

Basic Thermodynamics: Software Solutions – Part I

Dr. M. Thirumaleshwar



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Basic Thermodynamics: Software Solutions – Part I

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



Basic Thermodynamics: Software Solutions – Part I

1st edition

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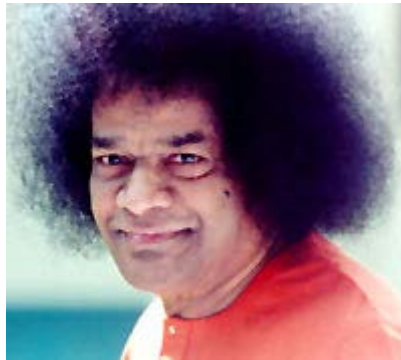
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Dedication

This work is lovingly dedicated at the lotus feet of



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

“Help Ever, Hurt Never!”

...Bhagavan Sri Sathya Sai Baba

Message by Rev.Fr. Joseph Lobo

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

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

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

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

Fr Joseph J. Lobo

Director – St Joseph Engineering College

Date: 21.03.2014

Preface

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

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

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

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

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

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

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

Comments are included generously in the codes so that the logic behind the solutions is clear. An introductory chapter gives a brief overview of the software used.

Advantages of using computer software to solve problems are many:

- 1) It helps in solving the problems fast and accurately
- 2) Parametric analysis (what – if analysis) and graphical visualization is done very easily. This helps in an in-depth analysis of the problem.
- 3) Once a particular type of problem is solved, it can be used as a *template* and solving similar problems later becomes extremely easy.
- 4) In addition, one can plot the data, curve fit, write functions for various properties or calculations and re-use them.
- 5) These possibilities create interest, curiosity and wonder in the minds of students and enthuse them to know more and work more.

This book is an expanded version of the teaching notes of the author, who has taught this subject over the past many years to Engineering students.

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

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

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

Part-1 contains the following:

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

Part-2 contains problems on following topics:

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

Part-3 contains problems on following topics:

- Chapter 6. II Law of Thermodynamics
- Chapter 7. Entropy

Part-4 contains problems on following topics:

Chapter 8. Availability and Irreversibility

Chapter 9. Real and Ideal gases and Gas Mixtures

Acknowledgements: Firstly, I would like to **thank all my students**, who have been an inspiration to me and without whose active involvement, this work would not have been possible.

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

Sincere thanks are due to **Rev. Fr. Joseph Lobo**, Director, SJEC, for his kindness, regard and words of encouragement, and for providing a very congenial and academic atmosphere in the college. **He has, very graciously, given a Message to this book to bless my effort.**

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

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

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

Finally, the author would like to express his sincere thanks and appreciation to **his wife, Kala**, who has given continuous support and encouragement, and made many silent sacrifices during the period of writing this book, so that this book becomes a reality.

M. Thirumaleshwar

March 2014

About the Author

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

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

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

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

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

An advertisement for SKF. It features a woman with long dark hair smiling in the foreground. In the background, a large white wind turbine is visible against a blue sky. The text 'Brain power' is written in large white letters on the left. On the right, there is a block of text about wind energy and SKF's role. At the bottom left, it says 'Plug into The Power of Knowledge Engineering. Visit us at www.skf.com/knowledge'. The SKF logo is in the bottom right corner.

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

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

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

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

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

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

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

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

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

About the Software used

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

1. Mathcad 2001 (Ref: www.ptc.com)
2. Engineering Equation Solver (EES) (Ref: www.fchart.com), and
3. The Expert System for Thermodynamics (TEST) (Ref: www.thermofluids.net)

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

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

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

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To the Student

Dear Student:

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

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

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

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

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

Use of Software in solving problems has many advantages:

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

How to use this Book?

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

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

Author

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1 Introduction To The Software Used

Learning objectives:

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

1.1 Introduction:

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

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

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

1.2 About the software:

1.2.1 Mathcad:

What is Mathcad?

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

Symbols in Mathcad worksheet:

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

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

A :=3 B :=5 C :=7 assigning values to variables A, B and C

A.B.C = 105 multiplication

2.A + 8.B – 4.C = 18 multiplication, addition and subtraction

$$\frac{A \cdot B}{C} = 2.143 \quad \dots \text{division}$$

$$B^2 - 4 \cdot A \cdot C = -59 \quad \dots \text{exponentiation}$$

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

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

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

'What-if' analysis in Mathcad:

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

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



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

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

where, k = thermal conductivity of the material, (W/(m.K))

A = area of cross-section of the rod, m^2

$(T_1 - T_2)$ = temperature difference between the two ends of rod, (where $T_1 > T_2$), and

L = Length of rod, m

Now, suppose that we are interested to find out the value of Q for rods made of different materials, say, copper, Aluminium and stainless steel. i.e. we would like to study the variation of Q with k , rest of the variables being held constant. This is done very easily and quickly in Mathcad, as follows: Let $T_1 = 300$ K, $T_2 = 200$ K, $L = 0.5$ m, $A = 0.785 \times 10^{-4} m^2$.

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

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

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

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

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

$$\text{Then, } Q(k, A, T_1, T_2, L) = 6.39 \quad \text{W....Ans.}$$

Aluminium: $k := 237 \text{ W/(m.K)}$mean value of k between 300 K and 200 K

$$\text{Then, } Q(k, A, T_1, T_2, L) = 3.721 \quad \text{W....Ans.}$$

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

$$\text{Then, } Q(k, A, T_1, T_2, L) = 0.216 \quad \text{W....Ans.}$$

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

Producing the results in tabular form:

Many times, we need the results to be presented in a tabular form. This is done very easily in Mathcad. Let us say, we need to produce a table of values for air standard efficiency (η_{otto}) of Otto cycle against the compression ratio (r_k).

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

To draw the Table: First, define a range variable r_k , varying from 6 to 15 with an increment of 1. Then typing ' $r_k =$ ' immediately gives the values of r_k one below the other; similarly, type ' $\eta_{\text{otto}}(\gamma, r_k) =$ ' and values of $\eta_{\text{otto}}(\gamma, r_k)$ appear one below the other. Arrange these two sets side by side, and we have the required results in a tabular form. This worksheet procedure is shown below:

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

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

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

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

Graphing in Mathcad:

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

We have:

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

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

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

Then click on the graphing palette, and select the x-y graph. A graphing area appears with two 'place holders', one on the x-axis and the other on the y-axis. Fill in the x-axis place holder with r_k . On the y-axis place holder, fill in $\eta_{\text{otto}}(\gamma, r_k)$. Click any where outside the graph and immediately the graph appears. Further, there are simple mouse-click commands for giving titles for the graph, x-axis and y-axis, and also for showing grid lines and legend. Logarithmic scaling also can be applied by simple mouse click commands. Entire worksheet is shown below:

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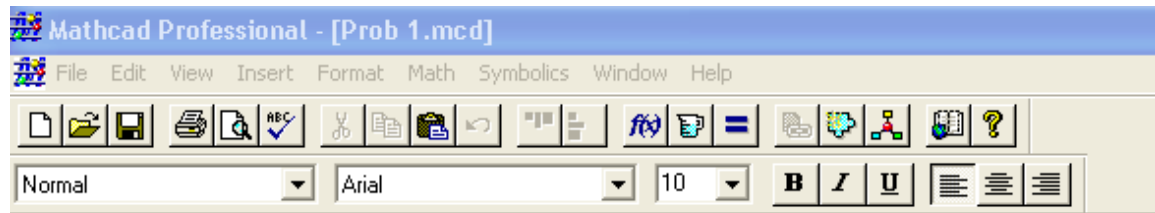
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Prob 1: Find out the air standard efficiency of Otto cycle for a compression ratio of 7. Draw a graph of compression ratio vs. air standard efficiency for compression ratios varying from 6 to 15.

We have for Air standard efficiency of Otto cycle:

$$\eta_{\text{otto}} = 1 - \frac{1}{r_k^{(\gamma-1)}} \quad \text{where } \gamma = \text{ratio of sp. heats for air}$$

$r_k = \text{compression ratio}$

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

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

To draw the graph:

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

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

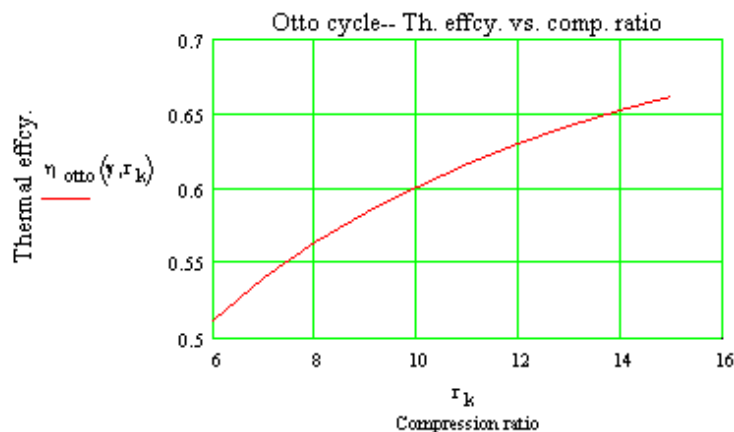
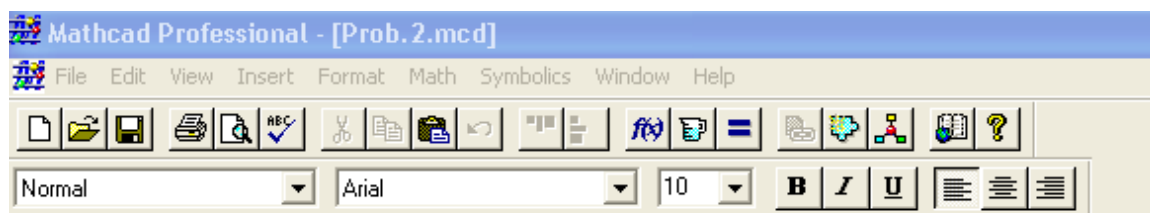


Fig. 1.1 Mathcad Worksheet for producing graph of Otto cycle efficiency

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

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



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

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

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

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

Solution:

Start with guess values for x , y and z :

$$x := 1 \quad y := 1 \quad z := 1 \quad \dots \text{guess values}$$

Given

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

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

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

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

$$\text{i.e.} \quad x=1.141 \quad y=0.816 \quad z=3.535 \quad \dots \text{Ans.}$$

Fig. 1.2 Mathcad Worksheet for solving simultaneous equations

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

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

1.2.2 Engineering Equation Solver (EES):

What is EES?

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

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Equations Window of EES:

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

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

Unit System:

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

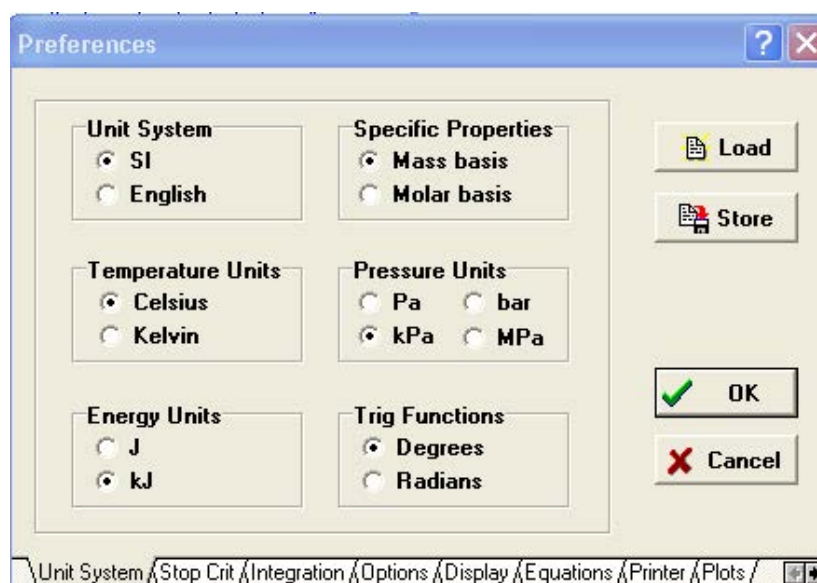


Fig. 1.3 EES screen shot – setting Unit system

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

Formatted equations Window:

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

Solutions Window:

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

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

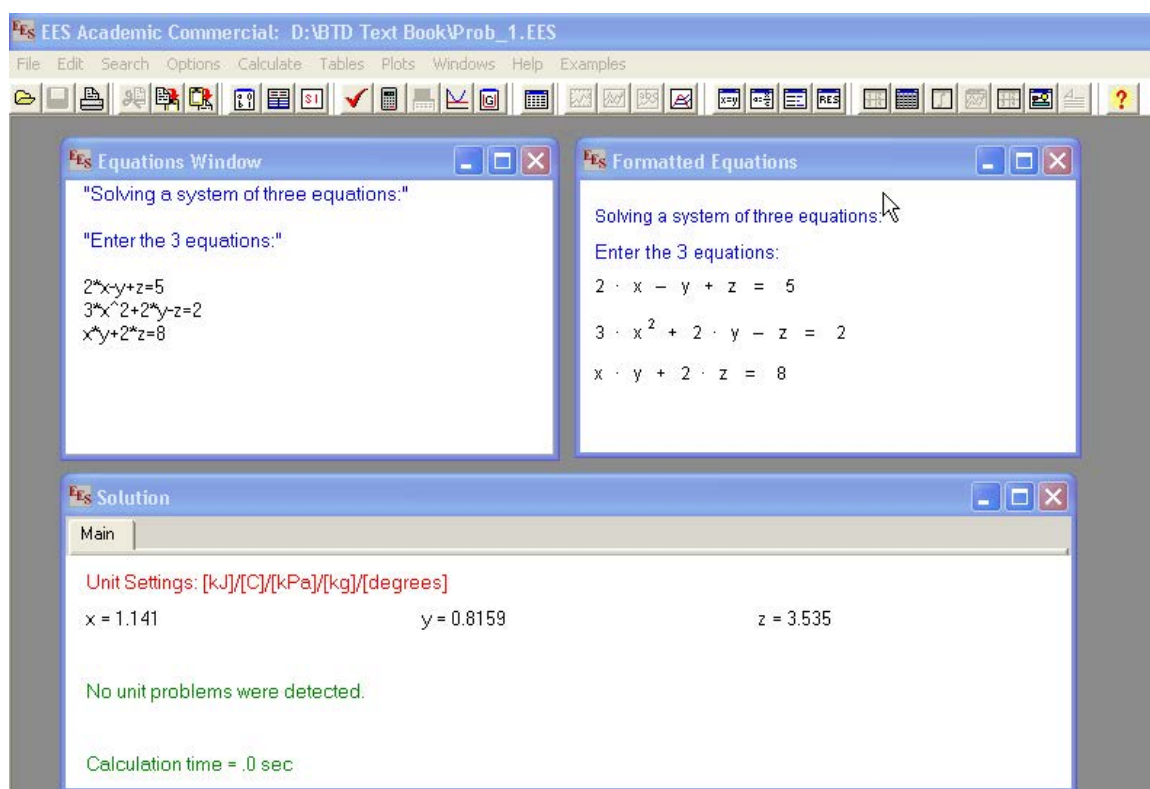


Fig. 1.4 EES Worksheet to solve a system of simultaneous equations

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

Parametric study in EES:

One of the most useful features of EES is its ability to provide parametric studies. For example, let us work out the Air standard efficiency of Otto cycle for various values of compression ratios. This is the same problem as worked out earlier with Mathcad.

