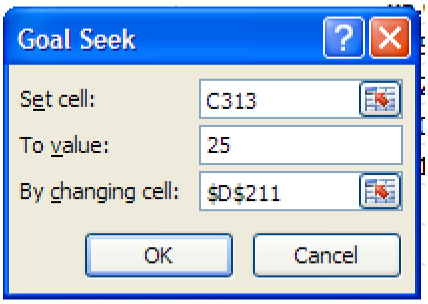
	A	B	C	D
305				
306		Using the VBA Function for a vertical plate:		
307				
308		delta_L	0.000	m
309		Re_f	259.511	
310		h_avg	9010.076	W/m^2.C
311		Q	9010.076	Q
312		m_cond	0.003942	kg/s
313		m_cond_per_hour	14.191	kg/h

Note: These values match with those obtained in the previous problem, as they should.

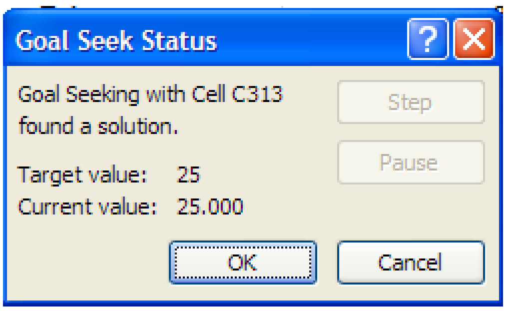
Now, if we have to find out the T_s required to get a condensation rate of 25 kg/h:

Apply Goal Seek to make cell C313 equal to 25 by changing cell D211 (i.e. value of T_s).

Applying Goal Seek has been explained in the previous problem. We get:



Click OK. And we get:



And value of T_s can be seen in cell D211:

	A	B	C	D	E	F
209						
210		Data:	Fluid =	Water		
211		Surface temp	T_s	79.3601	C	
212		Sat. temp.	T_sat	100.0	C	$T\_f = (T\_s + T\_sat)/2$
213		Avg. temp	T_f	89.7	C	
214		Height of plate	L	0.5	m	
215		Width of plate	B	0.2	m	
216		Inclination to vertical	theta	0.0	deg.	
217		Accn. due to gravity	g	9.810	m/s^2	

i.e. Value of T_s required to get a condensation rate of 25 kg/h = 79.36 01deg. C …. Ans.

Again, this matches with the value obtained in the previous problem.

Thus, we see that using a custom-written VBA Function is advantageous and helps in solving the problems faster and accurately, without having to spend time in entering tedious equations in the cells.

===

Prob. 3.2.24. Sat.steam at 1 atm condenses on a 0.3 m high, 1 m wide vertical plate maintained at 90 C. Determine: (a) the thickness of film at the bottom of the plate, delta_L, (b) film Reynolds No. Re_f, (c) heat transfer coeff. h_avg, (d) total heat transfer, Q, and (e) the condensation rate.

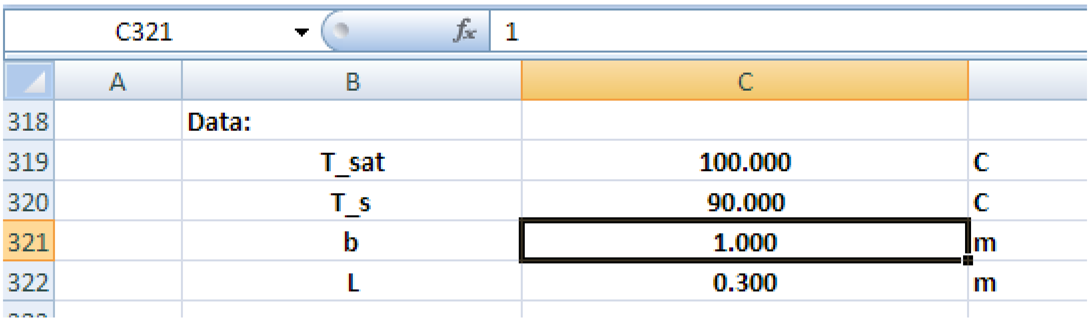
Also, plot the condensation rate for various values of T_s ranging from T_s = 50 C to 90 C.

EXCEL Solution:

Use the VBA Function for Vertical plate written earlier:

Following are the steps:

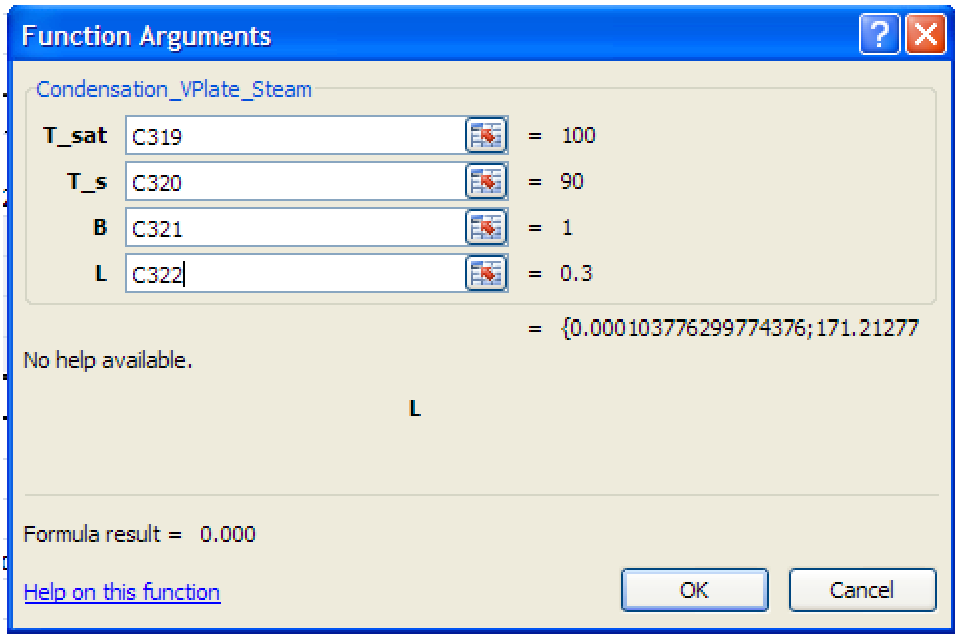
1. Set up the worksheet, enter data:



C321 | fx | 1

	A	B	C	
318		Data:		
319		T_sat	100.000	C
320		T_s	90.000	C
321		b	1.000	m
322		L	0.300	m

2. Select 5 consecutive cells in column and enter the VBA Function for Condensation on vertical plate as explained in the previous problem.
3. Fill up the arguments of the Function as shown:



Press (Ctrl + Shift + Enter), since it is an Array Function.

Results desired are displayed immediately in the selected cells:

	A	B	C	D
318		Data:		
319		T_sat	100.000	C
320		T_s	90.000	C
321		b	1.000	m
322		L	0.300	m
323				
324		delta_L	0.0001038	m
325		Re_f	171.213	
326		h_avg	9840.315	W/m^2.C
327		Q	29520.944	W
328		m_cond	0.012916	kg/s
329		m_cond_per_hour		kg/h
330				

4. Now, convert m_cond to m_cond_per_hour by multiplying by 3600:

C329 fx =C328*3600

	A	B	C	D
318		Data:		
319		T_sat	100.000	C
320		T_s	90.000	C
321		b	1.000	m
322		L	0.300	m
323				
324		delta_L	0.0001038	m
325		Re_f	171.213	
326		h_avg	9840.315	W/m^2.C
327		Q	29520.944	W
328		m_cond	0.012916	kg/s
329		m_cond_per_hour	46.497	kg/h

Thus:

Condensation rate is: 46.497 kg/h …. Ans.

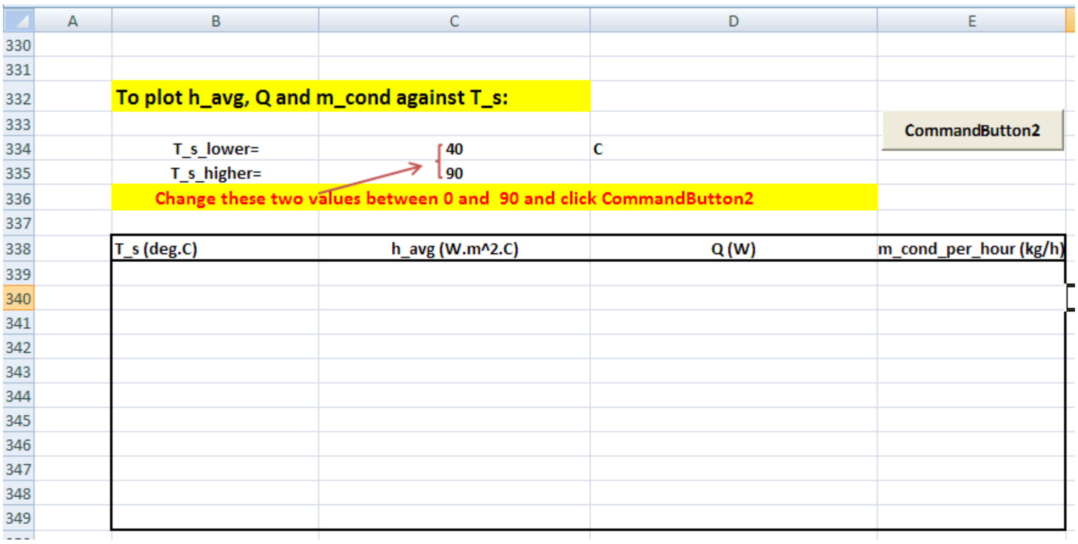
To plot m_cond against T_s:

Let us write a VBA program to do this.

1. Before that, set up a Table as shown:

We plan to give lower limit and upper limit of T_s, and then the program should fill up the Table for 10 equally divided values of T_s and also the program should be executed with a ControlButton.

For the procedure of inserting an ActiveX ControlButton, see the previous problem.



2. Now, double click on the ControlButton2 and we see the VBA program behind it:

```
Private Sub CommandButton2_Click()

End Sub
```

3. Now, modify this program as follows to perform the desired calculation steps:

```
Private Sub CommandButton2_Click()

Dim i As Integer
Dim T_s_initial As Double, T_s_final As Double, Inc As Double

T_s_initial = Range("C334") 'starting value for T_s
T_s_final = Range("C335") 'starting value for T_s

Inc = (T_s_final - T_s_initial) / 10

For i = 0 To 10

Range("C320") = T_s_initial + i * Inc 'Sets the T_s value to the starting or initial value

'Immediately, all other values will up-date themselves.
'And, copy them to their respective places in the Table:

Cells(339 + i, 2) = Range("C320") 'copies value of T_s to Table
Cells(339 + i, 3) = Range("C326") 'copies value of h_avg to Table
Cells(339 + i, 4) = Range("C327") 'copies value of Q to Table
Cells(339 + i, 5) = Range("C329") 'copies value of m_cond_per_hour to Table


Next i

End Sub
```

Read the comments in the above code to know what each line does.

4. Now, click on the CommandButton2 and immediately the calculations are done and the Table is filled up:

To plot h_avg, Q and m_cond against T_s:

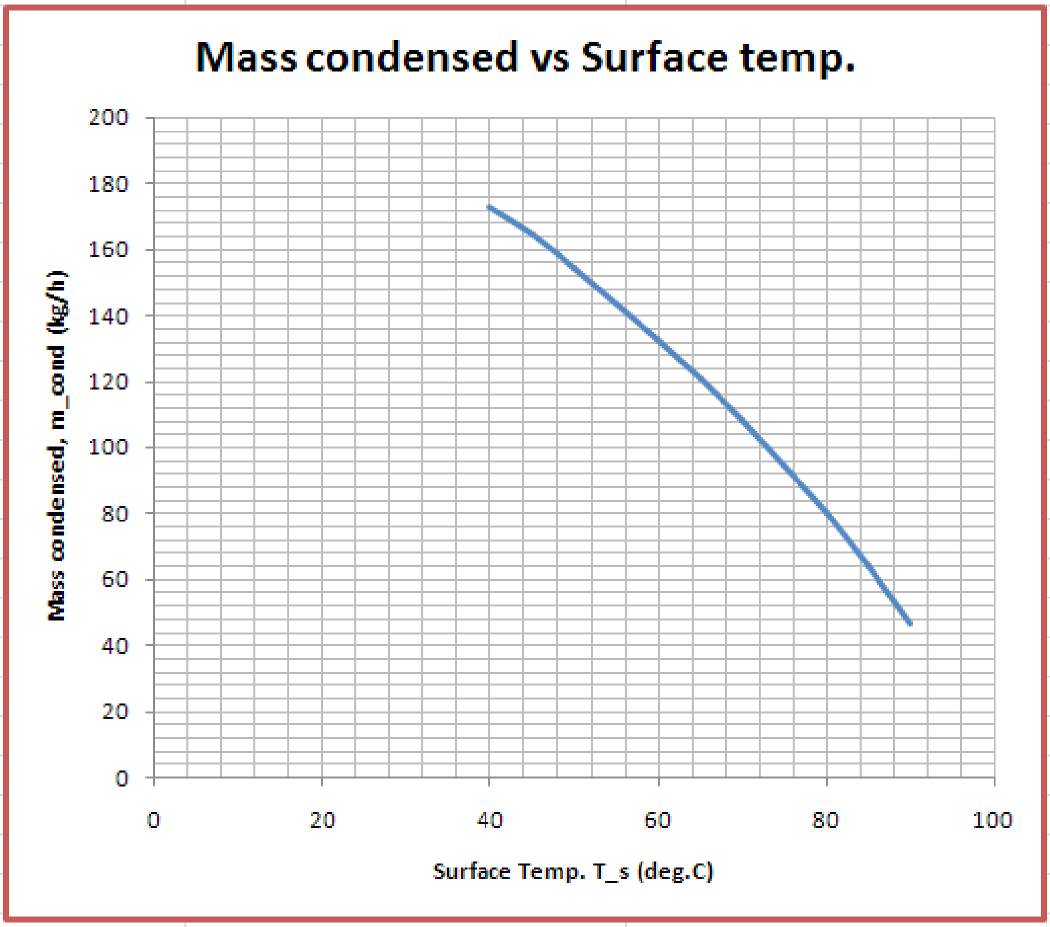
CommandButton2

T_s_lower= 40 C
T_s_higher= 90

Change these two values between 0 and 90 and click CommandButton2

T_s (deg.C)	h_avg (W.m^2.C)	Q (W)	m_cond_per_hour (kg/h)
40	6470.780	116474.047	172.700
45	6673.633	110114.948	164.231
50	6852.391	102785.871	154.206
55	7052.117	95203.579	143.680
60	7279.946	87359.347	132.632
65	7534.148	79108.556	120.830
70	7815.814	70342.327	108.094
75	8148.413	61113.096	94.486
80	8553.905	51323.430	79.839
85	9081.401	40866.307	63.966
90	9840.315	29520.944	46.497

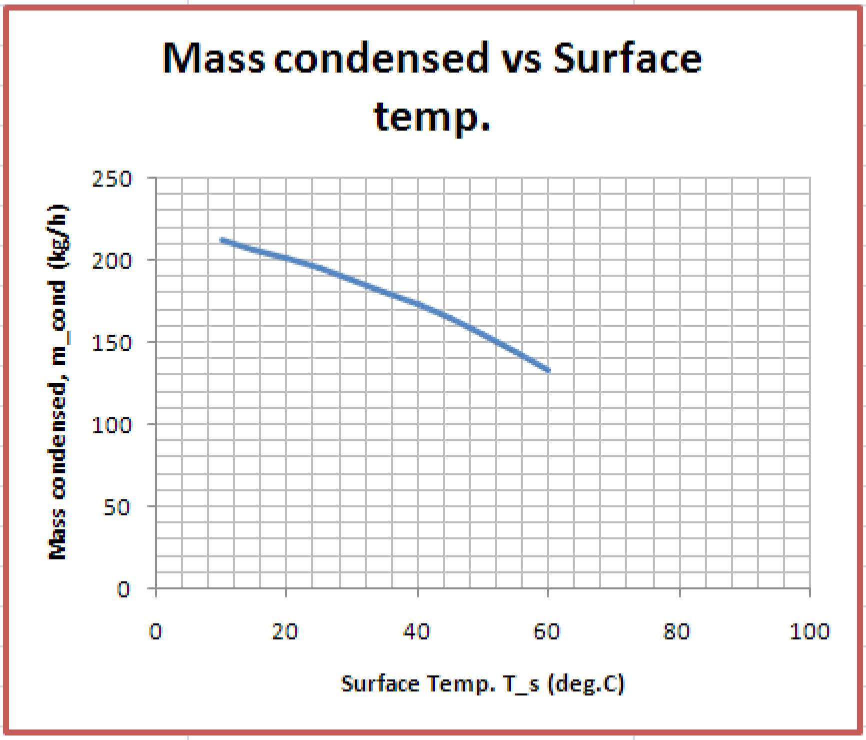
5. Now, plot m_cond against T_s:



6. Now, we can easily change the range of T_s as we desire, by changing cells C334 and C335. **As an example, for T_s between the limits 10 and 60 C:** Change cells C344 and C335 as shown and click CommandButton2 and we get:

	A	B	C	D	E
331					
332		To plot h_avg, Q and m_cond against T_s:			
333					CommandButton2
334		T_s_lower=	10	C	
335		T_s_higher=	60		
336		Change these two values between 0 and 90 and click CommandButton2			
337					
338		T_s (deg.C)	h_avg (W.m^2.C)	Q (W)	m_cond_per_hour (kg/h)
339		10	5470.928	147715.068	211.608
340		15	5616.357	143217.103	206.328
341		20	5770.951	138502.813	200.674
342		25	5932.619	133483.928	194.512
343		30	6093.910	127972.119	187.557
344		35	6271.017	122284.830	180.263
345		40	6470.780	116474.047	172.700
346		45	6673.633	110114.948	164.231
347		50	6852.391	102785.871	154.206
348		55	7052.117	95203.579	143.680
349		60	7279.946	87359.347	132.632

And, the plot up-dates itself immediately:



==

Prob.3.2.25. Consider a vertical tube, 1 m high, 80 mm dia, maintained at a uniform temp of 50 C, exposed to sat. steam at atm. pressure. Find out the heat transfer and steam condensation rate.

Note: This is the same as Prob.3.2.5, which was solved with Mathcad.

Now, we shall solve it with EXCEL.

EXCEL Solution:

This is the case of condensation of steam on a vertical cylinder.

Equations for the case of a vertical cylinder are the same as those for a vertical plate, if the Dia of the cylinder is much larger than the thickness of condensate film, which is generally true. Only change is in calculation of Q where the surface area for cylinder is: $\pi \cdot D \cdot L$:

First, let us write a VBA Function for the cases of: condensation of steam on a Vertical Cylinder:

```
Function Condensation_VCyl_Steam(T_sat As Double, T_s As Double, D As Double, L As Double) As Variant

'Condensation of Steam at T_sat on a Vertical Cylinder  held at T_s

'This is the same as for vertical plates, when the cyl dia is large...
'relative to the thickness of the liquid film (which is generally true)

'Calculates h_avg for laminar, wavy and turbulent film condensation
'based on value of Re_f

'Results are returned as an Array

'Note: positive x direction is from top of plate downwards; y dirn is from left to right
'x is the distance from top, b is the breadth of plate perpendicular to paper

Dim g As Double, Re As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, delta_l As Double, Re_f As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


'Properties of liquid at Tf:

rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
mu_l = SatH2O_muf_T(T_f + 273.15)
cp_l = SatH2O_cpf_T(T_f + 273.15)
k_l = SatH2O_kf_T(T_f + 273.15)
nu_l = mu_l / rho_l
Pr_l = SatH2O_Prf_T(T_f + 273.15)


'Properties of vapour and h_fg at Tsat:

rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
```

```
'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling"
delta_l = ((4 * k_l * mu_l * (T_sat - T_s) * L) / _
(rho_l * (rho_l - rho_v) * g * h_fg_prime)) ^ (1 / 4) '[m]....thickness of film at a
'distance L from top

Re = (4 * g * rho_l * (rho_l - rho_v) * delta_l ^ 3) / (3 * mu_l ^ 2) '...film Reynolds No.

If (Re > 0) And (Re <= 30) Then  'laminar film

   h_avg = 1.47 * k_l * Re ^ (-1 / 3) * (g / nu_l ^ 2) ^ (1 / 3)

   Re_f = Re 'Film Reynolds No. for laminar flow

ElseIf (Re > 30) And (Re <= 1800) Then 'wavy - laminar flow in film

      h_avg = ((Re * k_l) / (1.08 * Re ^ 1.22 - 5.2)) * (g / nu_l ^ 2) ^ (1 / 3)

      Re_f = (4.81 + (3.7 * L * k_l * (T_sat - T_s) / (mu_l * h_fg_prime)) * (g / nu_l ^ 2) ^ (1 / 3)) ^ 0.82

ElseIf (Re > 1800) Then    'turb. flow in film

   h_avg = ((Re * k_l) / (8750 + 58 * Pr_l ^ (-0.5) * (Re ^ 0.75 - 253))) * _
   (g / nu_l ^ 2) ^ (1 / 3)

   Re_f = ((0.069 * L * k_l * Pr_l ^ 0.5 * (T_sat - T_s) / (mu_l * h_fg_prime)) * _
   (g / nu_l ^ 2) ^ (1 / 3) - 151 * Pr_l ^ 0.5 + 253) ^ (4 / 3)

End If
```

```
Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s

Condensation_VCyl_Steam = Application.Transpose(Array(delta_l, Re_f, h_avg, Q, m_condensed))

End Function
```

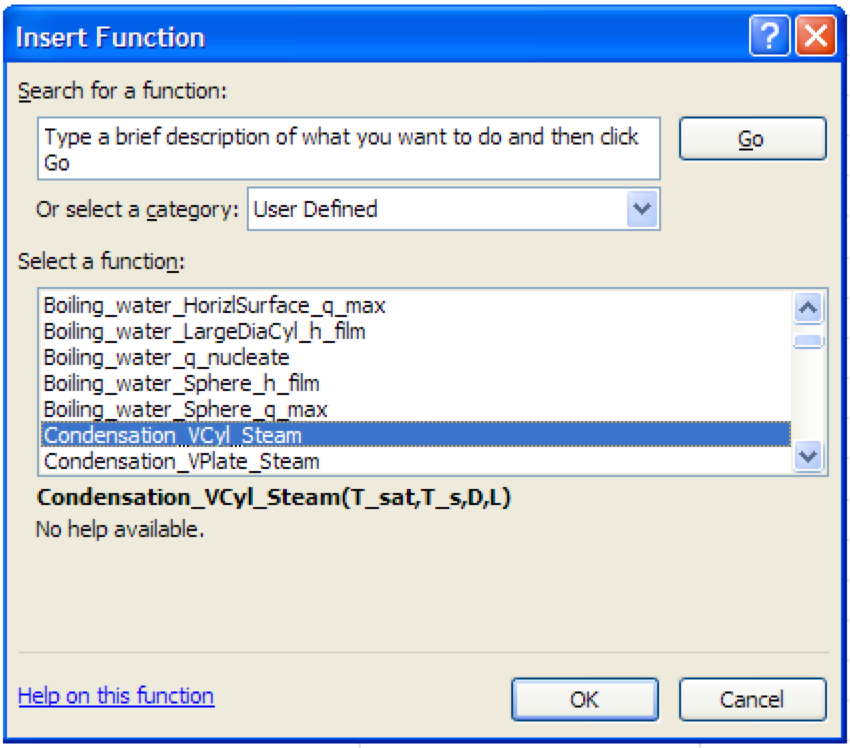
Now, let us solve the above problem.

Remember that the Function returns an Array containing: delta_L, Re_f, h_avg, Q and m_cond as earlier.

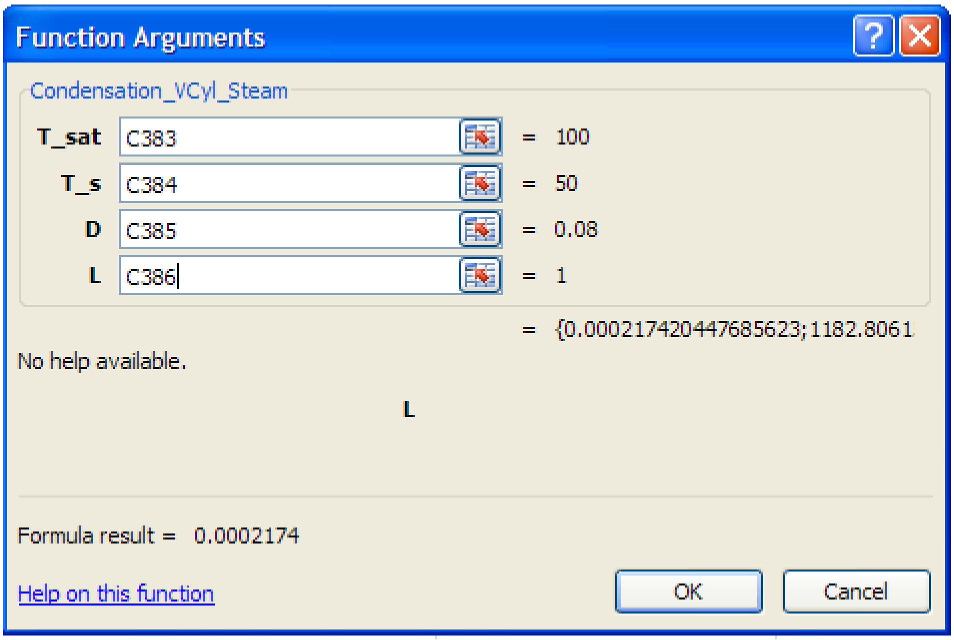
1. Set up the EXCEL worksheet, enter data:

	A	B	C	D
381				
382		Data:		
383		T_sat	100.000	C
384		T_s	50.000	C
385		D	0.080	m
386		L	1.000	m
387				
388		delta_L		m
389		Re_f		
390		h_avg		W/m^2.C
391		Q		W
392		m_cond		kg/s
393		m_cond_per_hour		kg/h

2. Now, **select the 5 consecutive cells** (i.e. cells C388 to C392) and enter the array Function for condensation of steam on Vertical cylinder: (See the previous problem for procedure of inserting a 'built-in' Function):



Click OK. Fill up the screen that shows up as follows:



Now, IMPORTANT: Press (Ctrl + Shift + Return or OK), since it is an Array Function. We get the results as shown below:

C389 | {=Condensation_VCyl_Steam(C383,C384,C385,C386)}

	A	B	C	D
381				
382		Data:		
383		T_sat	100.000	C
384		T_s	50.000	C
385		D	0.080	m
386		L	1.000	m
387				
388		delta_L	0.0002174	m
389		Re_f	1182.806	
390		h_avg	5604.515	W/m^2.C
391		Q	70428.408	W
392		m_cond	0.029350	kg/s
393		m_cond_per_hour		kg/h

In the above, the Function entered can be seen in the Formula bar.