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

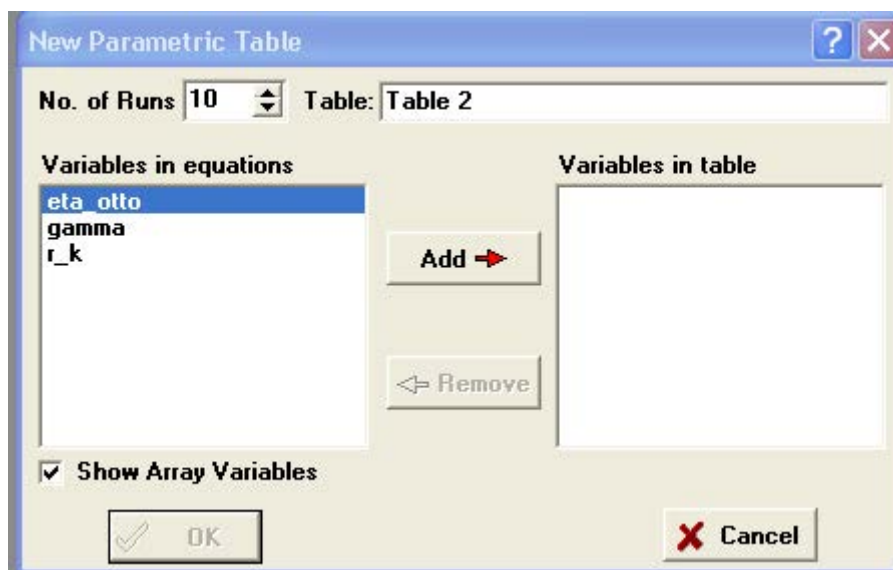


Fig. 1.5 EES screen shot – setting up the Parametric Table

Choose the variables `r_k` and `eta_otto` for the Table and click OK. The Parametric Table works much like a spreadsheet. You can type numbers directly into the cells. Numbers which you enter are shown in black and produce the same effect as if you set the variable to that value with an equation in the Equations window. Delete the `r_k=6` equation currently in the Equations window or enclose it in comment brackets `{ }`. This equation will not be needed because the value of `r_k` will be set in the table. Now enter the values of `r_k` for which `eta_otto` are to be determined. Values of `r_k` = 6 to 15 have been chosen for this example. Now, select Solve Table from the Calculate menu. The Solve Table dialog window will appear allowing you to choose the runs for which the calculations will be done. Click the OK button. A status window will be displayed, indicating the progress of the solution. When the calculations are completed, the values of `eta_otto` will be entered into the table.

Equations Window

```

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

```

Parametric Table

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

Fig. 1.6 EES Worksheet – calculations in Parametric Table

Graphing in EES:

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

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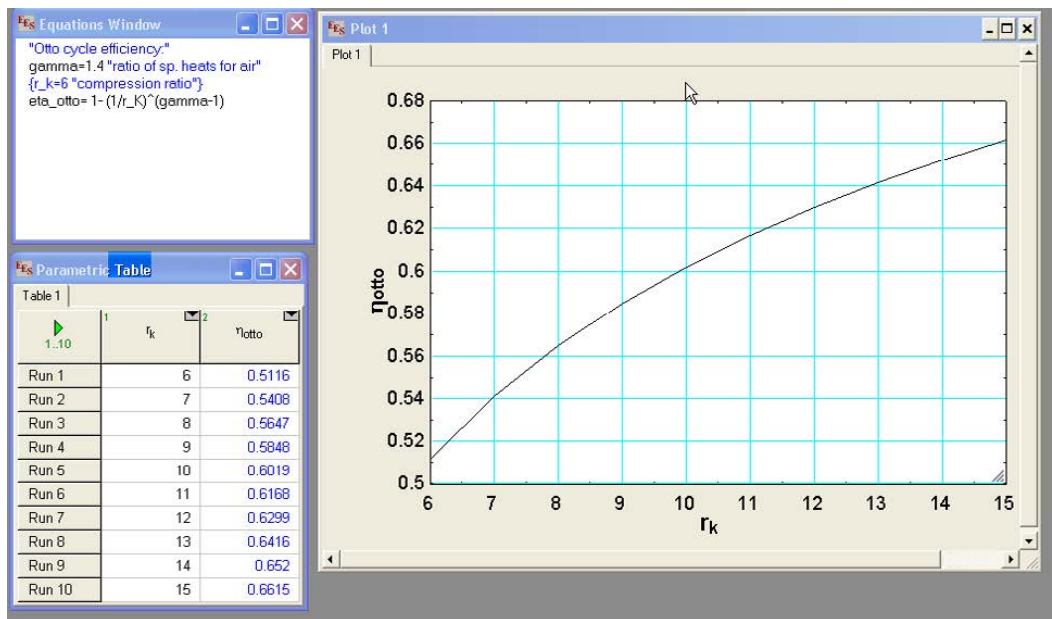


Fig. 1.7 EES graph – screen shot

Once created, there are a variety of ways in which the appearance of the plot can be changed. Refer to the EES manual for further study. Help can also be obtained at any time by pressing F1.

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

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

Procedure is as follows: We know that isentropic turbine work = $(h_1 - h_2)$ per kg of steam, where h_1 = enthalpy at inlet to the turbine, and h_2 = enthalpy at exit. In EES, open the Equations window. Enter the given data:

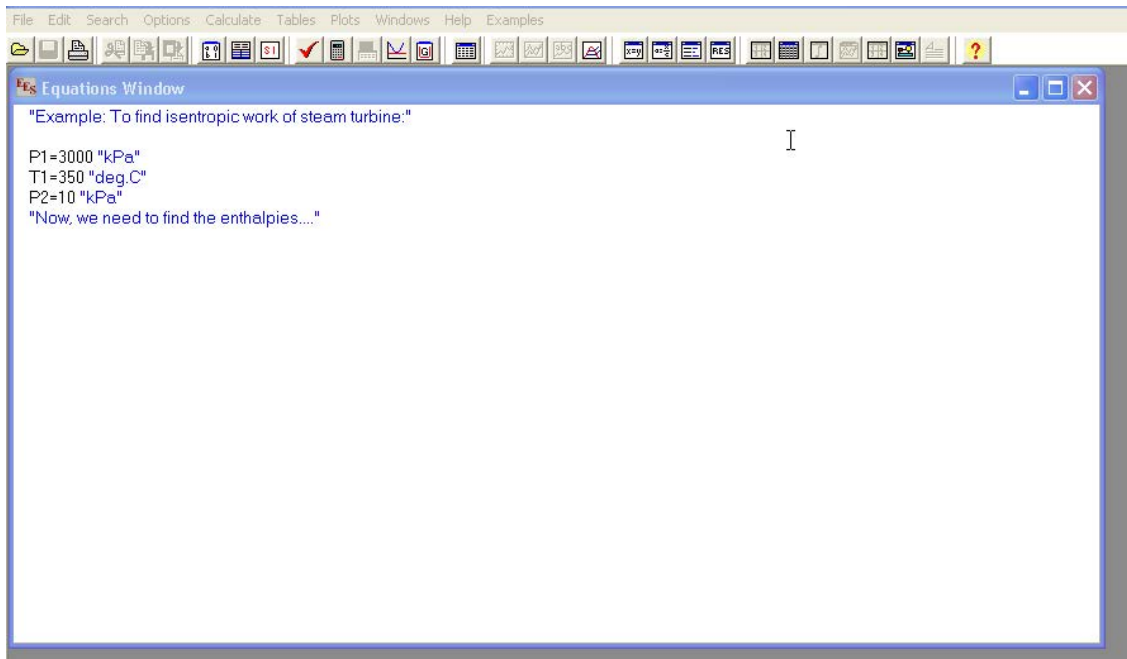


Fig. 1.8 EES Worksheet to find Isentropic work of Turbine

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

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

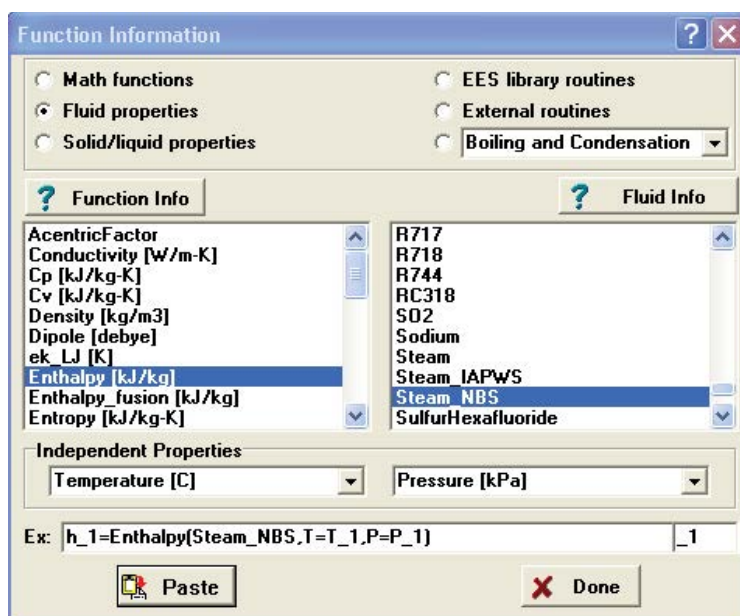


Fig. 1.9 EES – Function Info window

Now, paste the format on the equations window, taking care to enter the same notations for P and T used earlier. For state 2 at the exit of the turbine, input the pressure and entropy; the pressure at exit of turbine, P_2 , is given as 10 kPa and we know that $s_2 = s_1$ for isentropic expansion in turbine. To determine quality at state 2, input pressure P_2 and enthalpy h_2 .