Complete the last step by calculating m_cond per hour by multiplying the value in cell C392 by 3600. We get:

C393 | =C392*3600

	A	B	C	D
381				
382		Data:		
383		T_sat	100.000	C
384		T_s	50.000	C
385		D	0.080	m
386		L	1.000	m
387				
388		delta_L	0.0002174	m
389		Re_f	1182.806	
390		h_avg	5604.515	W/m^2.C
391		Q	70428.408	W
392		m_cond	0.029350	kg/s
393		m_cond_per_hour	105.661	kg/h

Thus:

The condensation rate is: 105.661 kg/h … Ans.

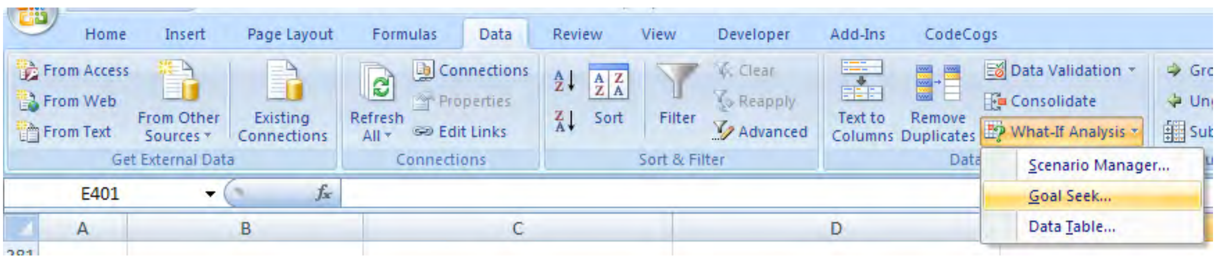
Note: This matches with the results obtained in Prob. 3.2.5.

(b) What should be the value of T_s to get a condensation rate of 125 kg/h?

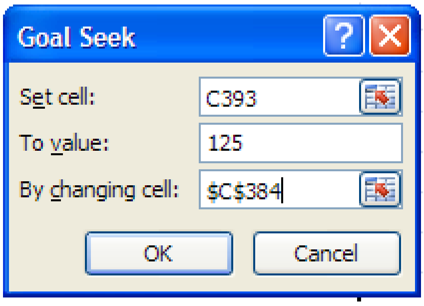
This is calculated by applying Goal Seek on cell C393 to make it 125 by changing cell C384 (i.e.value of T_s):

Following are the steps:

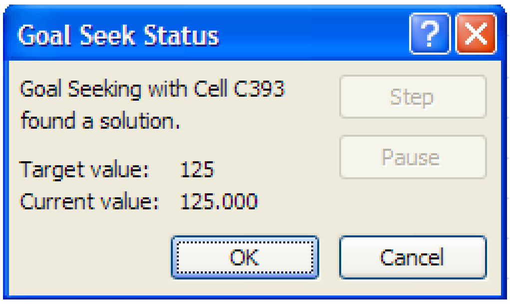
Go to Data – WhatIf Analysis – Goal Seek:



Click on Goal Seek. Fill up the screen that pops up as shown:



Click OK:



i.e. Goal Seek has found a solution. Click OK and see the value in cell C384 to get the required T_s:

C384 | fx | 33.5260406613353

	A	B	C	D
381				
382		**Data:**		
383		**T_sat**	**100.000**	**C**
384		**T_s**	**33.526**	**C**
385		**D**	**0.080**	**m**
386		**L**	**1.000**	**m**
387				
388		**delta_L**	**0.0002380**	**m**
389		**Re_f**	**1242.837**	
390		**h_avg**	**5084.249**	**W/m^2.C**
391		**Q**	**84941.168**	**W**
392		**m_cond**	**0.034722**	**kg/s**
393		**m_cond_per_hour**	**125.000**	**kg/h**

i.e. Value of T_s required to get a condensation rate of 125 kg/h is: 33.53 C … Ans.

Note: Values of delta_L, Re_f, h_avg, and Q also have got up-dated immediately.

===

Prob.3.2.26. Consider a horizontal tube, 1 m long, 50 mm dia, maintained at a uniform temp of 34 C, exposed to sat. steam at 0.2 bar. pressure. Find out the heat transfer and steam condensation rate.

EXCEL Solution:

Note that at 0.2 bar, sat. temp. T_sat = 60.06 C

Let us write a VBA Function to calculate h, Q and m_condensed for condensation of steam on a Horizl cylinder:

```
Function Condensation_on_HCyl_Steam(T_sat As Double, T_s As Double, D As Double, L As Double) As Variant

'Condensation of Steam at T_sat on a Horizl Cylinder  held at T_s

'Input: T_sat, T_s (C), D, L (m)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


'Properties of liquid at Tf:

rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
mu_l = SatH2O_muf_T(T_f + 273.15)
cp_l = SatH2O_cpf_T(T_f + 273.15)
k_l = SatH2O_kf_T(T_f + 273.15)
nu_l = mu_l / rho_l
Pr_l = SatH2O_Prf_T(T_f + 273.15)


'Properties of vapour and h_fg at Tsat:

rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
```

```
'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

h_avg = 0.729 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * D)) ^ (1 / 4) '[W/m^2-C] .... avg heat tr coeff over L

Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s


Condensation_on_HCyl_Steam = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

Read the comments in the above program to know what each line does.

Now, let us use this program to solve the above problem:

Following are the steps:

1. Set up the EXCEL worksheet, enter data:

C403 fx 1

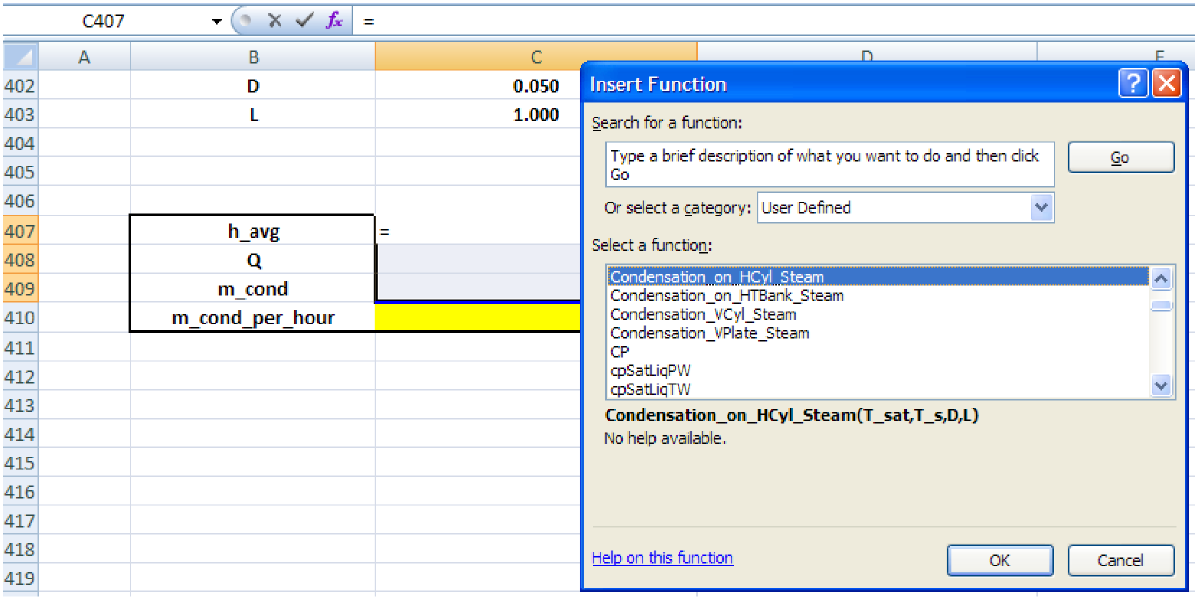
	A	B	C	
399		Data:		
400		T_sat	60.060	C
401		T_s	34.000	C
402		D	0.050	m
403		L	1.000	m
404				

2. Set up the worksheet for further calculation, remembering that we are going to use an Array Function:

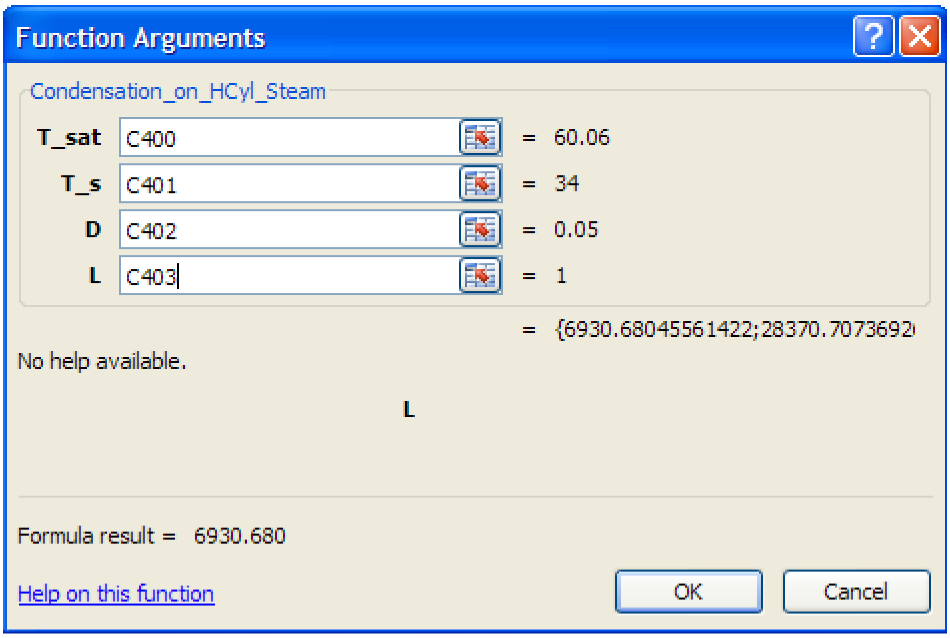
C417 fx

	A	B	C	D
399		Data:		
400		T_sat	60.060	C
401		T_s	34.000	C
402		D	0.050	m
403		L	1.000	m
404				
405				
406				
407		h_avg		W/m^2.C
408		Q		W
409		m_cond		kg/s
410		m_cond_per_hour		kg/h

3. Now, select three consecutive cells in column C, i.e. cells C407, C408 and C409, and insert the array Function:



4. Press OK. We get the following screen; fill it up as shown:



5. **IMPORTANT:** Now, apply (Ctrl + Shift + Return), since it is an Array Function. We get:

C407 | {=Condensation_on_HCyl_Steam(C400,C401,C402,C403)}

	A	B	C	D
399		Data:		
400		T_sat	60.060	C
401		T_s	34.000	C
402		D	0.050	m
403		L	1.000	m
404				
405				
406				
407		h_avg	6930.680	W/m^2.C
408		Q	28370.707	W
409		m_cond	0.011664	kg/s
410		m_cond_per_hour		kg/h

In the Formula bar, see the Array Function used for Condensation on Horizl cylinder.

6. Complete the last step to get condensation rate in kg/h in cell C410, by multiplying value in cell C409 by 3600:

D417

	A	B	C	D
399		Data:		
400		T_sat	60.060	C
401		T_s	34.000	C
402		D	0.050	m
403		L	1.000	m
404				
405				
406				
407		h_avg	6930.680	W/m^2.C
408		Q	28370.707	W
409		m_cond	0.011664	kg/s
410		m_cond_per_hour	41.990	kg/h

Thus:

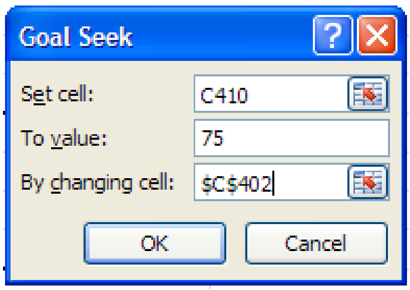
Heat transfer, q = 28370.7 W … ans.

Condensation rate = 41.99 kg/h …. Ans.

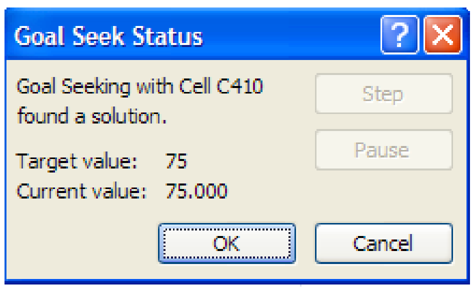
(b) What diameter is required to get a condensation rate of 75 kg/h?

Use Goal Seek in EXCEL to make cell C410 to 75 by changing cell C402 (i.e. value of D):

Click on: Data – WhatIf Analysis_GoalSeek. We get the following screen; fill it up as shown:



Click OK:



Goal seek has found a solution. Again, click OK and see the new value of D in cell C402:

C402 fx 0.108358014587117

	A	B	C	D
399		Data:		
400		T_sat	60.060	C
401		T_s	34.000	C
402		D	0.108	m
403		L	1.000	m
404				
405				
406				
407		h_avg	5712.196	W/m^2.C
408		Q	50674.380	W
409		m_cond	0.020833	kg/s
410		m_cond_per_hour	75.000	kg/h

Thus:

Dia required to get 75 kg/h of condensation rate is: D = 0.108 m … Ans.

==

Practically, the case of condensation on a bank of horizontal tubes in a vertical tier is more important than condensation on a single tube.

This is particularly relevant to Steam condensers where there are many columns (or Tiers), each Tier having many horizontal tubes, on which steam will condense at the condenser pressure.

Let us write a VBA Function for the case of condensation of steam on a Tier of horizontal tubes:

```
Function Condensation_on_HTBank_Steam(T_sat As Double, T_s As Double, D As Double, L As Double, _
N As Double, N_total As Double) As Variant

'Condensation of Steam at T_sat on a Horizl Tube Bank held at T_s
'i.e. A vertical Tier of N horizl tubes

'Input: T_sat, T_s (C), D, L (m), N (no. of tubes per Tier), N_total (total no. of
'tubes in all Tiers)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


'Properties of liquid at Tf:

rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
mu_l = SatH2O_muf_T(T_f + 273.15)
cp_l = SatH2O_cpf_T(T_f + 273.15)
k_l = SatH2O_kf_T(T_f + 273.15)
nu_l = mu_l / rho_l
Pr_l = SatH2O_Prf_T(T_f + 273.15)


'Properties of vapour and h_fg at Tsat:

rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)


'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

h_avg = 0.729 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * N * D)) ^ (1 / 4) '[W/m^2-C] .... avg heat tr coeff over L


Q = h_avg * N_total * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s


Condensation_on_HTBank_Steam = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

Now, use this Function to solve the following problem:

Problem 3.2.27. Consider a one-pass Condenser which has a total of 64 tubes, arranged in a square array. Tubes are 1.25 m long, 12 mm OD. Water flowing inside the tubes maintains the wall temp at 25 C. If the steam is condensing on the outside of tubes at 0.1 bar pressure, find: (i) the heat transfer (ii) the condensation rate.

EXCEL Solution:

We have, at 0.1 bar: T_sat = 45.81 C, and, T_s = 25 C.

Since it is a square array, there are 8 Tiers, each Tier having 8 horizontal tubes. i.e. N = 8, N_total = 64

1. Set up the EXCEL worksheet, enter data:

C423 f_x 64

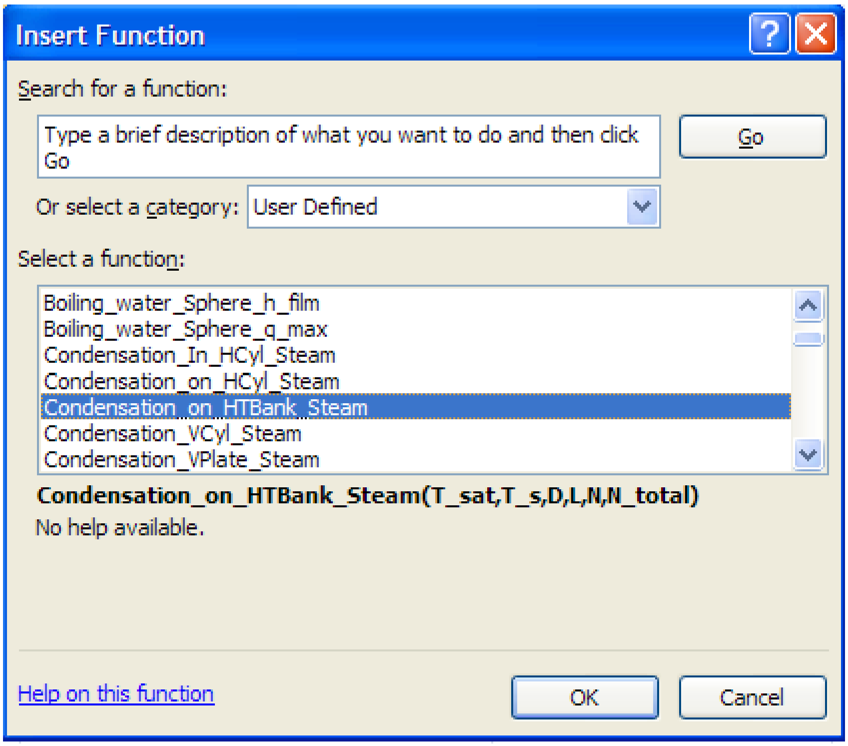
	A	B	C	
417		Data:		
418		T_sat	45.810	C
419		T_s	25.000	C
420		D	0.012	m
421		L	1.250	m
422		N	8	
423		N_total	64	

2. Set up the calculations for the Tube Bank, using the Array Function just written:

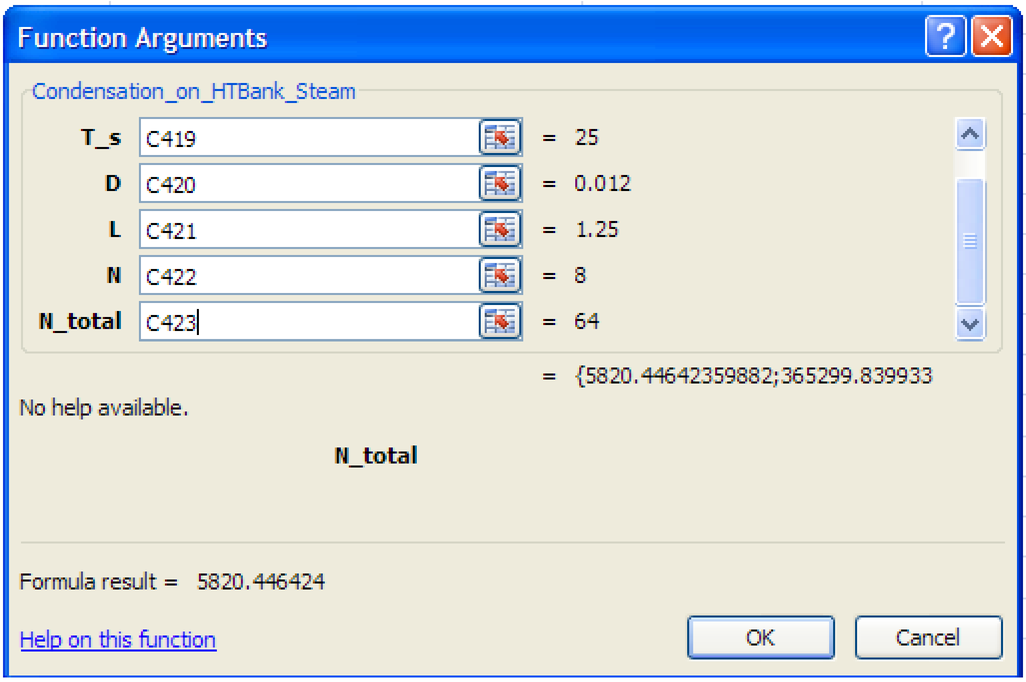
C428 f_x =C427*3600

	A	B	C	D
417		Data:		
418		T_sat	45.810	C
419		T_s	25.000	C
420		D	0.012	m
421		L	1.250	m
422		N	8	
423		N_total	64	
424				
425		h_avg		W/m^2.C
426		Q		W
427		m_cond		kg/s
428		m_cond_per_hour	0.000	kg/h

3. Select the cells C425, C426 and C427 and enter the Array Function:



Click OK. We get the following screen; fill it up as shown:



IMPORTANT: Now, press (Ctrl + Shift + Enter), since it is an Array Function. We get:

C427 | fx {=Condensation_on_HTBank_Steam(C418,C419,C420,C421,C422,C423)}

	A	B	C	D
417		Data:		
418		T_sat	45.810	C
419		T_s	25.000	C
420		D	0.012	m
421		L	1.250	m
422		N	8	
423		N_total	64	
424				
425		h_avg	5820.446424	W/m^2.C
426		Q	365299.839933	W
427		m_cond	0.149004	kg/s
428		m_cond_per_hour	536.413	kg/h

Thus:

Heat transferred, Q = 365299.84 W …. Ans.

Condensation rate = 536.413 kg/h … Ans.

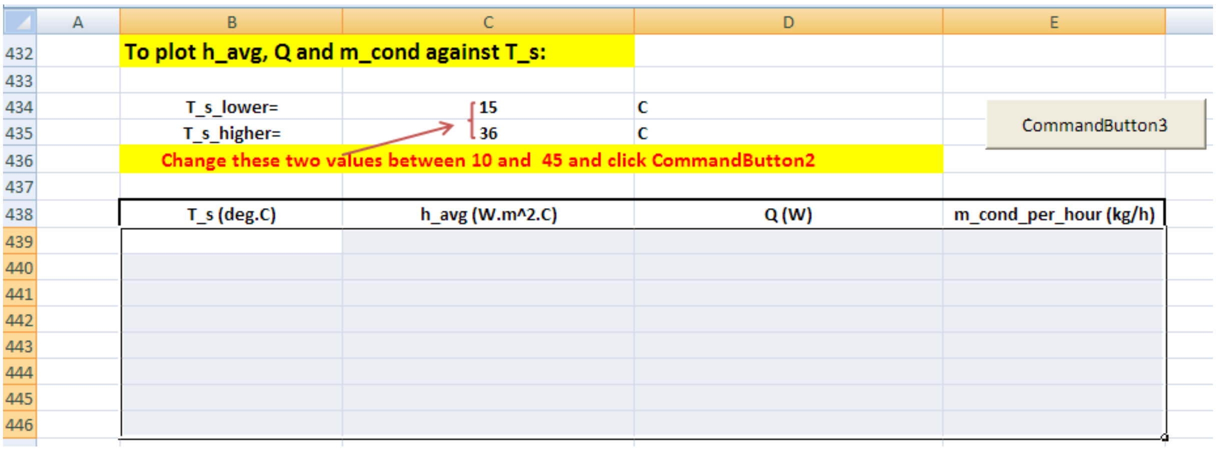
(b) For T_s varying from 15 C to 36 C, plot the condensation rate against T_s:

Let us write a VBA program to do this.

1. Before that, set up a Table as shown:

We plan to give lower limit and upper limit of T_s, and then the program should fill up the Table for 7 equally divided values of T_s and also the program should be executed with a ControlButton.

For the procedure of inserting an ActiveX ControlButton, see Problem 3.2.22.



2. Now, double click on the ControlButton3 and we see the VBA program behind it:

```
Private Sub CommandButton3_Click()

End Sub
```

---

3. Now, modify this program as follows to perform the desired calculation steps:

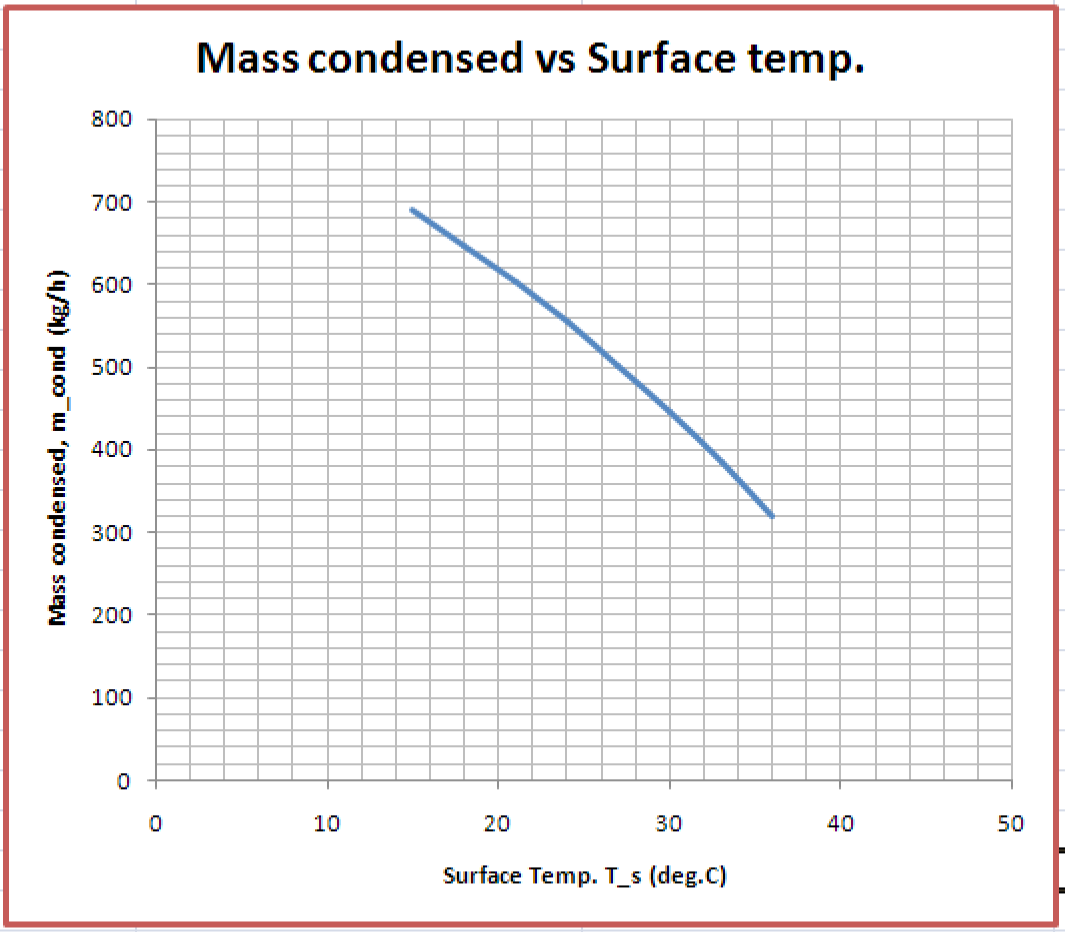
```
Private Sub CommandButton3_Click()


Dim i As Integer
Dim T_s_initial As Double, T_s_final As Double, Inc As Double

T_s_initial = Range("C434") 'starting value for T_s
T_s_final = Range("C435") 'starting value for T_s

Inc = (T_s_final - T_s_initial) / 7

For i = 0 To 7

Range("C419") = T_s_initial + i * Inc 'Sets the T_s value to the starting or initial value

'Immediately, all other values will up-date themselves.
'And, copy them to their respective places in the Table:

Cells(439 + i, 2) = Range("C419") 'copies value of T_s to Table
Cells(439 + i, 3) = Range("C425") 'copies value of h_avg to Table
Cells(439 + i, 4) = Range("C426") 'copies value of Q to Table
Cells(439 + i, 5) = Range("C428") 'copies value of m_cond_per_hour to Table

Next i

End Sub
```

Read the comments in the above code to know what each line does.

4. Now, click on the CommandButton3 and immediately the calculations are done and the Table is filled up:

	A	B	C	D	E
432		To plot h_avg, Q and m_cond against T_s:			
433					
434		T_s_lower=	15	C	
435		T_s_higher=	36	C	CommandButton3
436	You may change T_s such that: T_s higher < 45 and T_s_lower > 0, Then click CommandButton3.				
437					
438		T_s (deg.C)	h_avg (W.m^2.C)	Q (W)	m_cond_per_hour (kg/h)
439		15	5115.017	475291.304	689.929
440		18	5298.407	444393.233	647.304
441		21	5501.440	411646.348	601.680
442		24	5734.516	377201.641	553.249
443		27	6007.410	340798.132	501.597
444		30	6327.369	301700.556	445.604
445		33	6723.455	259754.282	384.996
446		36	7247.254	214419.168	318.922

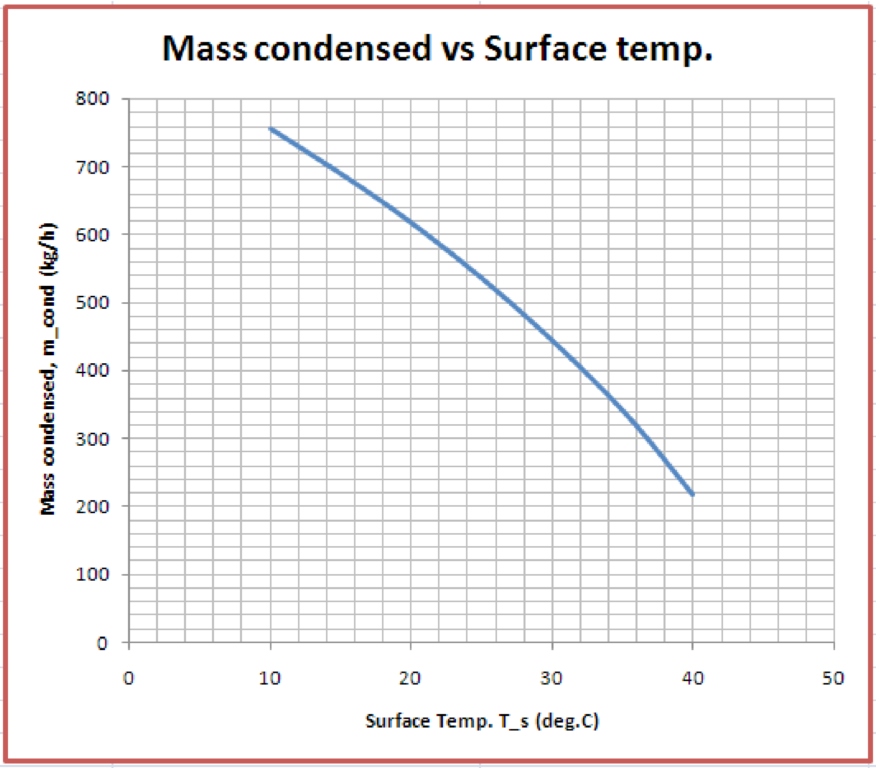
5. Now, plot m_cond against T_s:



6. Now, we can easily change the range of T_s as we desire, by changing cells C434 and C435. **As an example, for T_s between the limits 10 and 40 C:** Change cells C434 and C435 as shown and click CommandButton3 and we get:

	A	B	C	D	E
432		**To plot h_avg, Q and m_cond against T_s:**			
433					
434		T_s_lower=	10	C	CommandButton3
435		T_s_higher=	40	C	
436	You may change T_s such that: T_s higher < 45 and T_s_lower > 0, Then click CommandButton3.				
437					
438		T_s (deg.C)	h_avg (W.m^2.C)	Q (W)	m_cond_per_hour (kg/h)
439		10	4850.412	523846.512	756.077
440		14.28571429	5074.320	482441.042	699.735
441		18.57142857	5335.103	438276.570	638.814
442		22.85714286	5641.651	390538.681	572.053
443		27.14285714	6021.628	339010.287	499.048
444		31.42857143	6503.887	282095.465	417.343
445		35.71428571	7189.665	218910.618	325.493
446		40	8349.039	146296.424	218.624

And, the plot updates itself immediately:



==

Prob.3.2.28. Consider a horizontal tube, 4 m long, 30 mm ID, maintained at a uniform temp of 110 C, inside which sat. steam at 2.701 bar condenses. Assuming low vap. velocity, find out the heat transfer and steam condensation rate.

EXCEL Solution:

Note that at 2.701 bar, sat. temp. T_sat = 130 C

Let us write a VBA Function to calculate h, Q and m_condensed for condensation of steam on inside a Horizontal cylinder:

```
Function Condensation_In_HCyl_Steam(T_sat As Double, T_s As Double, D As Double, L As Double, U_v As Double) As Variant

'Condensation of Steam at T_sat inside a Horizl Cylinder  held at T_s

'Input: T_sat, T_s (C), D, L (m), U_v (vap. velocity, m/s)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double, mu_v As Double, Re_vap As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


 'Properties of liquid at Tf:

 rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
 mu_l = SatH2O_muf_T(T_f + 273.15)
 cp_l = SatH2O_cpf_T(T_f + 273.15)
 k_l = SatH2O_kf_T(T_f + 273.15)
 nu_l = mu_l / rho_l
 Pr_l = SatH2O_Prf_T(T_f + 273.15)


 'Properties of vapour and h_fg at Tsat:

 rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
 mu_v = SatH2O_mug_T(T_sat + 273.15)
 h_fg = SatH2O_hfg_T(T_sat + 273.15)
```

```
'Calculations:

h_fg_prime = h_fg + (3 / 8) * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

Re_vap = rho_v * U_v * D / mu_v '..Vapour Reynolds No...must be < 35000!!

If (Re_vap <= 35000) Then

h_avg = 0.555 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * D)) ^ (1 / 4) '[W/m^2-C] .... avg internal heat tr coeff over L

ElseIf (Re_vap > 35000) Then

    MsgBox ("Re_vap must be <= 35000. Now, Re_vap =" & Re_vap)

End If


Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s


Condensation_In_HCyl_Steam = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

Now, let us solve the above problem:

1. Set up the EXCEL worksheet, enter data:

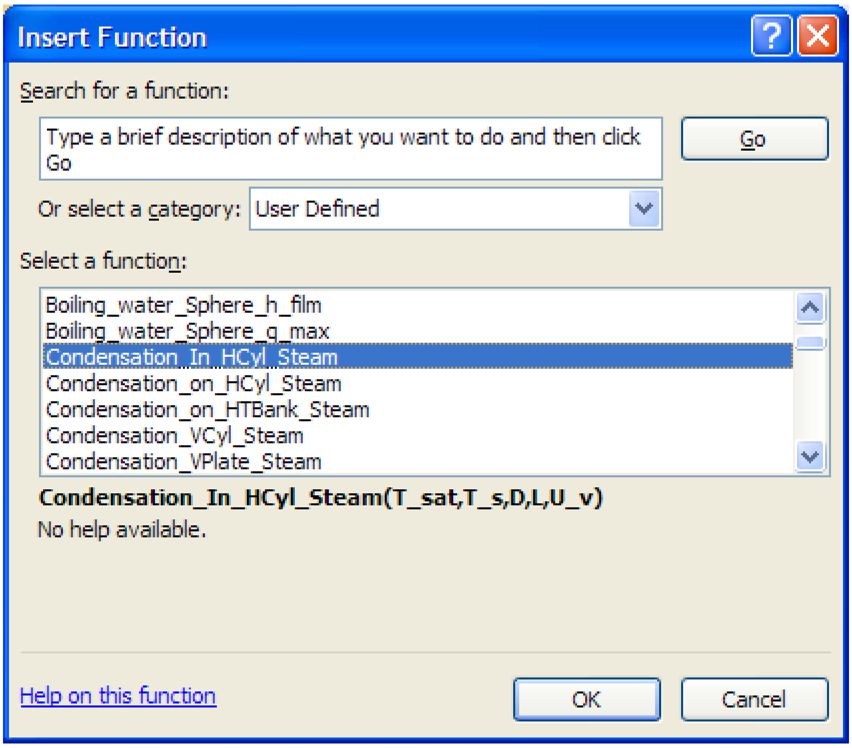
	A	B	C	D
475				
476		**Data:**		
477		**T_sat**	**130.000**	**C**
478		**T_s**	**110.000**	**C**
479		**D**	**0.030**	**m**
480		**L**	**4.000**	**m**
481		**U_v**	**0**	**m/s...vap. Velocity**
482				

2. Set up the calculations for the condensation inside the horizl cylinder, using the Array Function just written:

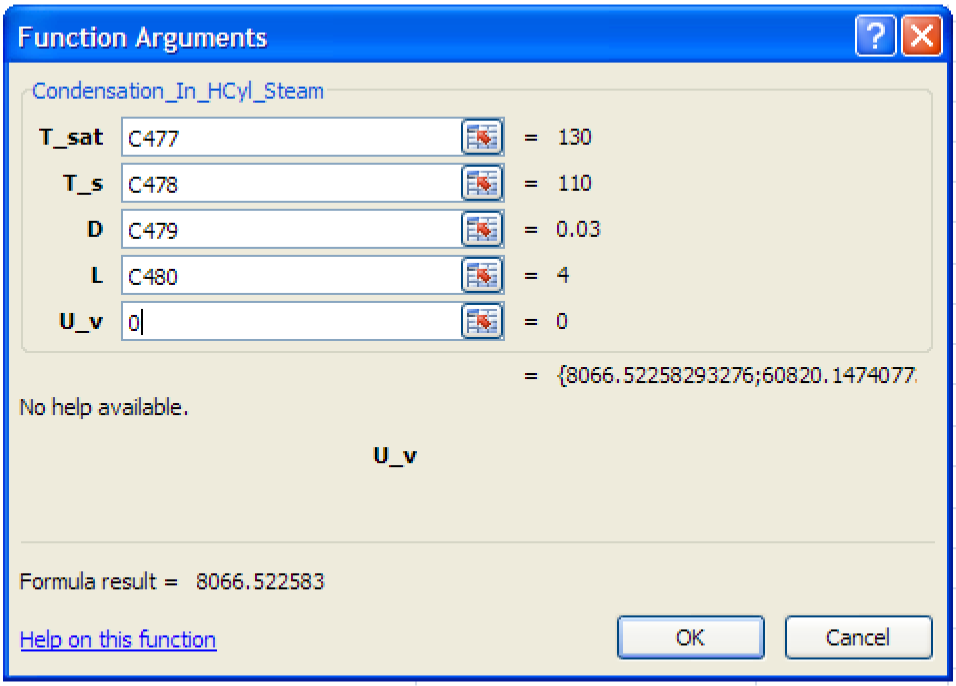
C487 | =C486*3600

	A	B	C	D
475				
476		Data:		
477		T_sat	130.000	C
478		T_s	110.000	C
479		D	0.030	m
480		L	4.000	m
481		U_v	0	m/s...vap. Velocity
482				
483				
484		h_avg		W/m^2.C
485		Q		W
486		m_cond		kg/s
487		m_cond_per_hour	0.000	kg/h

3. Select the cells C484, C485 and C486 and enter the Array Function:



Click OK. We get the following screen; fill it up as shown:



IMPORTANT: Now, press (Ctrl + Shift + Enter), since it is an Array Function. We get:

C484 | {=Condensation_In_HCyl_Steam(C477,C478,C479,C480,C481)}

	A	B	C	D
476		Data:		
477		T_sat	130.000	C
478		T_s	110.000	C
479		D	0.030	m
480		L	4.000	m
481		U_v	0	m/s...vap. Velocity
482				
483				
484		h_avg	8066.522583	W/m^2.C
485		Q	60820.147408	W
486		m_cond	0.027578	kg/s
487		m_cond_per_hour	99.281	kg/h

Thus:

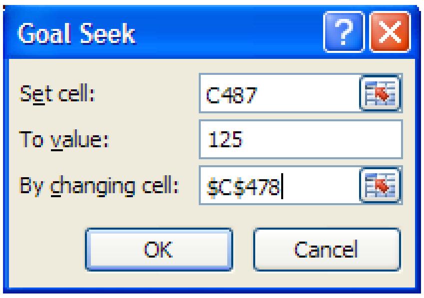
Heat transferred, Q = 60820.15 W …. Ans.

Condensation rate = 99.28 kg/h … Ans.

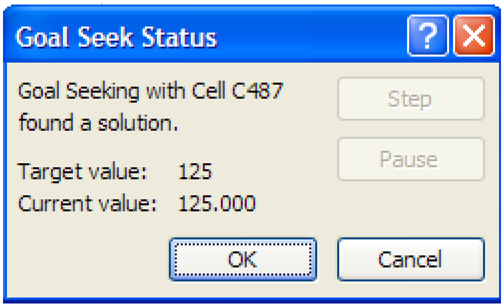
(b) What should be the surface temp, T_s, if we need to get a condensation rate of 125 kg/h?

Use Goal Seek in EXCEL to make cell C487 to 125 by changing cell C478 (i.e. value of T_s):

Click on: Data – WhatIf Analysis_GoalSeek. We get the following screen; fill it up as shown:



Click OK:


Goal Seek Status
Goal Seeking with Cell C487
found a solution.
Target value: 125
Current value: 125.000
Step
Pause
OK
Cancel

Goal seek has found a solution. Again, click OK and see the new value of T_s in cell C478:

C478 | fx 102.362061326824

	A	B	C	D
476		Data:		
477		T_sat	130.000	C
478		T_s	102.362	C
479		D	0.030	m
480		L	4.000	m
481		U_v	0	m/s...vap. Velocity
482				
483				
484		h_avg	7389.803180	W/m^2.C
485		Q	76996.261555	W
486		m_cond	0.034722	kg/s
487		m_cond_per_hour	125.000	kg/h

Thus:

Surface temp required to get 125 kg/h of condensation rate is: T_s = 102.36 C … Ans.

==

VBA Functions for properties of Ammonia (NH3) (i.e. R717):

Many times, we need properties of NH3 at a given temp while solving problems on condensation. *But, EXCEL does not have built-in property functions for NH3.*

So, we shall use these Tables on properties of Sat. NH3, shown below and write Functions in VBA to find out various properties. The required properties are found at the given temp (in K) by interpolation.

Following are the steps:

1. First, enter the data table in EXCEL as shown below:

Ref: https://www.thermalfluidscentral.org/encyclopedia/index.php/Thermophysical_Properties:_Ammonia

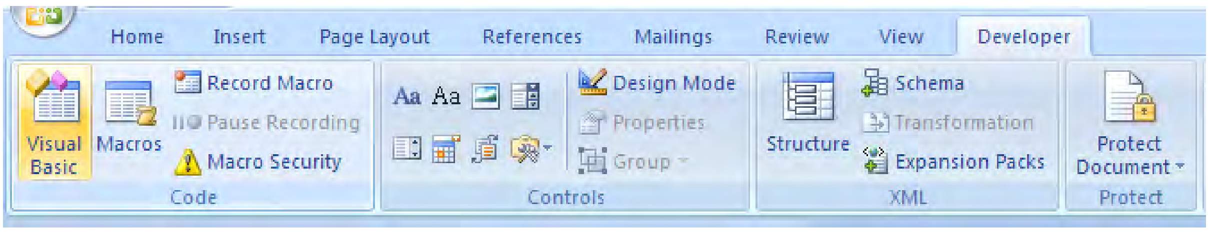
Thermophysical Properties: Ammonia

Ammonia, NH_3, Molecular Mass: 17.0, (T_{sat} = 239.9 K; Tm = 195.5 K)

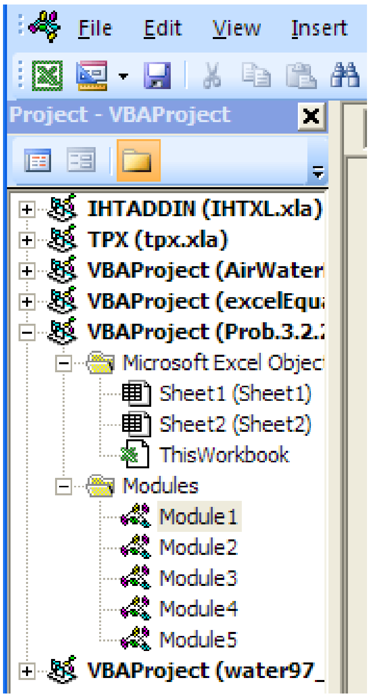
Temp. K	p_v saturation pressure (10^5 Pa)	h_{lv} latent heat (kJ/kg)	ρ_ℓ liquid density (kg/m³)	ρ_v vapor density (kg/m³)	μ_ℓ liquid viscosity (10-6 N-s/m²)	μ_v vapor viscosity (10^{-6} N-s/m²)	k_ℓ liquid thermal conductivity (W/m-K)	k_v vapor thermal conductivity (W/m-K)	σ liquid surface tension a (10^{-3}N/m)	$c_{p,\ell}$ liquid specific heat (kJ/kg-K)	$c_{p,v}$ vapor specific heat a (kJ/kg-K)
200	0.008646	1477	728.9	0.08899	407	7.64	0.709	0	0	4.606	1.979
210	0.017746	1451	717.5	0.1746	369	8.02	0.685	0	0	4.375	2.033
220	0.033811	1425	705.8	0.319	334	8.4	0.661	0.0158	0	4.346	2.083
230	0.060439	1398	693.7	0.5489	302	8.78	0.638	0.0171	0	4.382	2.151
240	0.10226	1369	681.4	0.8972	273	9.16	0.615	0.0184	33.9	4.431	2.237
250	0.16496	1339	668.9	1.404	245	9.54	0.592	0.0199	31.5	4.483	2.343
260	0.25529	1307	656.1	2.115	220	9.93	0.569	0.0211	29.2	4.539	2.467
270	0.381	1273	642.9	3.086	197	10.31	0.546	0.0224	26.9	4.597	2.611
280	0.55077	1237	629.2	4.38	176	10.7	0.523	0.0239	24.7	4.662	2.776
290	0.77413	1198	615	6.071	157.7	11.07	0.5	0.0256	22.4	4.734	2.963
300	1.0614	1159	600.2	8.247	141	11.45	0.477	0.0277	20.2	4.815	3.18
310	1.4235	1113	584.6	11.01	126	11.86	0.454	0.0302	18	4.909	3.428
320	1.8721	1066	568.2	14.51	113.4	12.29	0.431	0.0332	15.9	5.024	3.725
330	2.4196	1014	550.9	18.89	101.9	12.74	0.408	0.0368	13.7	5.17	4.088
340	3.0789	958	532.4	24.4	92.1	13.22	0.385	0.0415	11.7	5.366	4.545
350	3.8641	895	512.3	31.34	83.2	13.74	0.361	0.0467	9.6	5.639	5.144
360	4.7902	825	490.3	40.18	75.4	14.35	0.337	0.0536	7.67	6.042	5.978
370	5.874	745	465.5	51.65	68.5	15.07	0.313	0.0614	5.74	6.677	7.217
380	7.1352	649	436.5	67.16	61.1	15.96	0.286	0.07	3.98	7.795	9.312
390	8.5977	529	400.2	89.85	50.3	17.14	0.254	0.08	2.21	10.27	13.86

Note that temp range is: T = 200 K – 390 K.

2. Now, the various properties are required as a function of T. So, the VBA program we write will search for the temp in the column B and if it finds the exact match, it will return the required property by reading the same in that row. If the exact temp match is not available (this is the more likely scenario), it will locate two consecutive cells where one temp is lower than required T, and the other temp is higher than T. Also, the corresponding values of the property at these two temperatures are noted. Then, a linear interpolation is made between these two values of the property and the same is returned.
3. Now, write the VBA code. Go to Developer – Visual Basic –



Click on Visual Basic:



And, click on Module1, wherein VBA programs for properties of Air were written. Go to the end of that Module and write programs for NH3.

One example is shown below, for density of liquid, rho_f:

```
(General)                                    (Declarations)

Function SatNH3_rho_f_T(T As Double) As Double
'gives density of liq rho_f(kg/m^3)as a function of T (K) at sat. temp T(K)
'Reads rho_f values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, rho_f1 As Double, rho_f2 As Double

If T < 200 Or T > 390 Then

 MsgBox ("T must be between 200 K and 390 K !!")
 End
 End If

For i = 0 To 19

   If Cells(96 + i, 13) = T Then
      SatNH3_rho_f_T = Cells(96 + i, 16)
   End If
   If Cells(96 + i, 13) < T And Cells(96 + i + 1, 13) > T Then
      T_1 = Cells(96 + i, 13).Value
      T_2 = Cells(96 + i + 1, 13).Value
      rho_f1 = Cells(96 + i, 16).Value
      rho_f2 = Cells(96 + i + 1, 16).Value
      SatNH3_rho_f_T = (rho_f1 + (T - T_1) * (rho_f2 - rho_f1) / (T_2 - T_1))
   End If

Next i

End Function
```

In the above code:

1st line: declares name of the function, with dimensions of variables involved

Lines 2, 3: comments – explain about the Function

Line 4, 5: declarations of dimensions of internal variables, i.e. variables available only inside the Function

Line 6 to 9: If statement to give an error message if value of T entered is beyond the values available in the Table

Line 10: Beginning of For…Next construct. Note that the construct will search in the 20 lines of the Table

Lines 11, 12, 13: If the exact match for T is found, Function returns the value of 'rho' in the column P

Lines 14 to 20: If he exact match of T is not there in the Table, then locate the values of T just below T and just above T,, and name them as T_1 and T_2. Also, note the corresponding values of rho as rho_f1 and rho_f2. And, then, calculate the value of rho at the required T by interpolation.

Line 21: Go to the next i in the loop

Line 22: End statement of Function.

4. Similar Functions are written for other properties of NH3, as functions of T. i.e.

For density of vap….SatNH3__rho_g_T(T)

For th. conductivity of liq….SatNH3_k_f_T(T)

For th. conductivity of vap….SatNH3_k_g_T(T)

For sp. heat of liq….SatNH3_cp_f_T(T)

For sp. heat of vap….SatNH3_cp_g_T(T)

For surface tension….SatNH3_sigma_f_T(T)

For dynamic viscosity of liq….SatNh3_mu_f_T(T)

For dynamic viscosity of vap….SatNh3_mu_g_T(T), and

For heat of vaporization of liq….SatNh3_h_fg_T(T)

Now, using these VBA Functions for properties of NH3, write Functions for condensation of Sat NH3 on vertical plates, vertical cylinders, Horizl cylinder, Tube bank with horizl tubes in a vertical tier, condensation inside horizontal cylinder etc.

One example of a VBA program for **condensation of NH3 on the outside of a horizl cylinder** is shown below:

```
Function Condensation_on_HCyl_NH3(T_sat As Double, T_s As Double, D As Double, L As Double) As Variant

'Condensation of NH3 at T_sat on a Horizl Cylinder  held at T_s

'Input: T_sat, T_s (C), D, L (m)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


 'Properties of liquid at Tf:

 rho_l = SatNH3_rho_f_T(T_f + 273.15)
 mu_l = SatNH3_mu_f_T(T_f + 273.15)
 cp_l = SatNH3_cp_f_T(T_f + 273.15)
 k_l = SatNH3_k_f_T(T_f + 273.15)
 nu_l = mu_l / rho_l
 Pr_l = cp_l * mu_l / k_l


 'Properties of vapour and h_fg at Tsat:

 rho_v = SatNH3_rho_g_T(T_sat + 273.15)
 h_fg = SatNH3_h_fg_T(T_sat + 273.15)


'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

h_avg = 0.729 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * D)) ^ (1 / 4) '[W/m^2-C] .... avg heat tr coeff over L

Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s


Condensation_on_HCyl_NH3 = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

Now, the above program is an Array Function and returns h_avg, Q and Mass_condensed in a vertical array.

Let us solve a problem using this Function:

Prob. 3.2.29. Sat. NH3 vapour at 10 C condenses on the outside of a 2 cm OD, 5 m long horizontal tube whose outer surface is maintained at -10 C. Determine: (a) rate of heat transfer (b) rate of condensation of NH3.