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

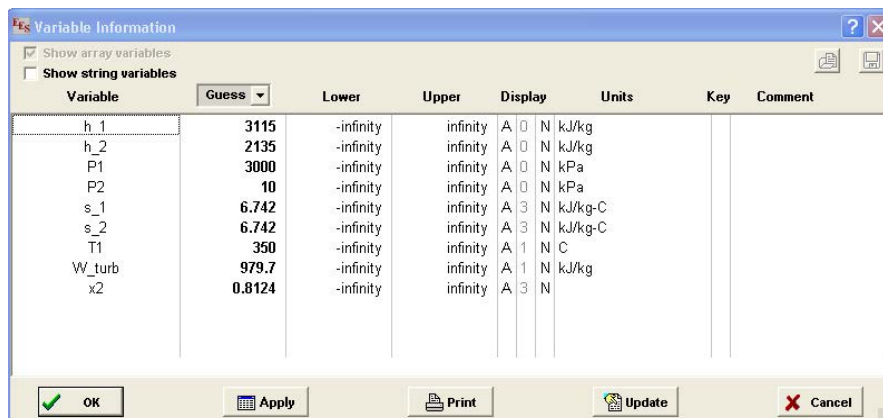


Fig. 1.10 EES – Variable Info window to set Units

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

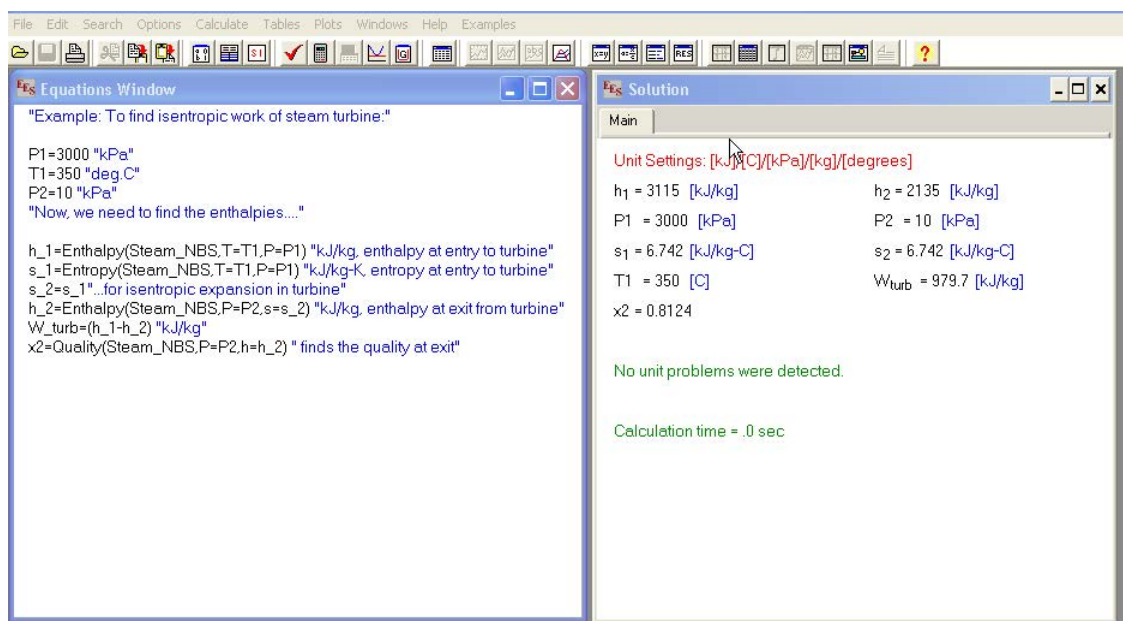


Fig. 1.11 EES Solution Window-- Isentropic work of Turbine

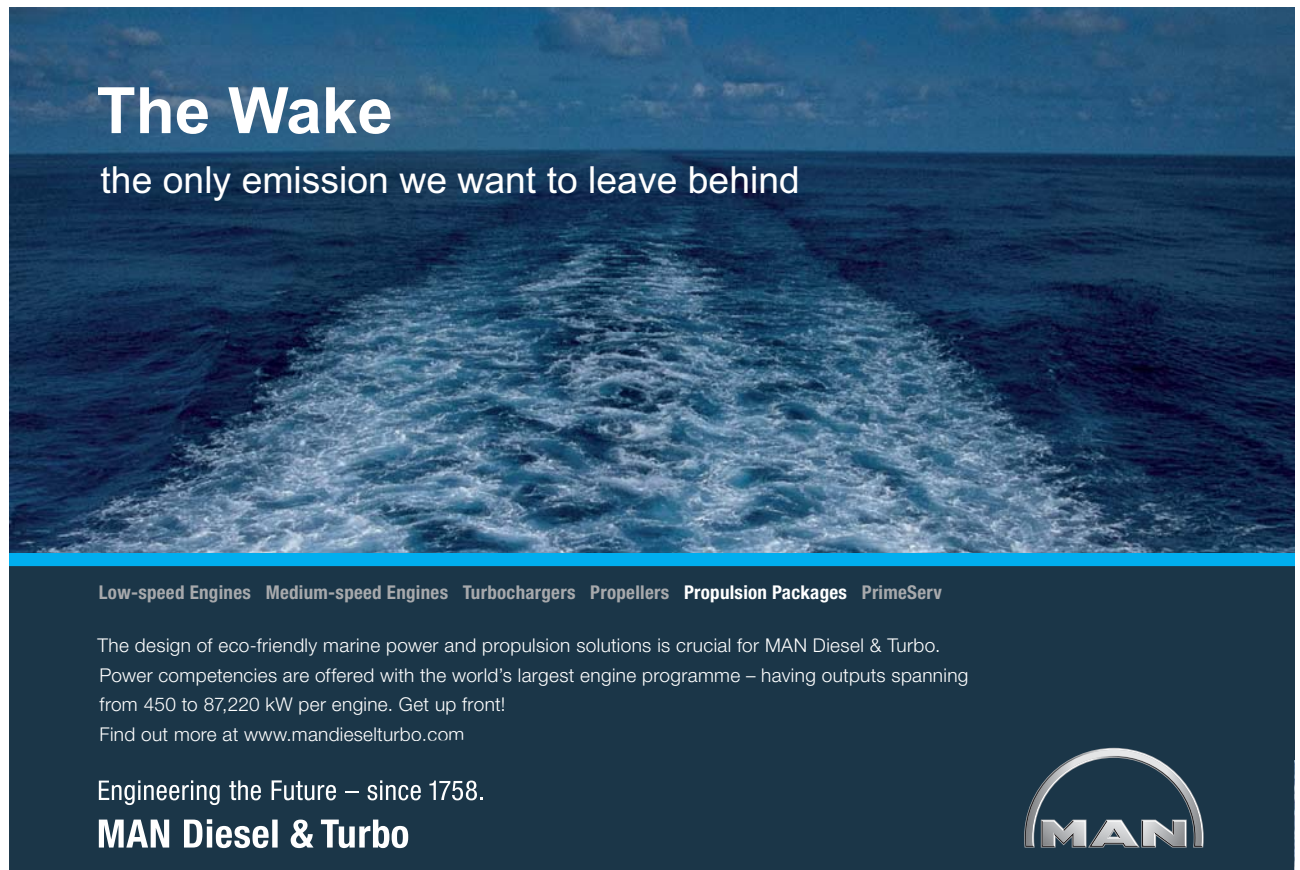
Thus, we see that EES is a very versatile software. It is easy to learn, has an intuitive interface, and is particularly suited to solve problems in Thermodynamics because of its built-in functions for a large number of substances. EES is developed by Prof. Klein and his colleagues who teach Thermodynamics and Heat Transfer at Wisconsin University, USA.

1.2.3 The Expert System for Thermodynamics (TEST):

What is TEST?

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

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



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

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

Systematic approach to solve thermodynamic problems:

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

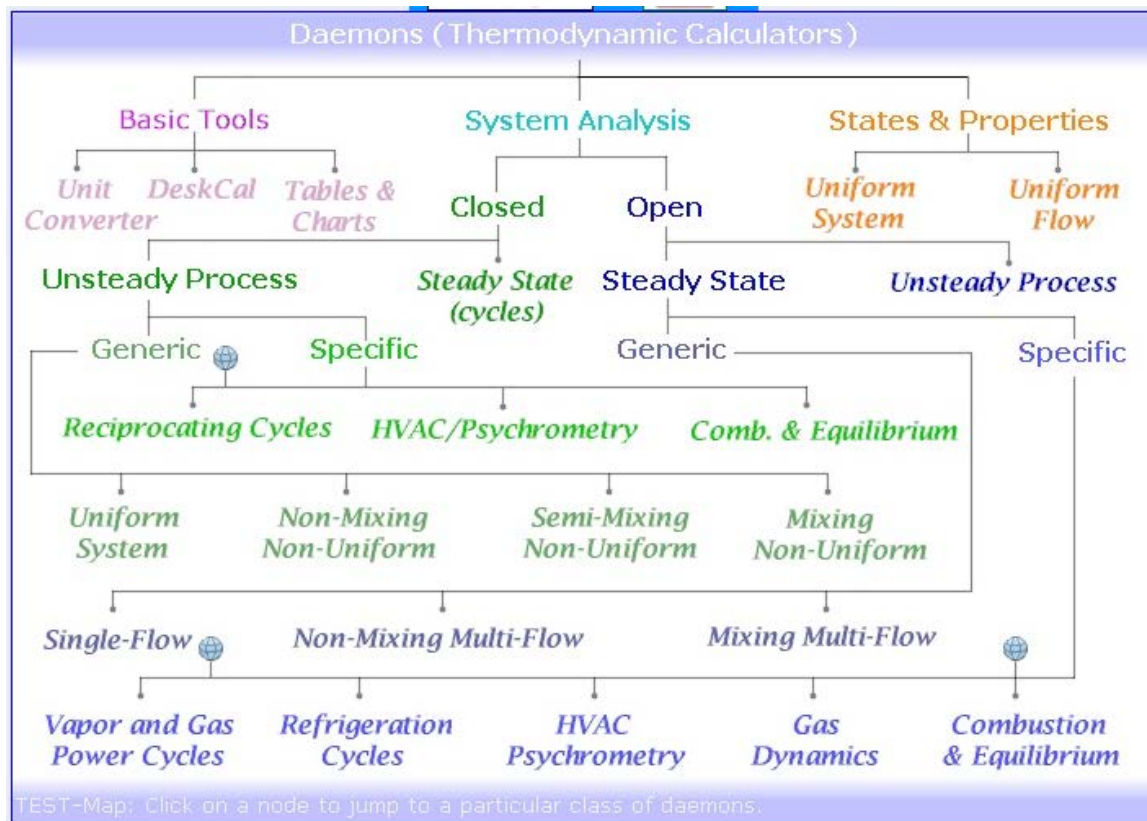




Fig. 1.12 TEST – Map

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

thermofluids.net > Daemons > States > System

Home of TEST

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

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

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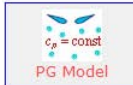


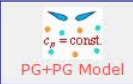


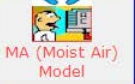
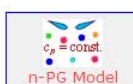


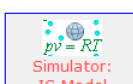
		<p>Pure Perfect Gas: The perfect gas (PG) model is the simplest gas model. It obeys the ideal gas equation of state ($p\nu=RT$); moreover, the specific heats are assumed constants. Noble gases, He, Ar, Ne, etc., are genuinely perfect gases. Beside a wide selection, new gases can be constructed by assigning custom material properties. A perfect gas can be considered as a simplified ideal gas.</p> <p>Examples: Evaluate the change in entropy of a fixed volume of argon, heated from a given initial pressure and temperature to a given final state. For specific examples, click on the help icon at the bottom margin of the daemon.</p>	
		<p>Pure Ideal Gas: An ideal gas (IG) is a gas that obeys the ideal gas equation of state ($p\nu=RT$). Specific heats are temperature dependent. As a result the IG model is more accurate than the PG model when variation in temperature is significant. Choose from an wide selection of gases.</p> <p>Examples: Evaluate the change in internal energy of a fixed volume of carbon dioxide, heated from a given initial pressure and temperature to a given final state. For specific examples, click on the help icon at the bottom margin of the daemon.</p>	
		<p>Pure Real Gas: Based on the generalized <i>compressibility chart</i> ($p\nu=ZRT$), the <i>real gas</i> (RG) model can handle a large number of fluids in their liquid, vapor or gaseous states. But generality comes at the expense of accuracy.</p> <p>Examples: Evaluate the change in entropy of a fixed mass of propane, compressed from a given initial pressure and temperature to a given final pressure at the super critical region. For specific examples, click on the help icon at the bottom margin of the daemon.</p>	
Gases:			<p>Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.</p> <p>Examples: Evaluate properties of a flow of a mixture of two gases, O₂ and CO₂, given the mass or mole fraction of O₂ (gas-A). For specific examples, click on the help icon at the bottom margin of the daemon.</p>
			
			<p>General Mixture: Mixture can contain an unlimited number, n, of species. Composition can be specified through mass, volume, mass fraction, or mole fraction.</p> <p>Examples: Evaluate mixture and partial properties (including chemical potential) of a mixture of several gases For specific examples, click on the help icon at the bottom margin of the daemon.</p>
			<p>Ideal Gas Equilibrium (IGE) Mixture: An initial (reactants) mixture, (say, 1 kmol of O₂ and 3.76 kmol of N₂) is specified. Thereafter, any state can be calculated (say, for a given temperature and pressure) with the mixture composition itself a variable. Possible species in the equilibrium mixture are user selected (say, O₂, N₂, NO, NO₂, O, N, and O₃) to keep computational time reasonable.</p> <p>Examples: Suppose air is heated at 100 kPa from 300 K to 5000 K. The difference in any property, say, enthalpy, calculated from the PG model, IG model, and the IGE model will be different. While the PG and IG model are based on frozen composition, the IGE model will include the effect of dissociation and new species formation. However the result will also depend on if all the likely species are included by the user during the mixture set up. For specific examples, click on the help icon at the bottom margin of the daemon.</p>
			<p>State Simulation by RIAs: These rich internet applications (RIAs) can be used to explore an equilibrium state. Unlike the daemons, the RIAs do not require a thorough thermodynamic background and can be used to gain practical insight alongside learning the underlying theory.</p> <p>Examples: Explore how the volume of a gas changes as the temperature or pressure of the gas is changed. For specific examples, click on the help icon at the bottom margin of the daemon.</p>

Fig. 1.13 TEST – Material models

Depending upon the problem, choose the material model.