EXCEL Solution:

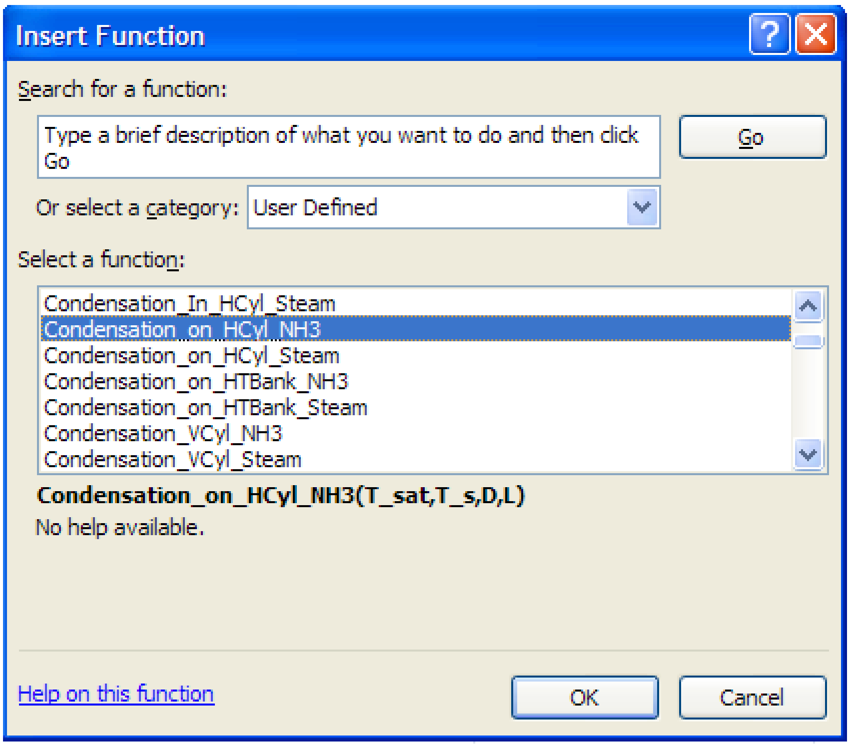
We shall use the VBA program written above for condensation on a horizl tube:

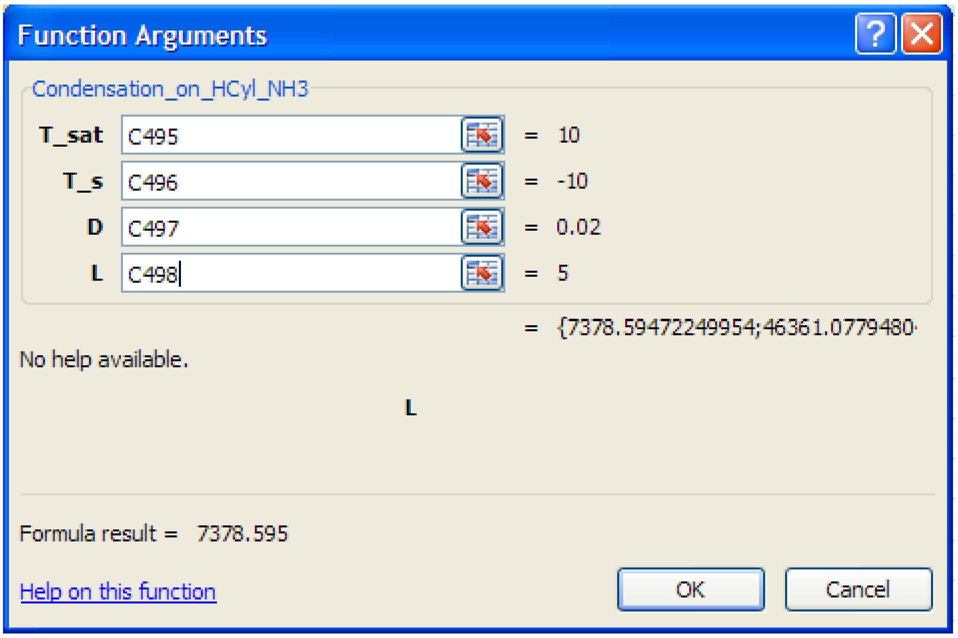
Following are the steps:

1. Set up the EXCEL worksheet, enter data:

	A	B	C	D
493				
494		Data: Fluid: Ammonia		
495		T_sat	10.000	C
496		T_s	-10.000	C
497		D	0.020	m
498		L	5.000	m
499				
500				
501				
502		h_avg		W/m^2.C
503		Q		W
504		m_cond		kg/s
505		m_cond_per_hour	0.000	kg/h

2. Select cells C502to C504 and enter the Array Function for condensation of NH3 on the outside of a horizontal cylinder. Remember to press (Ctrl + Shift + Enter) after selecting the Function from the 'User Defined' category, and entering the required parameters for the Function:





Press (Ctrl+Shift+OK) since it is an Array Function, and we get:

C502 | {=Condensation_on_HCyl_NH3(C495,C496,C497,C498)}

	A	B	C	D
493				
494		Data: Fluid: Ammonia		
495		T_sat	10.000	C
496		T_s	-10.000	C
497		D	0.020	m
498		L	5.000	m
499				
500				
501				
502		h_avg	7378.595	W/m^2.C
503		Q	46361.078	W
504		m_cond	0.036008	kg/s
505		m_cond_per_hour	129.630	kg/h

Thus:

h_avg = 7378.6 W/m^2.C …. Ans.

Q = 46361.1 W …. Ans.

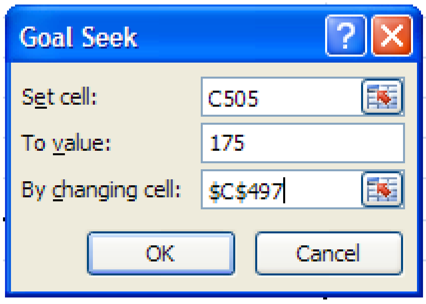
m_cond_per_hour = 129.63 kg/h …. Ans.

(b) What should be the diameter if we need to have a condensation rate of 175 kg/h?

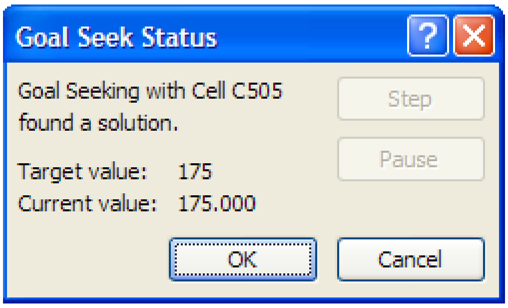
This is easily calculated by applying Goal seek to cell C505 (i.e. m_cond_per_hour) to make it 175 by changing cell C497 (i.e. D).

The procedure is:

Go to Data – WhatIf Analysis – Goal Seek Click on Goal Seek. We get the following screen; fill it up as shown:



Click OK. We get:



Goal Seek has found a solution. Again, click OK and see the result in cell C497:

C497 | f_x 0.0298406322119435

	A	B	C	D
493				
494		Data: Fluid: Ammonia		
495		T_sat	10.000	C
496		T_s	-10.000	C
497		D	0.0298	m
498		L	5.000	m
499				
500				
501				
502		h_avg	6676.197	W/m^2.C
503		Q	62587.419	W
504		m_cond	0.048611	kg/s
505		m_cond_per_hour	175.000	kg/h

Thus: Value of D required to get a condensation rate of 175 kg/h = 0.0298 m … Ans.

Note that correspondingly, values of h_avg and Q also have changed.

===

VBA Functions for properties of Refrigerant R134a:

R134a is a substitute for R12, since R12 is phased out due to its contribution to ozone layer depletion. *But, EXCEL does not have built-in property functions for R134a.*

So, we shall use these Tables on properties of Sat. R134a, shown below and write Functions in VBA to find out various properties. The required properties are found at the given temp (in K) by interpolation.

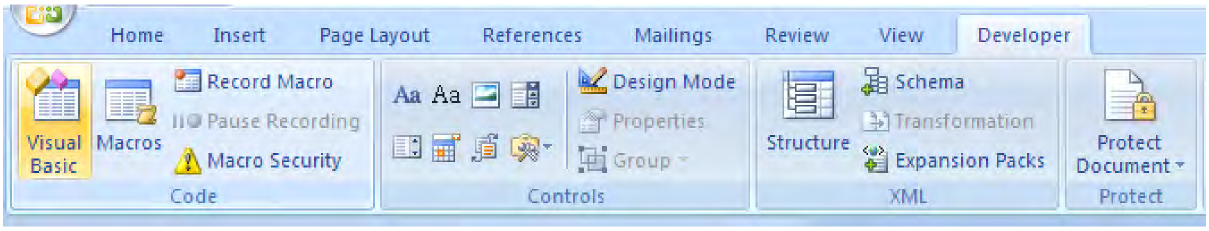
Following are the steps:

1. First, enter the data table in EXCEL as shown below:

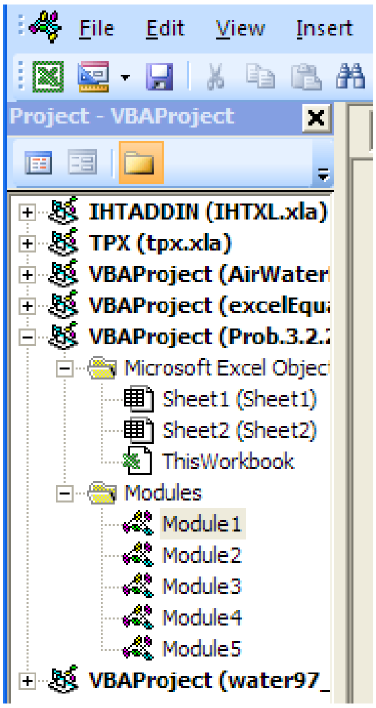
	M	N	O	P	Q	R	S	T	U	V	W	X
117	Ref: https://www.thermalfluidscentral.org/encyclopedia/index.php/Thermophysical_Properties:_Freon%C2%AE-134a											
118	**Thermophysical Properties: Freon®-134a**											
119												
120	Freon-134a, CF3CH2F, Molecular Mass: 102.0, (T_{sat} = -26.4°C; T_m = -101 °C)											
121	TTemp. K	p_v saturation pressure (10^5 Pa)	h_{lv} latent heat (kJ/kg)	ρ_ℓ liquid density (10^3 kg/m³)	ρ_v vapor density (kg/m³)	μ_ℓ liquid viscosity (10^{-3} N-s/m²)	μ_v vapor viscosity (10^{-7} N-s/m²)	k_ℓ liquid thermal conductivity (W/m-K)	k_v vapor thermal conductivity (W/m-K)	σ liquid surface tension (10-3N/m)	$c_{p,\ell}$ liquid specific heat (kJ/kg-K)	$c_{p,v}$ vapor specific heat (kJ/kg-K)
122	213	0.1591	237.95	1.474	0.9268	0.663	83	0.121	0.00656	20.8	1.223	0.692
123	233	0.5121	225.86	1.418	2.769	0.472	91.2	0.111	0.00817	17.6	1.255	0.749
124	253	1.3273	212.91	1.358	6.785	0.353	99.2	0.101	0.00982	14.51	1.293	0.816
125	273	2.928	198.6	1.295	14.428	0.271	107.3	0.092	0.01151	11.56	1.341	0.897
126	293	5.7171	182.28	1.225	27.778	0.211	115.81	0.0833	0.01333	8.76	1.405	1.001
127	313	10.166	163.02	1.147	50.075	0.163	125.5	0.0747	0.01544	6.13	1.498	1.145
128	333	16.818	139.13	1.053	81.413	0.124	137.9	0.0661	0.01831	3.72	1.66	1.387

Note that temp range is: T = 213 K – 333 K.

2. Now, the various properties are required as a function of T. So, the VBA program we write will search for the temp in the column B and if it finds the exact match, it will return the required property by reading the same in that row. If the exact temp match is not available (this is the more likely scenario), it will locate two consecutive cells where one temp is lower than required T, and the other temp is higher than T. Also, the corresponding values of the property at these two temperatures are noted. Then, a linear interpolation is made between these two values of the property and the same is returned.
3. Now, write the VBA code. Go to Developer – Visual Basic –



Click on Visual Basic:



And, click on Module1, wherein VBA programs for properties of Air, NH3 etc. were written. Go to the end of that Module and write programs for R134a.

One example is shown below, for density of liquid, rho_f:

```
Function R_134a_rho_f_T(T As Double) As Double
'gives rho_f of R134a (kg/m^3)as a function of T (K) at sat. temp T(K)
'Reads rho_f values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, rhof1 As Double, rhof2 As Double

If T < 213 Or T > 333 Then

 MsgBox ("T must be between 213 K and 333 K !!")

 End

End If

For i = 0 To 6

   If Cells(122 + i, 13) = T Then
       R_134a_rho_f_T = Cells(122 + i, 16) * 10 ^ 3
   End If
   If Cells(122 + i, 13) < T And Cells(122 + i + 1, 13) > T Then
      T_1 = Cells(122 + i, 13).Value
      T_2 = Cells(122 + i + 1, 13).Value
      rhof1 = Cells(122 + i, 16).Value
      rhof2 = Cells(122 + i + 1, 16).Value
      R_134a_rho_f_T = (rhof1 + (T - T_1) * (rhof2 - rhof1) / (T_2 - T_1)) * 10 ^ 3
   End If

Next i

End Function
```

In the above code:

1st line: declares name of the function, with dimensions of variables involved

Lines 2, 3: comments – explain about the Function

Line 4, 5: declarations of dimensions of internal variables, i.e. variables available only inside the Function

Line 6 to 9: If statement to give an error message if value of T entered is beyond the values available in the Table

Line 10: Beginning of For…Next construct. Note that the construct will search in the 7 lines of the Table

Lines 11, 12, 13: If the exact match for T is found, Function returns the value of 'rho' in the column P

Lines 14 to 20: If he exact match of T is not there in the Table, then locate the values of T just below T and just above T,, and name them as T_1 and T_2. Also, note the corresponding values of rho as rhof1 and rhof2. And, then, calculate the value of rho at the required T by interpolation.

Line 21: Go to the next i in the loop

Line 22: End statement of Function.

4. Similar Functions are written for other properties of R134a, as functions of T. i.e.

For density of vap….R134a__rho_g_T(T)

For th. conductivity of liq….R134a_k_f_T(T)

For th. conductivity of vap….R134a_k_g_T(T)

For sp. heat of liq….R134a_cp_f_T(T)

For sp. heat of vap….SatNH3_cp_g_T(T)

For surface tension….R134a_sigma_f_T(T)

For dynamic viscosity of liq….R134a_mu_f_T(T)

For dynamic viscosity of vap….R134a_mu_g_T(T), and

For heat of vaporization of liq….R134a_hfg_T(T)

Now, using these VBA Functions for properties of R134a, we can write Functions for condensation of R134a on vertical plates, vertical cylinders, Horizl cylinder, Tube bank with horizl tubes in a vertical tier, condensation inside horizontal cylinder etc.

One example of a VBA program for **condensation of R134a inside of a horizontal cylinder** is shown below:

```
Function Condensation_In_HCyl_R134a(T_sat As Double, T_s As Double, D As Double, L As Double, U_v As Double) As Variant

'Condensation of R134a at T_sat inside a Horizl Cylinder  held at T_s

'Input: T_sat, T_s (C), D, L (m), U_v (vap. velocity, m/s)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double, mu_v As Double, Re_vap As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


 'Properties of liquid at Tf:

 rho_l = R_134a_rho_f_T(T_f + 273.15)
 mu_l = R_134a_mu_f_T(T_f + 273.15)
 cp_l = R_134a_cp_f_T(T_f + 273.15)
 k_l = R_134a_k_f_T(T_f + 273.15)
 nu_l = mu_l / rho_l
 Pr_l = cp_l * mu_l / k_l


 'Properties of vapour and h_fg at Tsat:

 rho_v = R_134a_rho_g_T(T_sat + 273.15)
 h_fg = R_134a_hfg_T(T_sat + 273.15)
 mu_v = R_134a_mu_g_T(T_sat + 273.15)


'Calculations:

h_fg_prime = h_fg + (3 / 8) * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

Re_vap = rho_v * U_v * D / mu_v '..Vapour Reynolds No...must be < 35000!!

If (Re_vap <= 35000) Then

h_avg = 0.555 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * D)) ^ (1 / 4) '[W/m^2-C] .... avg internal heat tr coeff over L

ElseIf (Re_vap > 35000) Then

    MsgBox ("Re_vap must be <= 35000. Now, Re_vap =" & Re_vap)

End If
```

```
Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s

Condensation_In_HCyl_R134a = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

Now, the above program is an Array Function and returns h_avg, Q and Mass_condensed inside a horizontal cylinder.

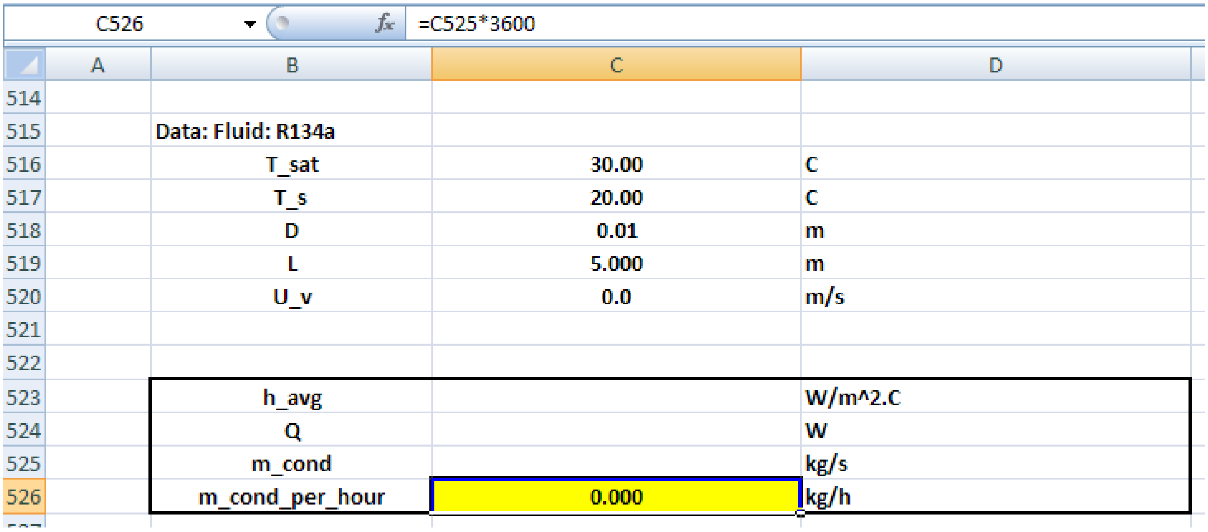
Let us solve a problem using this Function:

Prob. 3.2.30. Sat. R134a vapour at 30 C condenses inside a horizontal tube of 1 cm ID, 5 m long and the tube surface is maintained at 20 C. Determine: (a) rate of heat transfer (b) rate of condensation of R134a. Assume that the entering vapour has negligible velocity (i.e. U_v = 0).

EXCEL Solution:

We shall use the VBA Function for condensation of R134a inside a horizontal cylinder, written above.

1. Set up the EXCEL worksheet for this problem. Remember that the Function we are going to use is an Array Function:

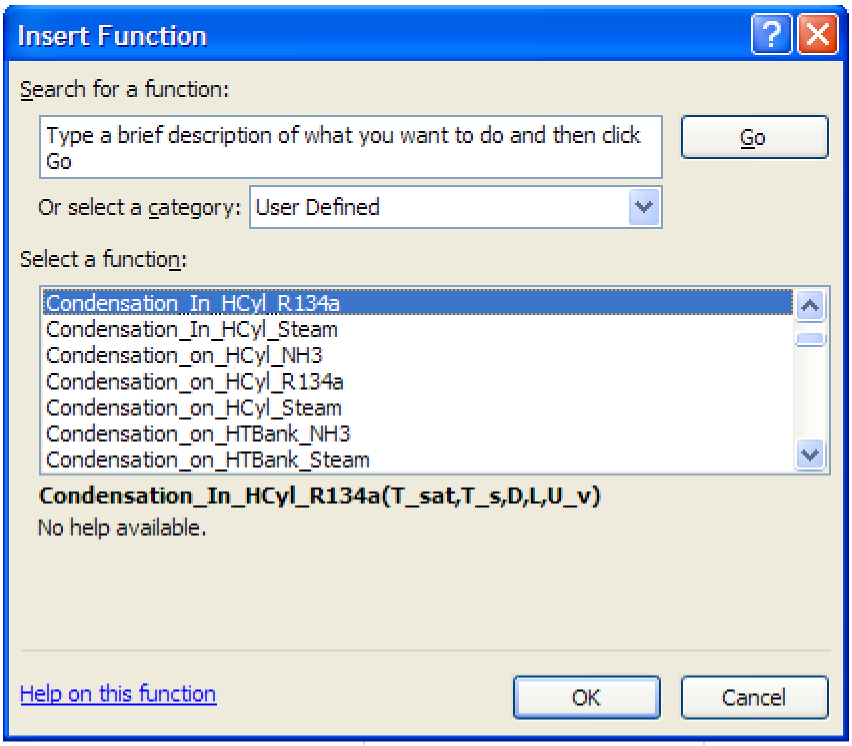


C526 =C525*3600

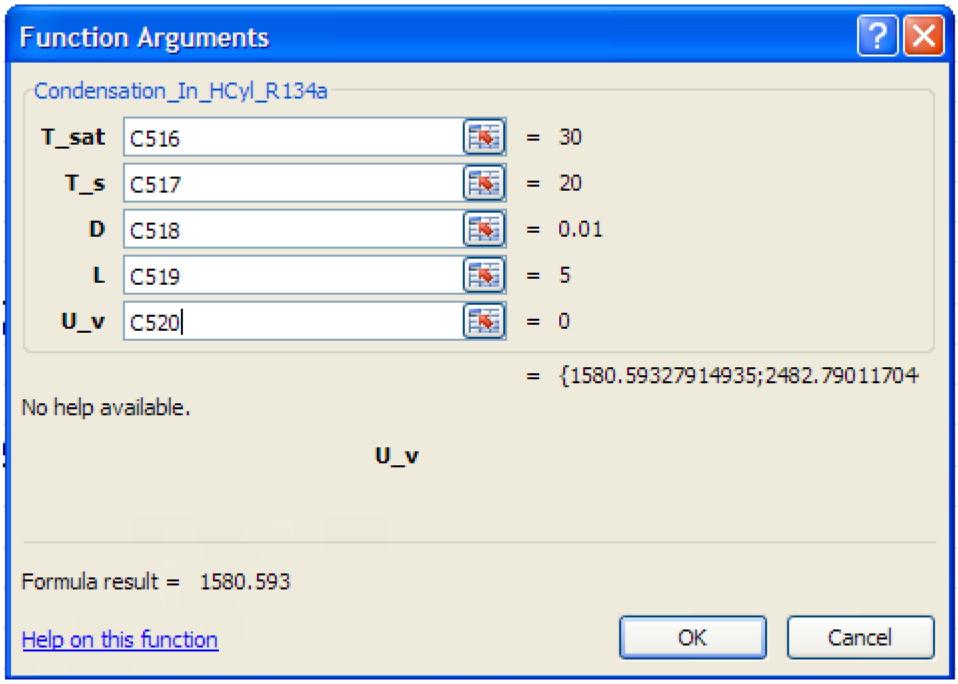
	A	B	C	D
514				
515		Data: Fluid: R134a		
516		T_sat	30.00	C
517		T_s	20.00	C
518		D	0.01	m
519		L	5.000	m
520		U_v	0.0	m/s
521				
522				
523		h_avg		W/m^2.C
524		Q		W
525		m_cond		kg/s
526		m_cond_per_hour	0.000	kg/h

2. Select the cells C523 to C525 and select the Array Function for condensation of R134a inside a horizontal cylinder from the 'User Defined' category:

We have:



Click OK. We get the following screen. Fill it up as shown:



Press (Ctrl+Shift+OK) since it is an Array Function, and we get:

C525   fx {=Condensation_In_HCyl_R134a(C516,C517,C518,C519,C520)}

	A	B	C	D
514				
515		Data: Fluid: R134a		
516		T_sat	30.00	C
517		T_s	20.00	C
518		D	0.01	m
519		L	5.000	m
520		U_v	0.0	m/s
521				
522				
523		h_avg	1580.593	W/m^2.C
524		Q	2482.790	W
525		m_cond	0.013959	kg/s
526		m_cond_per_hour	50.252	kg/h

Thus:

h_avg = 1580.59 W/m^2.C …. Ans.

Q = 2482.79 W …. Ans.

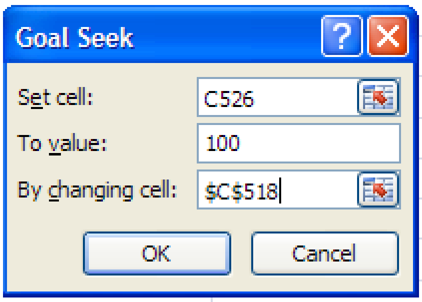
m_cond_per_hour = 50.252 kg/h …. Ans.

(b) What should be the diameter if we need to have a condensation rate of 100 kg/h?

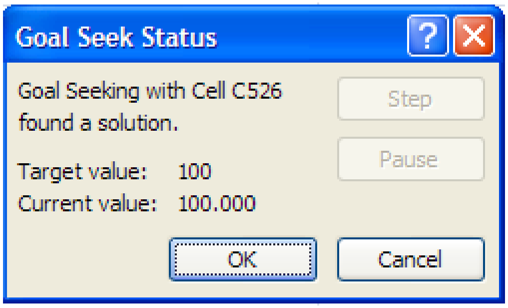
This is easily calculated by applying Goal seek to cell C526 (i.e. m_cond_per_hour) to make it equal to 100 by changing cell C518 (i.e. D).

The procedure is:

Go to Data-WhatIf Analysis- Goal Seek Click on Goal Seek. We get the following screen; fill it up as shown:



Click OK. We get:



Goal Seek has found a solution. Again, click OK and see the result in cell C518:

C518 fx 0.0250299248479914

	A	B	C	D
514				
515		Data: Fluid: R134a		
516		T_sat	30.00	C
517		T_s	20.00	C
518		D	0.03	m
519		L	5.000	m
520		U_v	0.0	m/s
521				
522				
523		h_avg	1256.624	W/m^2.C
524		Q	4940.657	W
525		m_cond	0.027778	kg/s
526		m_cond_per_hour	100.000	kg/h

Thus: Value of D required to get a condensation rate of 100 kg/h = 0.03 m … Ans.

Note that correspondingly, values of h_avg and Q also have changed.

==

References

1. M. Thirumaleshwar, *Fundamentals of Heat & Mass Transfer*, Pearson Education, India, 2006.
2. Yunus A Cengel, *Heat and Mass Transfer*, 3rd Ed., McGraw Hill Co.
3. F.P. Incropera and D.P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 5th Ed., John Wiley & Sons.
4. Domkundwar et al, *A Course in Heat & Mass Transfer*, Dhanpat Rai & Co, 5th Ed, 1999.
5. Frank Kreith and Mark S Bohn, *Principles of Heat Transfer*, PWS Publ. Co. (Intl. Thomson Publ.), 5th Ed., 1997.