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

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

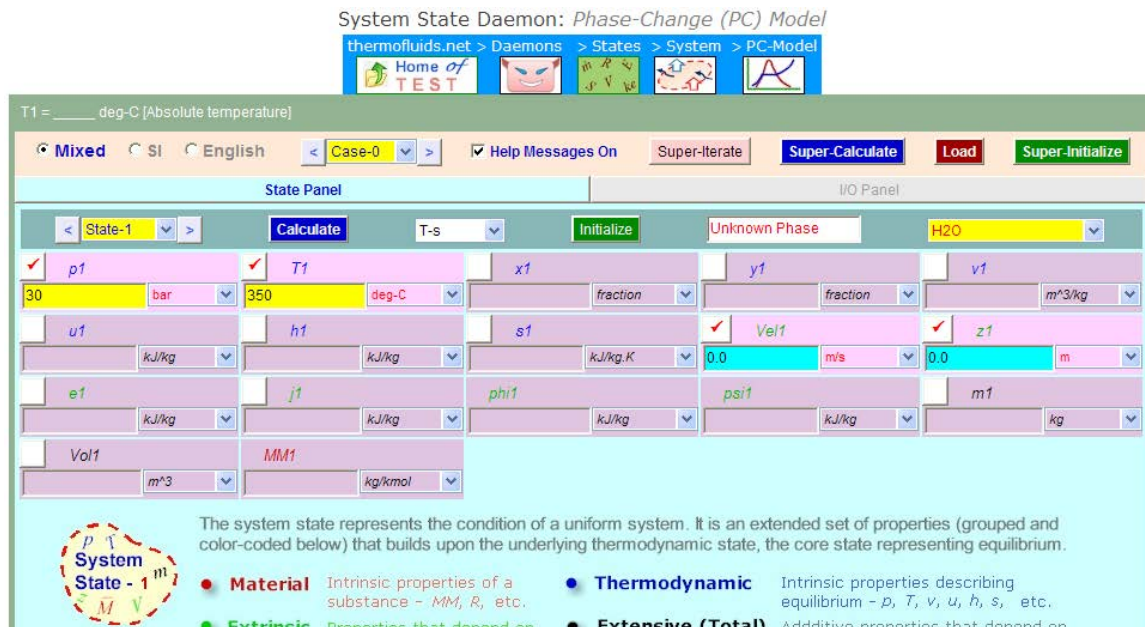


Fig. 1.14 TEST – to find properties of Steam

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

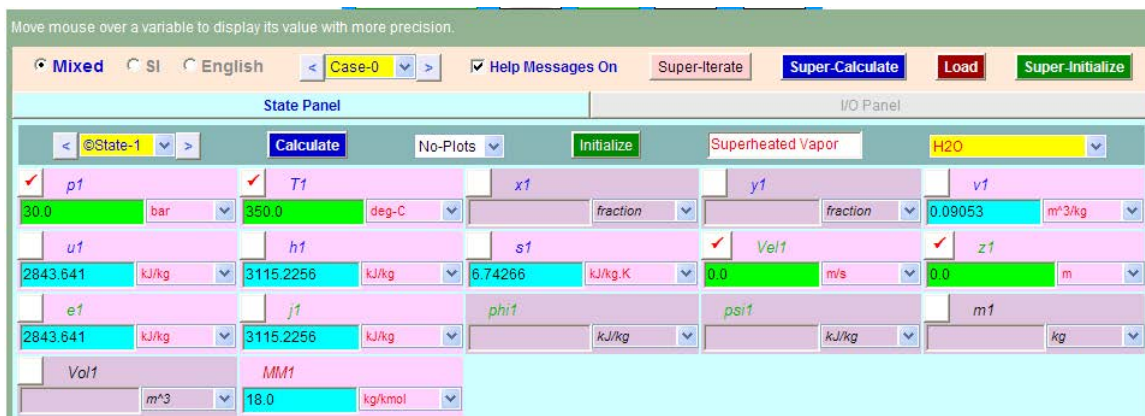


Fig. 1.15 (a) TEST – properties of Steam at 30 bar, 350 C

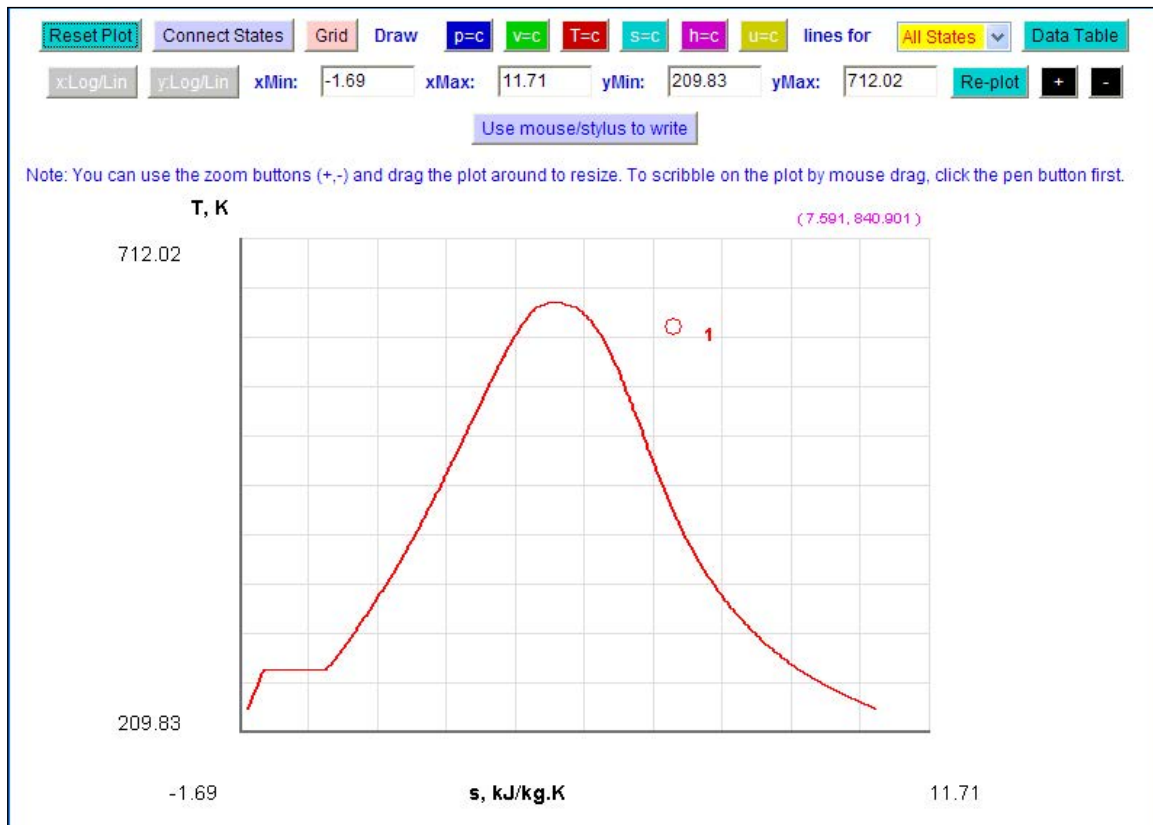


Fig. 1.15 (b) TEST – T-s plot for Steam at 30 bar, 350 C

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

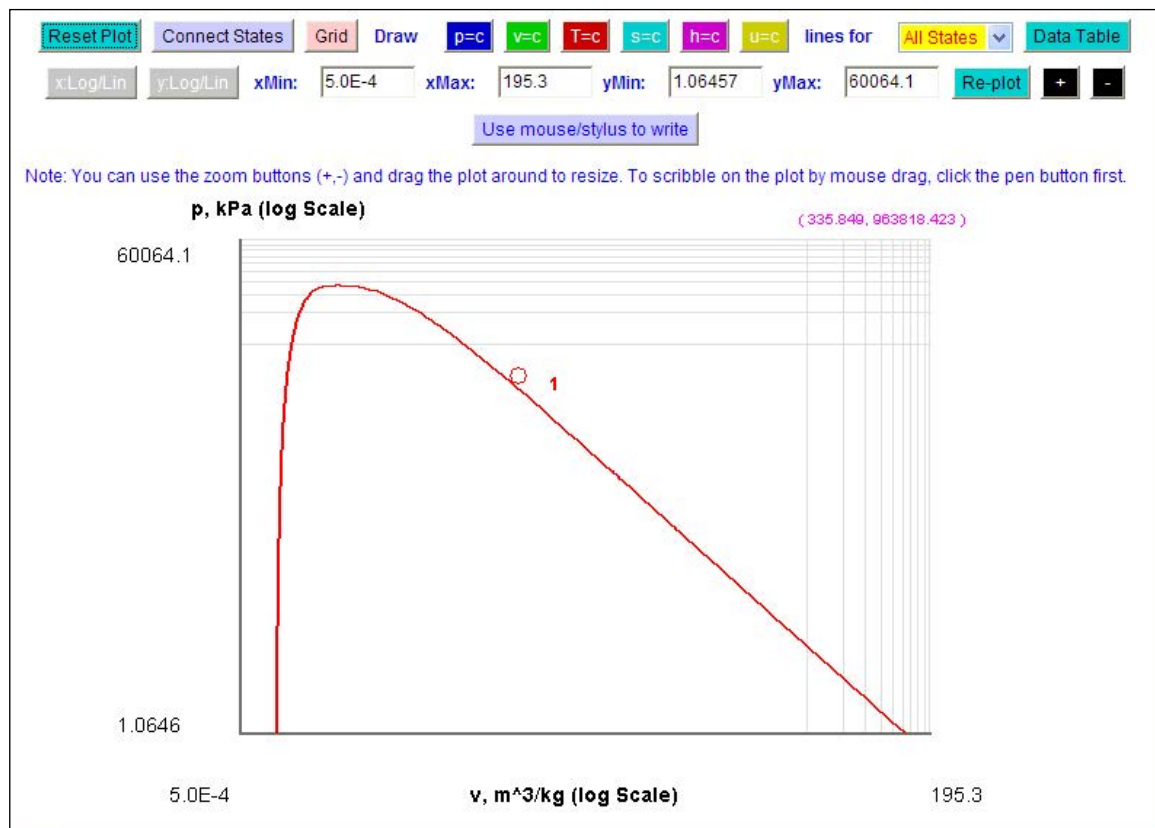
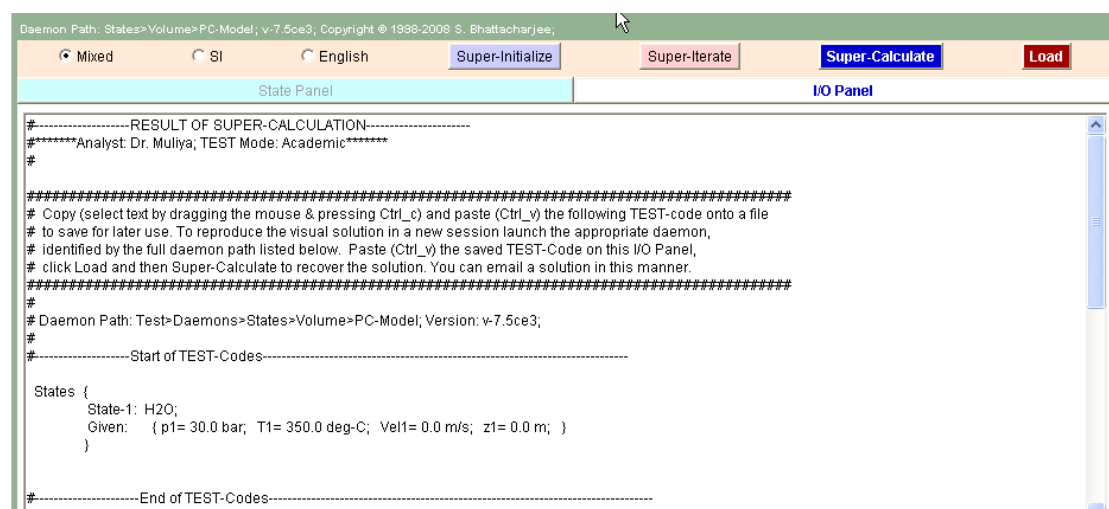


Fig. 1.16 TEST – Steam at 30 bar, 350 C- state point on p-v plot

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



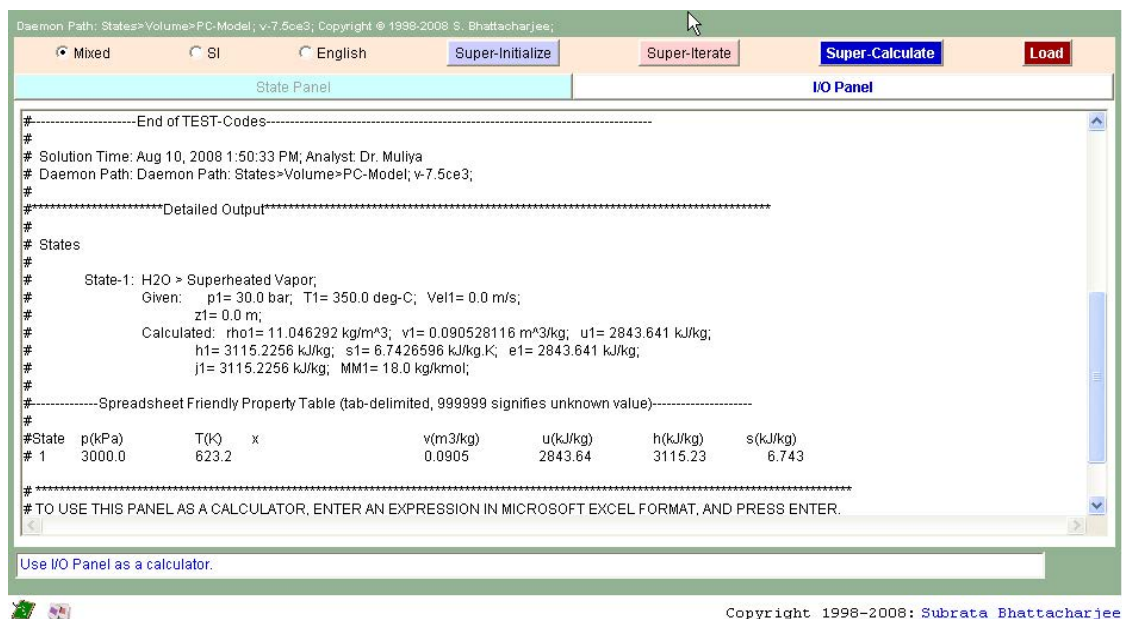


Fig. 1.17 TEST – codes for properties of Steam at 30 bar, 350 C

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

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

1.2.4 Comparison of Mathcad, EES and TEST:

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

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


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

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

Table 1.1 Comparison of Mathcad, EES and TEST5

1.3 'Free' Software:


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



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

1.3.1 ChemicalLogic SteamTab Companion:

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

As you start the program, following screen appears:

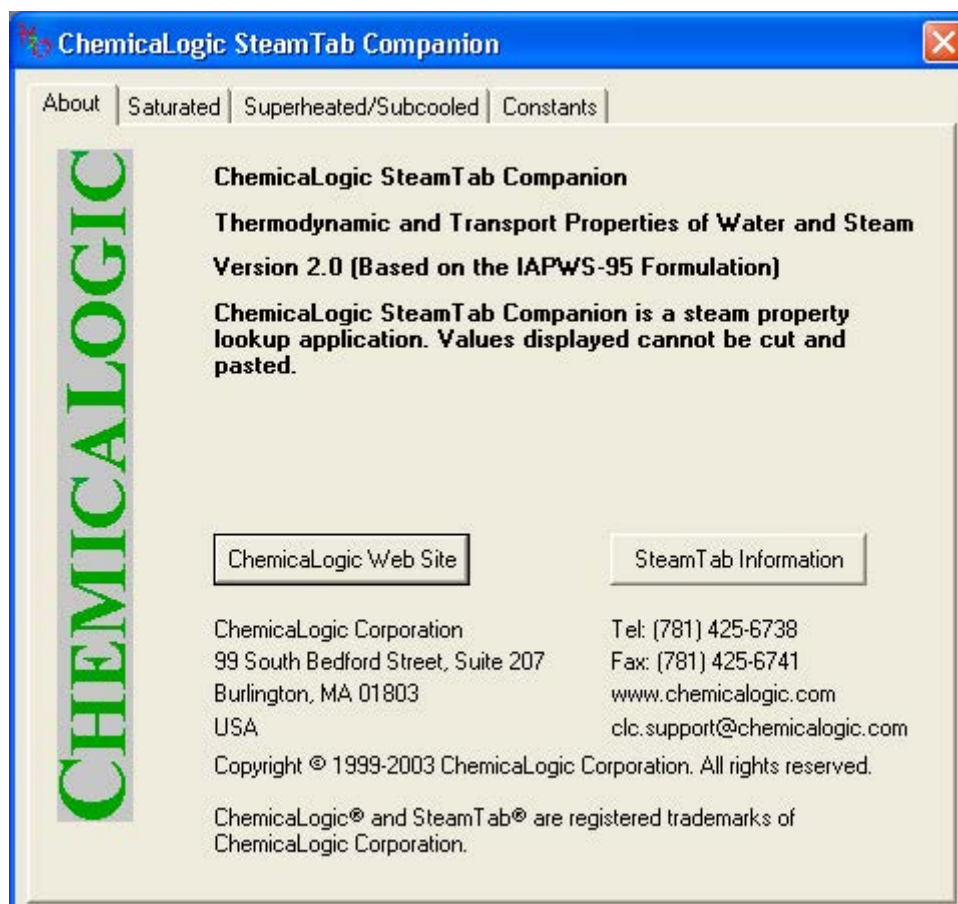


Fig. 1.18 About SteamTab Companion

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

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

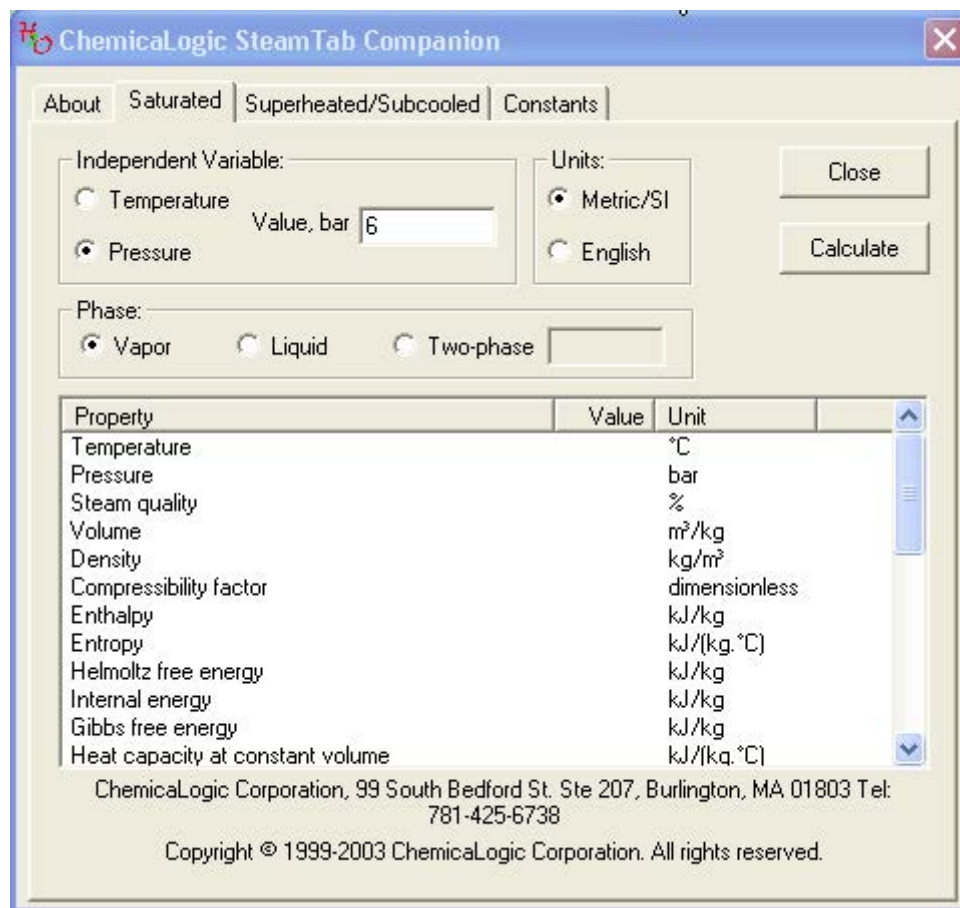


Fig. 1.19 Sat. properties of Steam

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

ChemicalLogic SteamTab Companion

About Saturated Superheated/Subcooled Constants

Independent Variable:
☐ Temperature
☒ Pressure Value, bar

Units:
☒ Metric/SI
☐ English

Phase:
☒ Vapor ☐ Liquid ☐ Two-phase

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

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

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

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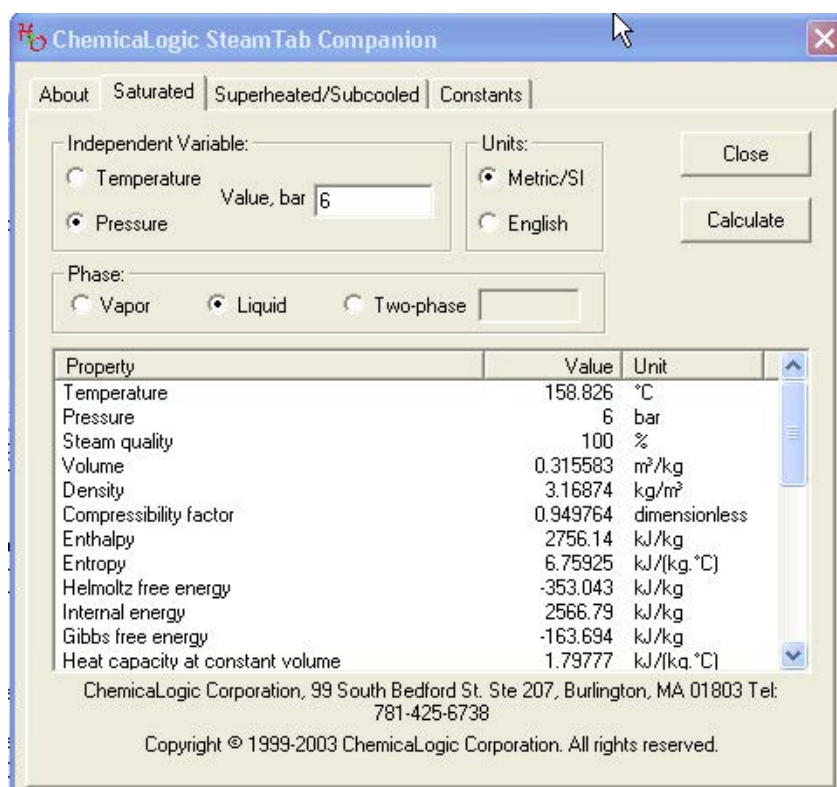


Fig. 1.20 (b) Sat. Liq. properties of Steam at $P = 6$ bar

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

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

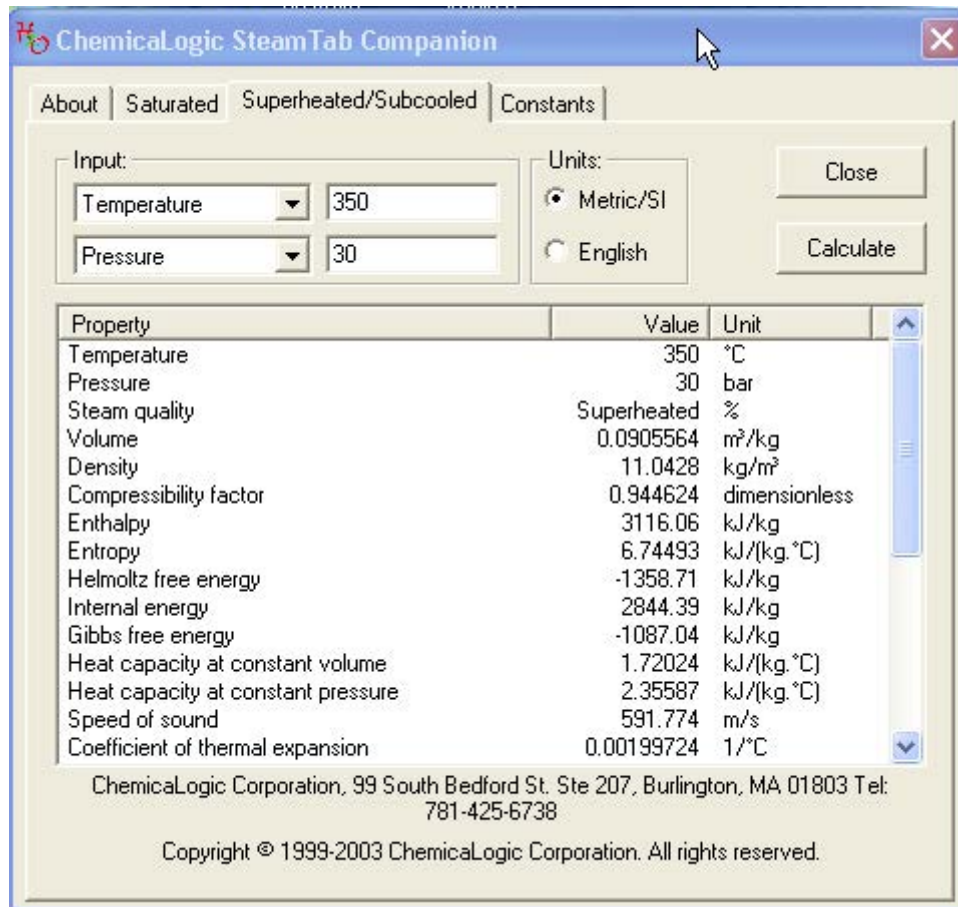


Fig. 1.21 Superheated/Subcooled, properties of Steam at P = 6 bar

Note that at 30 bar, 350 C, enthalpy (h_1) = 3116.06 kJ/kg, and entropy (s_1) = 6.74493 kJ/kg-C.

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

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

Now, if isentropic expansion occurs in a turbine to a pressure of 10 kPa, what is the exit enthalpy and the isentropic work of the turbine? To solve this, input P = 0.1 bar and $s_2 = s_1 = 6.74493$ kJ/kg-C. Results are in the following screen shot:

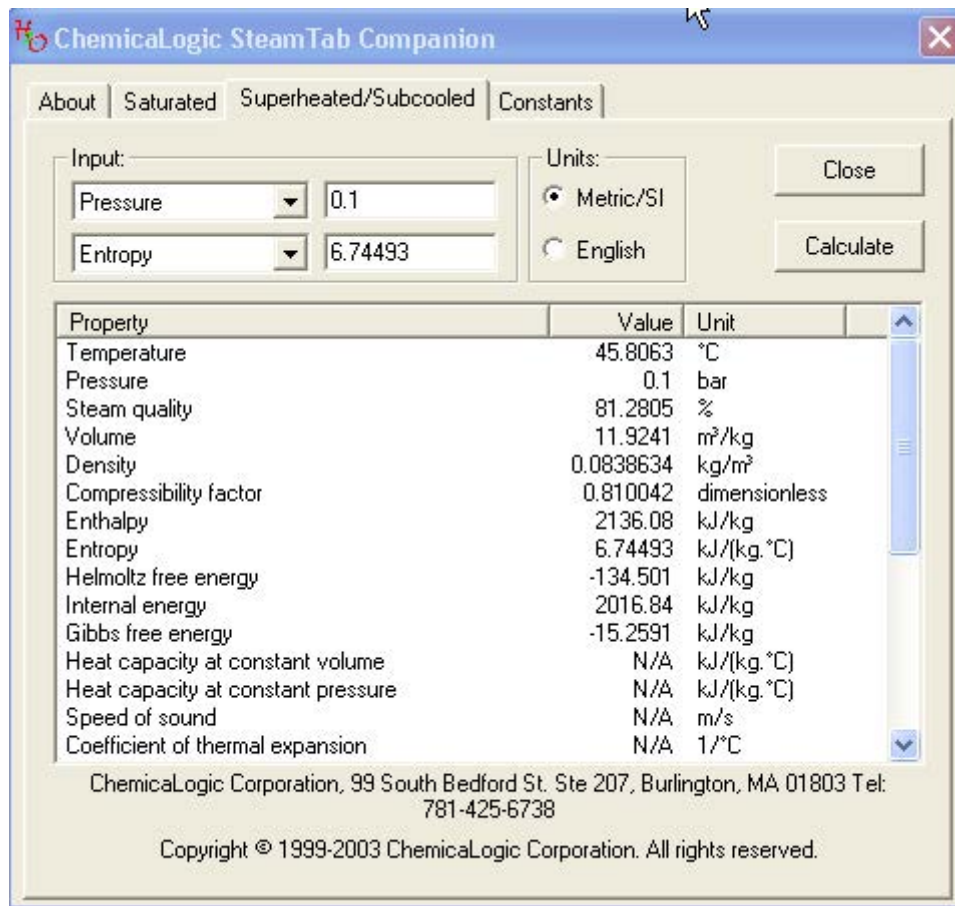


Fig. 1.22 Superheated/Subcooled properties of Steam at $P = 0.1$ bar, $s = 6.74493$ kJ/kg-C

Read from the above fig: $h_2 = 2136.08$ kJ/kg. Therefore, Isentropic work of turbine = $(h_1 - h_2) = 979.98$ kJ/kg. (Compare this with the value of $W = 979.7$ kJ/kg, obtained with EES). And, quality at exit of turbine, $x_2 = 81.2805\%$, whereas with EES, we got $x_2 = 81.24\%$.

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

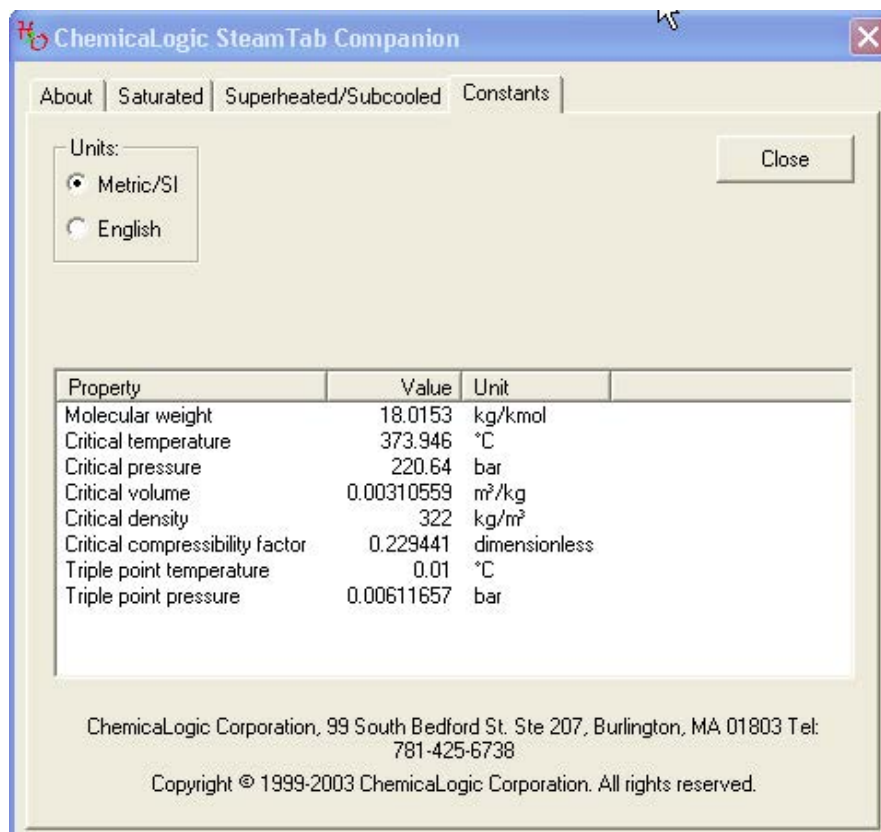


Fig. 1.23 Constants for Steam/Water

Two *disadvantages* of this software are:

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

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

1.3.2 SteamTable from M/s Figener S/A:

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

As you open the program, following screen appears:

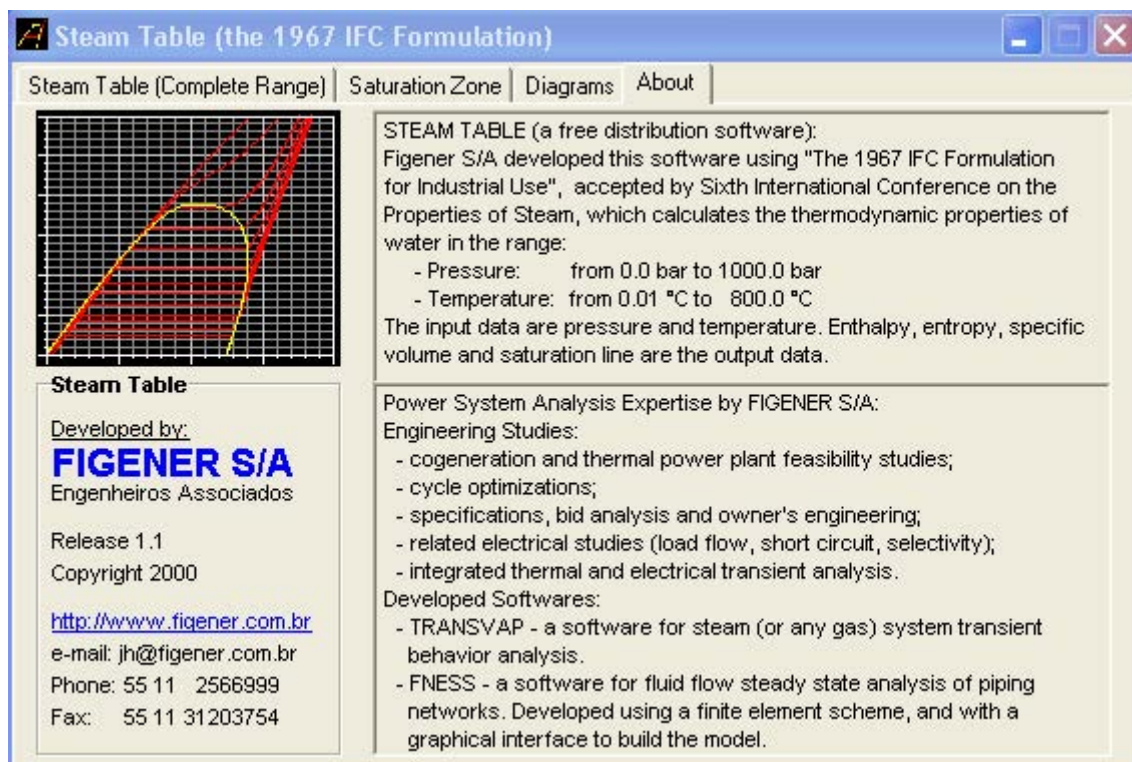


Fig. 1.24 SteamTable – opening screen

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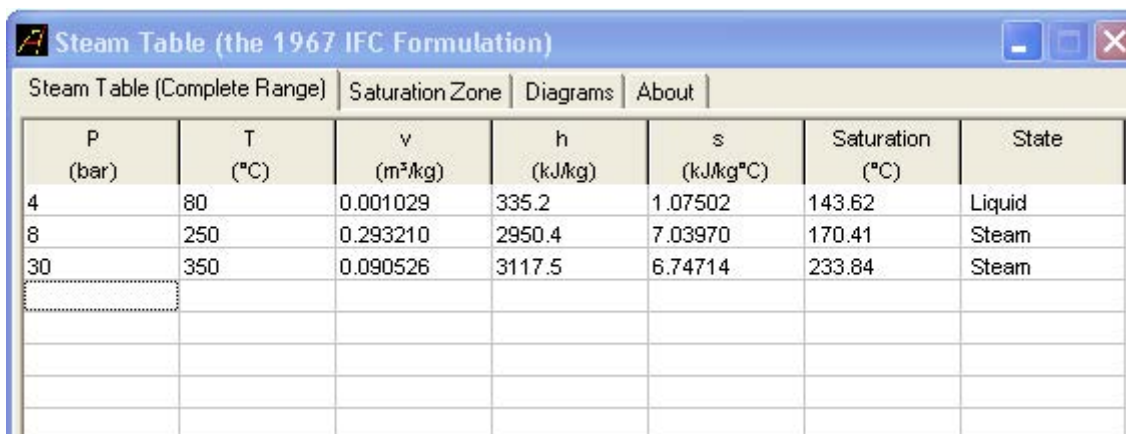
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As can be seen, four tabs: 'About' (i.e. above screen), 'Steam table (complete range)', 'Saturation zone' and 'Diagrams'.

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



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

Fig. 1.25 SteamTable – Properties at different P and T

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

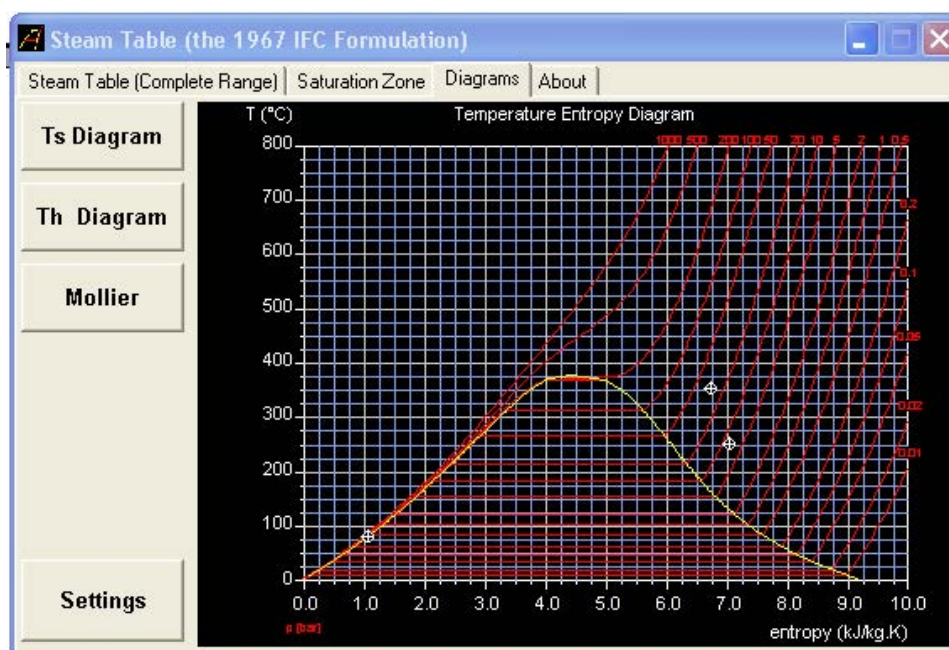
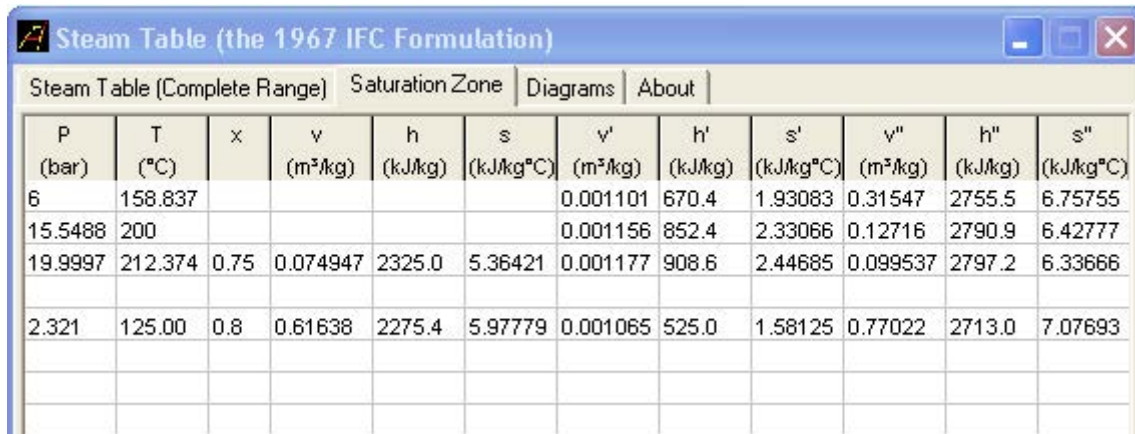


Fig. 1.26 SteamTable – state points on T-s diagram

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

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



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

Fig. 1.27 SteamTable – properties in Sat. zone



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

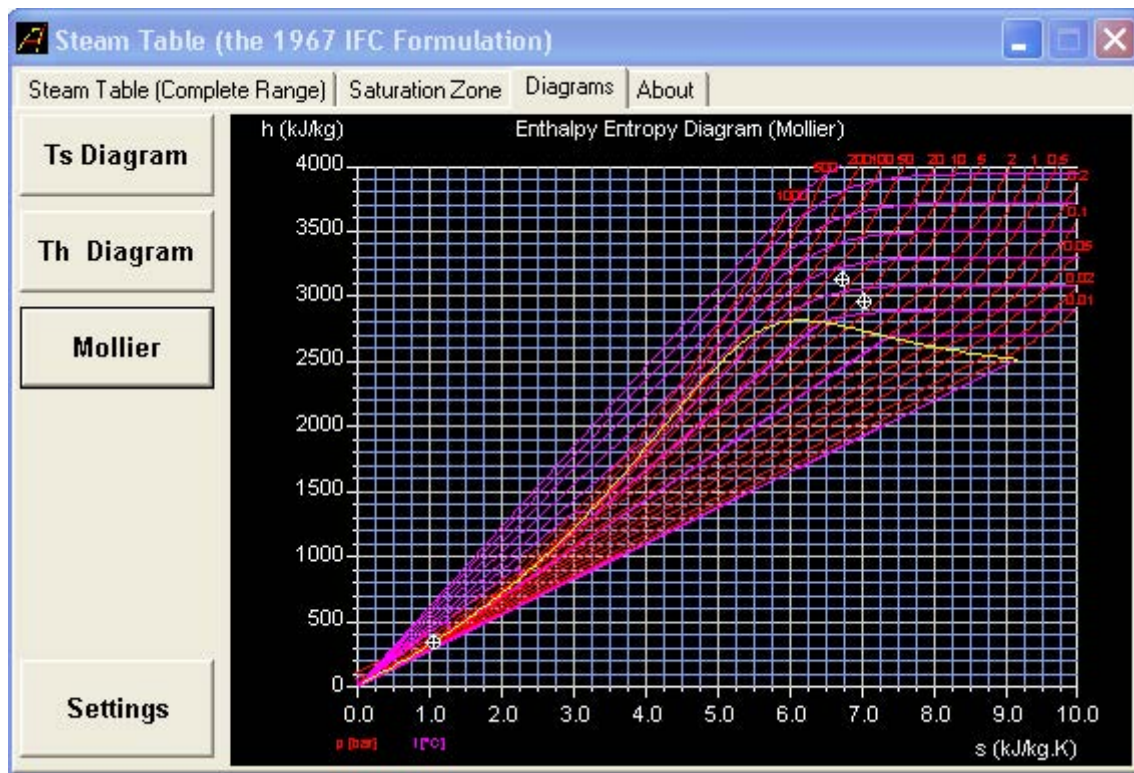


Fig. 1.28 SteamTable – State points in Mollier diagram

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

1.3.3 Humidity Calculator from M/s Vaisala, Finland:

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

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

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

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



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In the advanced version the user can also choose to output dew point (equilibrium over super-cooled water instead of ice) for values below the freezing point of water (0°C/32°F). For gas dependent humidity parameters (e.g., ppm by weight and mixing ratio) a wide selection of carrier gases is available in addition to air (natural gas, CO₂, SF₆, Ar, O₂, N₂, H₂). The user can specify additional carrier gases but must provide the molecular weight of the gas. Wet bulb calculation can be performed based on standard or WMO coefficients, as well as custom values given by the user”.

When you start the Humidity Calculator, following screen appears:

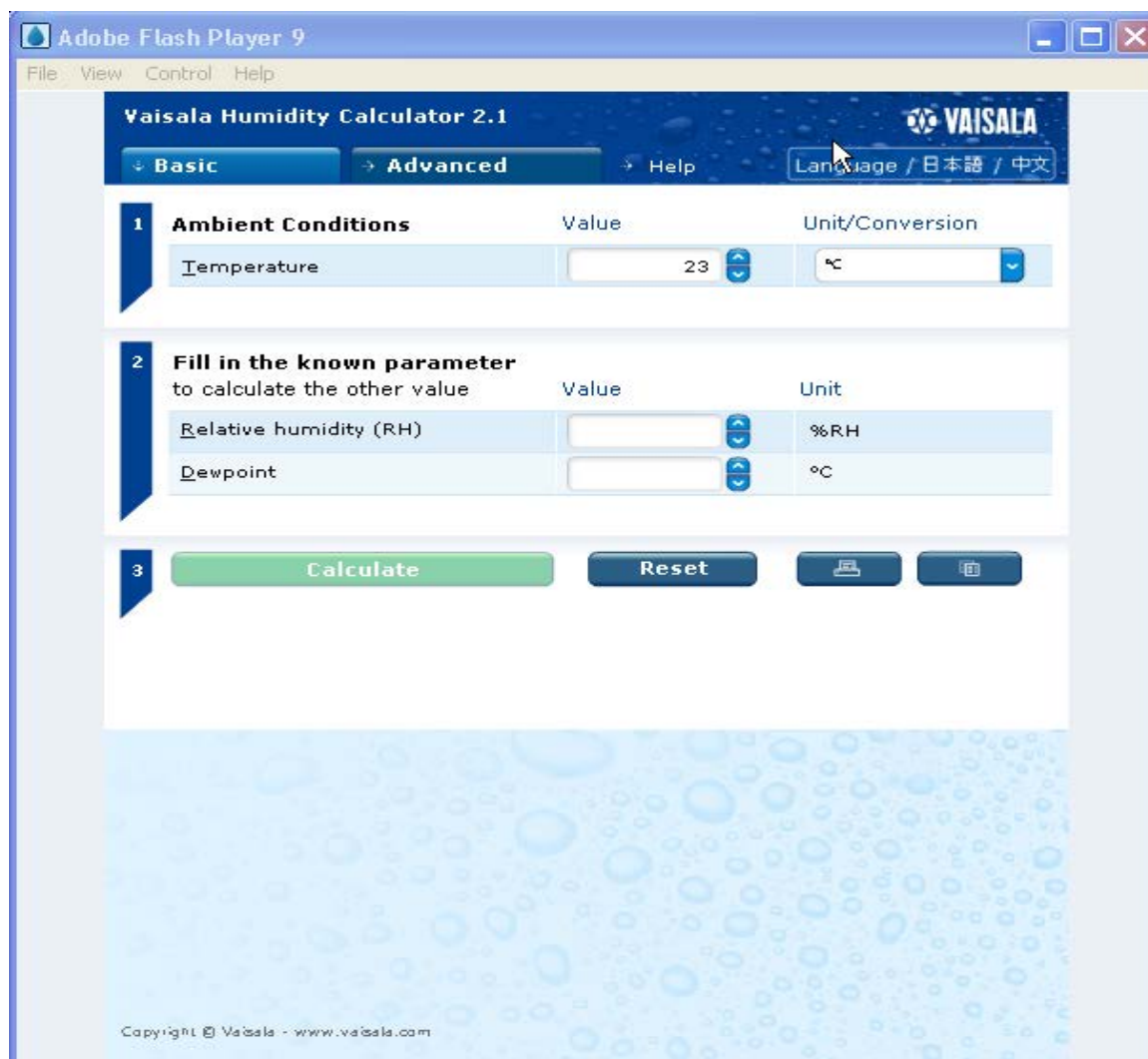


Fig. 1.29 Vaisala Humidity Calculator – opening screen (Basic version)

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

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

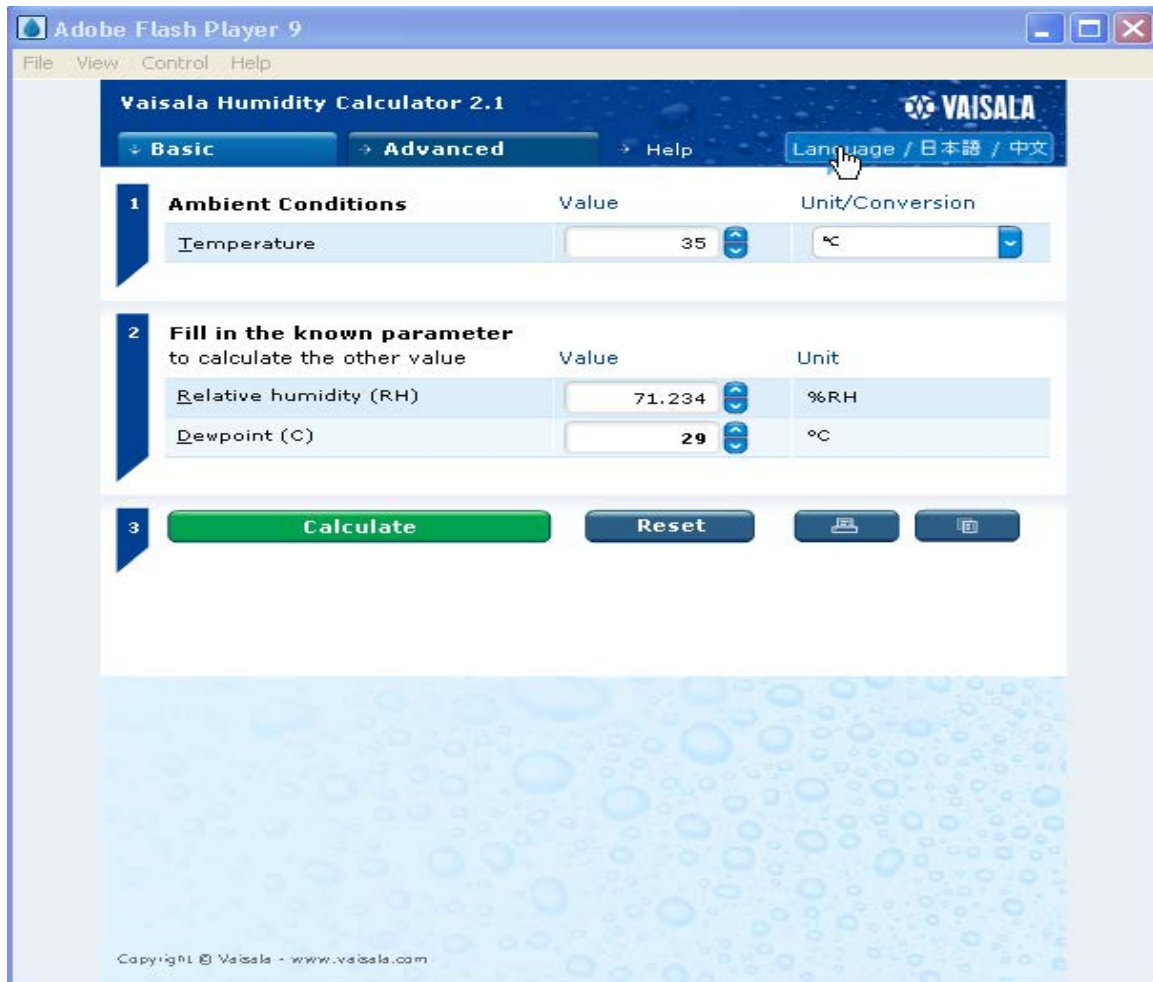


Fig. 1.30 Vaisala Humidity Calculator – typical calculation in Basic Version

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

Vaisala Humidity Calculator 2.1

Basic Advanced Help Language / 日本語 / 中文

1 Ambient Conditions

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

2 Fill in the known parameter to calculate other values

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

3 Calculate Reset

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Fig. 1.31 Vaisala Humidity Calculator – Advanced version

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

Vaisala Humidity Calculator 2.1

Basic Advanced Help Language / 日本語 / 中文

1 Ambient Conditions

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

2 Fill in the known parameter to calculate other values

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

3 Calculate Reset

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

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

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

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



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1.3.4 Free Unit conversion program – ‘Uconeer’ from Katmar Software:

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

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

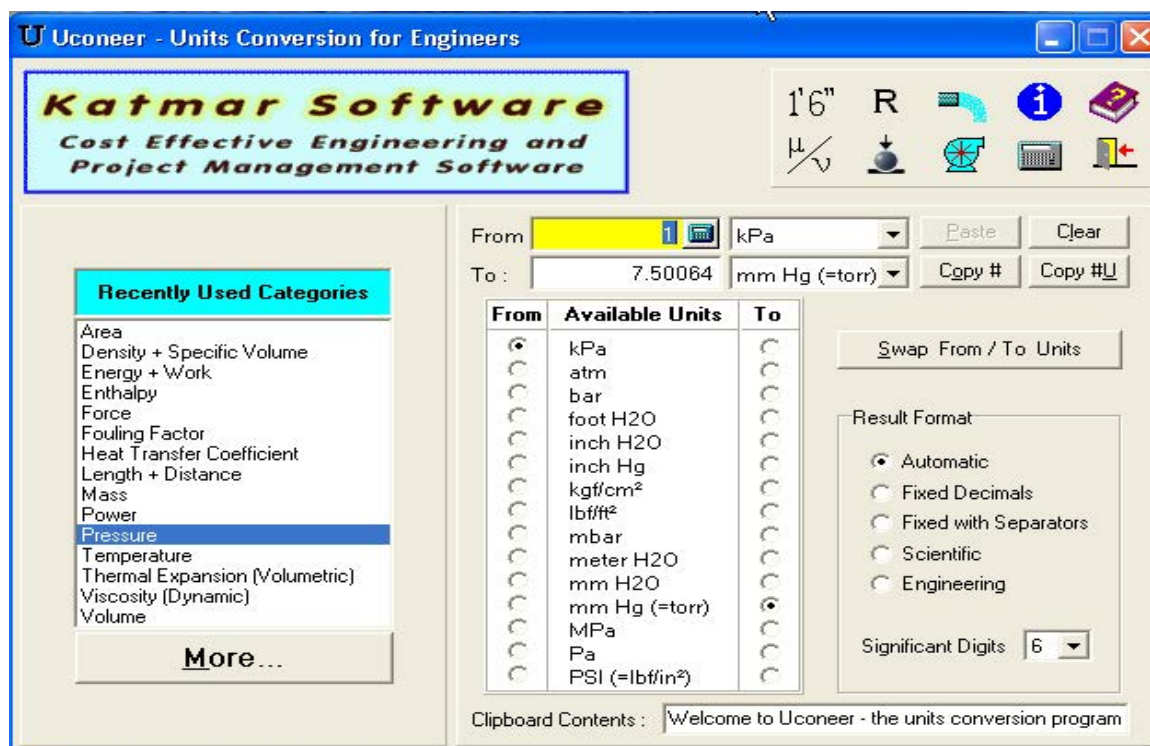


Fig. 1.33 Uconeer – Units conversion program

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

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

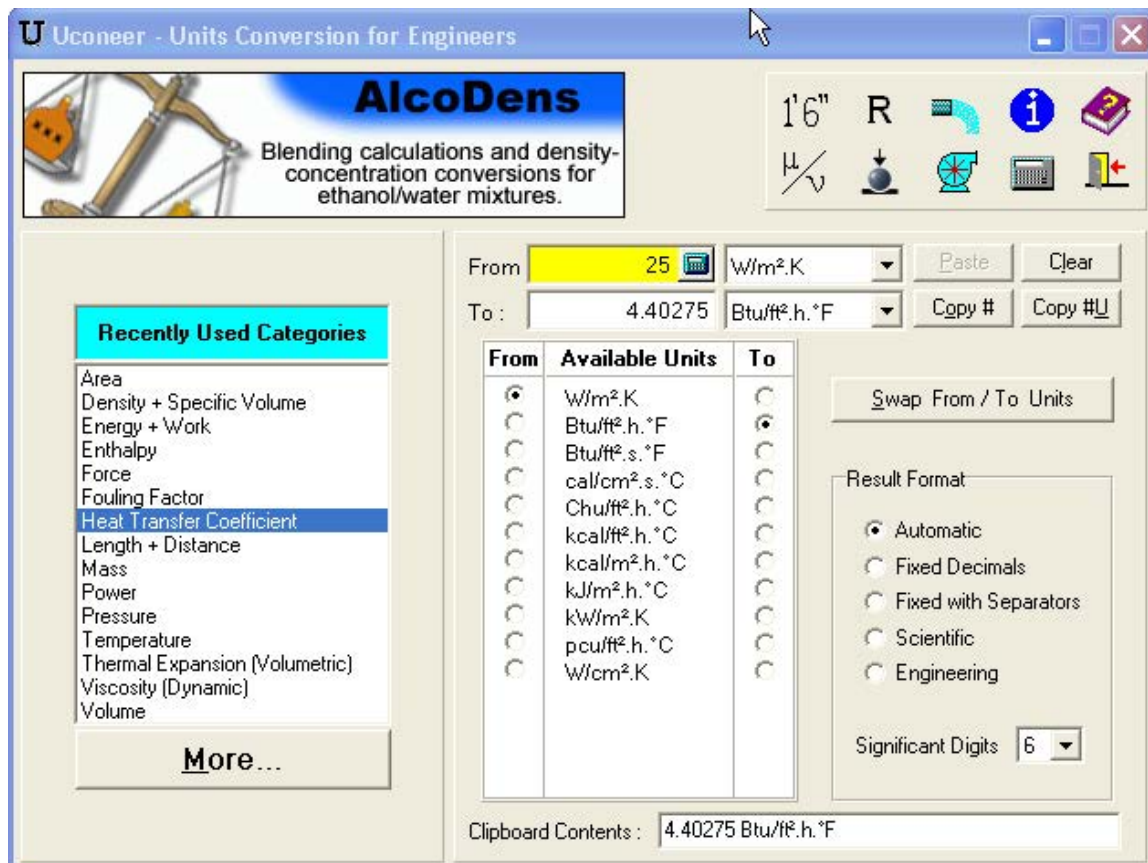


Fig. 1.34 Uconeer – Units conversion for heat transfer coefficient

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

1.4 Summary:

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

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

1.5 References:

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

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

Learning objectives:

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

2.1 Introduction:

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

2.2 International System of Units (SI):

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

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

Table 2.1. SI base units

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



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

Table 2.2. Examples of SI derived units

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

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

Table 2.3. SI derived units with special names and symbols

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

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

^(a) The radian and steradian may be used advantageously in expressions for derived units to distinguish between quantities of a different nature but of the same dimension; some examples are given in Table 4.

^(b) In practice, the symbols rad and sr are used where appropriate, but the derived unit "1" is generally omitted.

^(c) In photometry, the unit name steradian and the unit symbol sr are usually retained in expressions for derived units.

^(d) Other quantities expressed in sieverts are ambient dose equivalent, directional dose equivalent, personal dose equivalent, and organ equivalent dose.

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

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

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

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

Prefixes of SI Units are shown below:

SI Unit Prefixes		
Factor	Prefix	Symbol
10 ¹²	tera	T
10 ⁹	giga	G
10 ⁶	mega	M
10 ³	kilo	k
10 ²	hecto	h
10 ⁻²	centi	c
10 ⁻³	milli	m
10 ⁻⁶	micro	μ
10 ⁻⁹	nano	n
10 ⁻¹²	pico	p

Correct usage of SI Units:

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

Important in SI-metric:

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

3. SI symbols should be preceded by digits and *a space must separate the digits from the symbol*.
 - o **RIGHT:** It was 300 mm wide. The millimeter width was given.
 - o **WRONG:** It was 300mm wide. The mm width was given.
4. Symbols *always are written in the singular form* (even when more than one is meant).
 - o **RIGHT:** 1 mm, 500 mm, 1 kg, 36 kg
 - o **WRONG:** 500 mms, 36 kgs
 - o **BUT:** It is correct to pluralize written-out metric unit names: 25 kilograms, 250 milliliters
5. The symbol for a compound unit that is *a quotient of two units is indicated by a solidus or by a negative exponent*.
 - o **RIGHT:** km/h or km·h⁻¹ (for kilometers per hour)
 - o **WRONG:** kmph or kph (do *not* use p as a symbol for “per”.)
 - o **BUT:** It is correct to say or write “kilometers per hour”.
6. The meaning of an SI symbol can be changed if you substitute a capital letter for a lower case letter.
 - o **RIGHT:** mm (for millimeter, which means 1/1000 of a meter)
 - o **WRONG:** MM or Mm (M is the prefix for mega, which means one million; a megameter is a million meters)



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

Table 2.5 Examples of incorrect SI-metric usage:

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

2.3 Conversion of Units:

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

FPS System:

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

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

Quantity	Multiply	by	to get
Length	m	3.2808	ft
	ft	0.304804	m
Area	m ²	10.7639	ft ²
	ft ²	0.092903	m ²
Volume	m ³	35.3147	ft ³
	ft ³	0.028317	m ³
Mass	kg	2.204586	lb
	lb	0.4536	kg
Density	kg/m ³	0.062428	lb/ft ³
	lb/ft ³	16.01845	kg/m ³
Temperature	K	0.555556	R
	R	1.8	K
Mass transfer coeff.	m/s	11811	ft/h
	ft/h	8.47E-05	m/s
Vol. Flow rate	m ³ /s	127130	ft ³ /h
	ft ³ /h	7.87E-06	m ³ /s
Acceleration	m/s ²	42520000	ft/h ²
	ft/h ²	2.35E-08	
Energy	J	0.000948	Btu
	Btu	1054.997	J
Force	N	0.22481	lbf
	lbf	4.448201	N
Heat transfer rate	W	3.4123	Btu/h
	Btu/h	0.293057	W
Heat flux	W/m ²	0.317209	Btu/h ft ²
	Btu/h ft ²	3.152496	W/m ²
Heat gen. rate	W/m ³	0.096684	Btu/h ft ³
	Btu/h ft ³	10.34297	W/m ³
Heat transfer coeff.	W/m ² .K	0.17611	Btu/h ft ² F
	Btu/h ft ² F	5.678269	W/m ² .K
Kin. Visc.& diffusivity	m ² /s	10.76426	ft ² /s
	ft ² /s	0.0929	m ² /s
Latent heat	J/kg	0.00043	Btu/lb
	Btu/lb	2325.852	J/kg

Mass flow rate	kg/s	7936.6	lbm/h
	lbm/h	0.000126	kg/s
Pressure and stress	N/m ²	0.020886	lbf/ft ²
	lbf/ft ²	47.87896	N/m ²
Sp. heat	J/kg.K	0.000239	Btu/lbm.F
	Btu/lbm.F	4186.553	J/kg.K
Thermal conductivity	W/m.K	0.57782	Btu/h ft F
	Btu/h ft F	1.730643	W/m.K
Thermal resistance	K/W	0.5275	F/h.Btu
	F/h.Btu	1.895735	K/W
Dynamic viscosity	kg/m.s	2419.1	lbm/ft.h
	lbm/ft.h	0.000413	kg/m.s

Table 2.6 Conversion Factors

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



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2.4 Examples of Unit conversion:

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

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

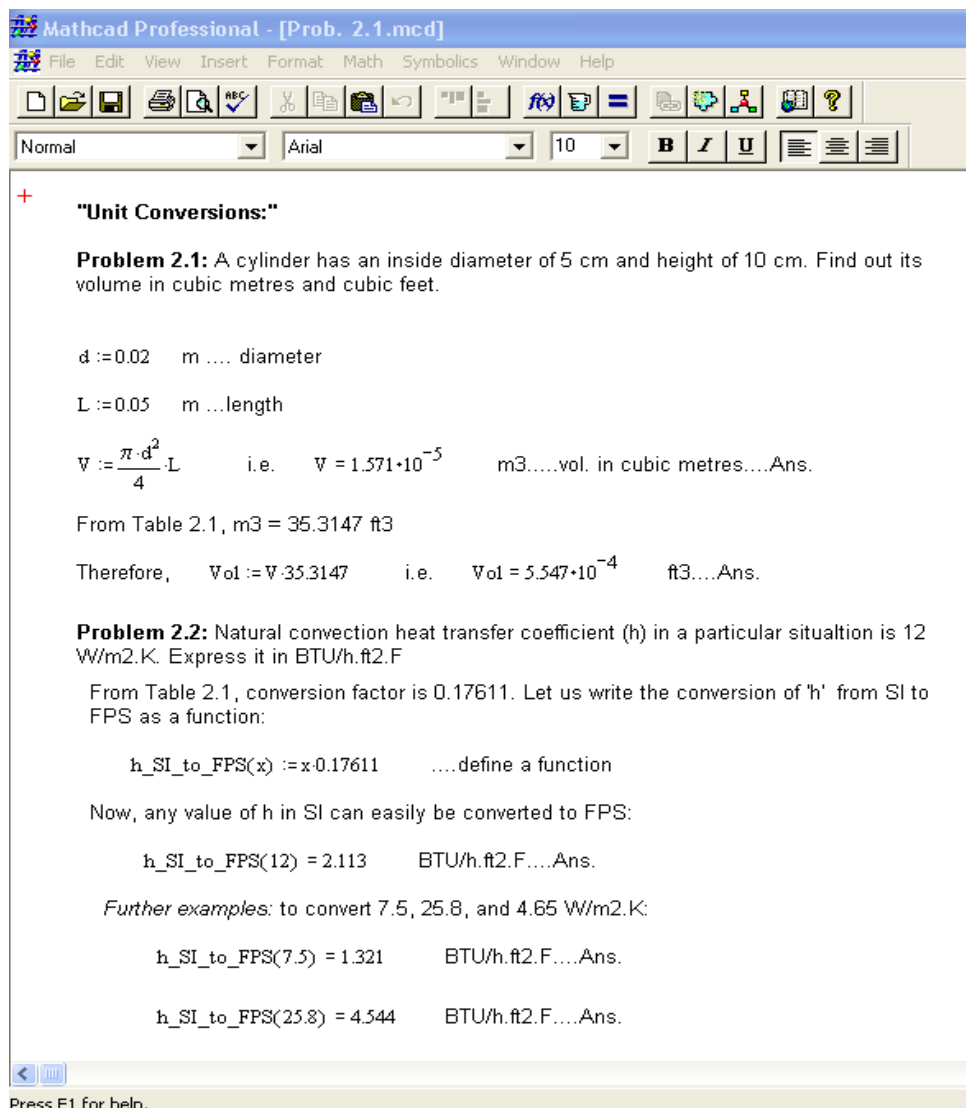


Fig. 2.1 Mathcad Worksheet for Unit conversion

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

Prob. 2.3 Convert a value of heat transfer coeff. of $25.8 \text{ W/m}^2\text{K}$ to $\text{BTU/h.ft}^2\text{F}$ using Uconeer software.

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

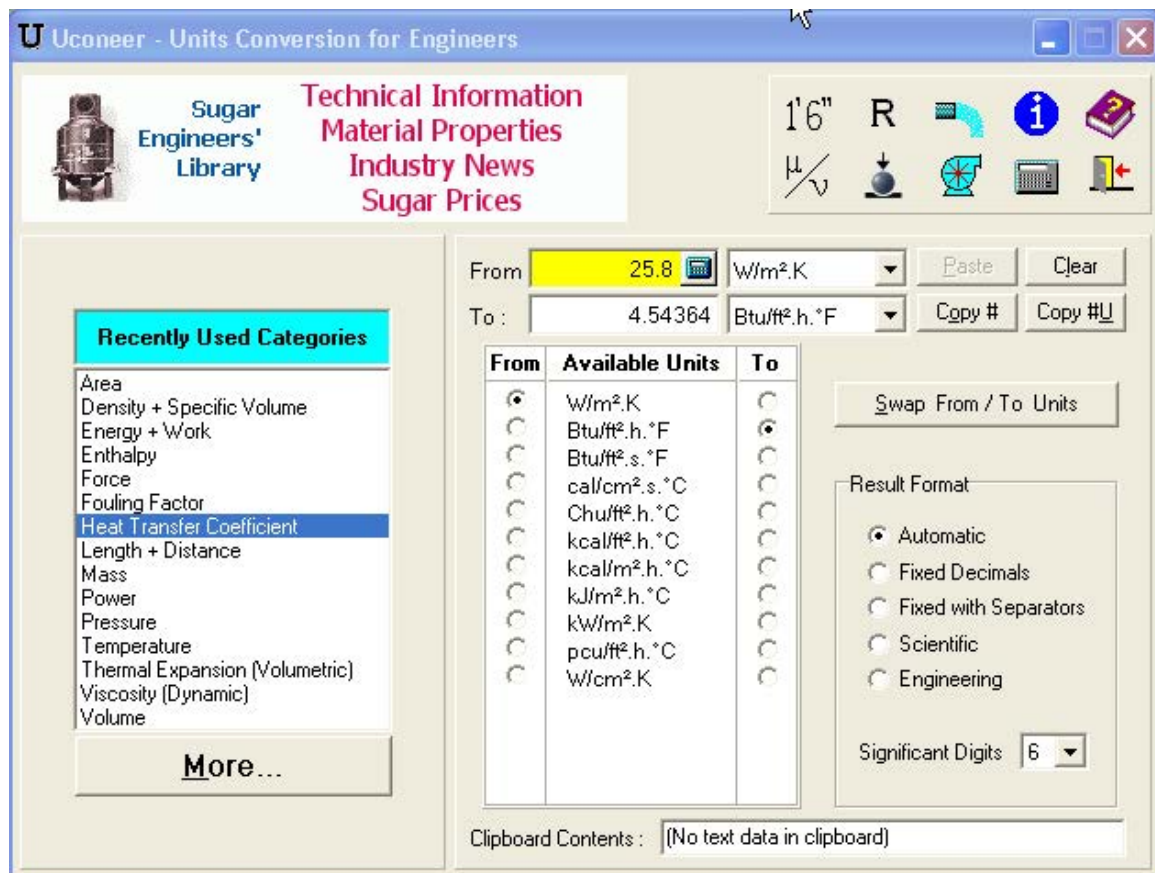


Fig. 2.2 Unit conversion with Uconeer

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

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

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

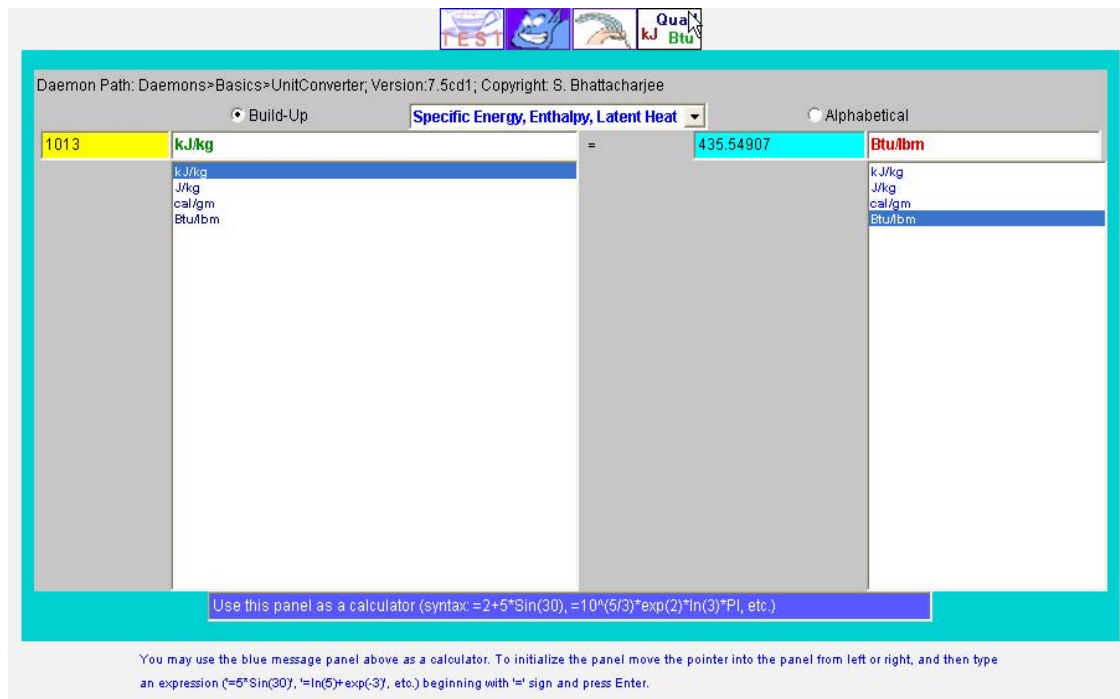


Fig. 2.3 Unit conversion in TEST software

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2.5 Examples of Pressure calculations with Manometers:

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

Formulae:

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

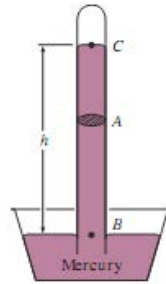


Fig. 2.4 The barometer

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

$$P_2 = P_1 = P_{\text{atm}} + \rho \cdot g \cdot h \quad \text{Pa.....eqn.} \quad (2.2)$$

where, ρ = density of fluid in kg/m^3 , h = vertical height of fluid column in m, g = accn.

direct to gravity = 9.81 m/s^2 at sea level
or,

Second principle to remember is: in a body of liquid the pressures are the same at all points at the same horizontal level. i.e. in the fig. below, $P_1 = P_2$.

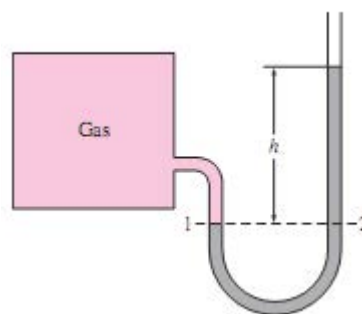


Fig. 2.5 The basic manometer

i.e

$$P_2 = P_1 = P_{\text{atm}} + \rho \cdot g \cdot h \quad \dots \text{eqn.} \quad (2.2)$$

or,

$$P_1 - P_{\text{atm}} = \Delta P = \rho \cdot g \cdot h \quad \dots \text{eqn.} \quad (2.3)$$

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

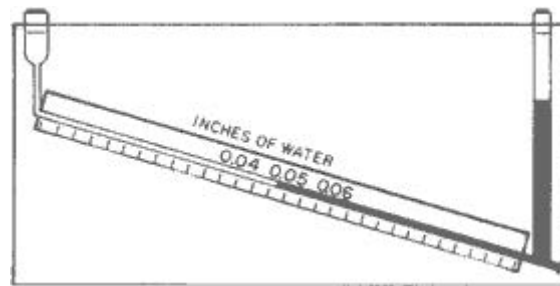
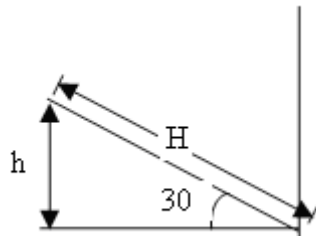


Fig. 2.6 Inclined manometer



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

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

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

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

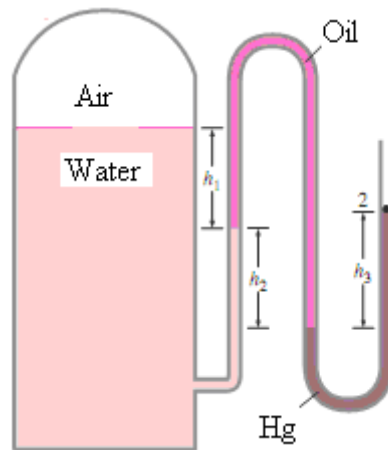


Fig. 2.7 Manometer with 3 fluids

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

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

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

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Now, let solve a few problems on pressure measurement.

Following problem is solved in Mathcad.

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

$$h := 20 \text{ m} \dots \text{depth} \quad \rho := 1025 \text{ kg/m}^3 \dots \text{density}$$

$$g := 9.81 \text{ m/s}^2 \quad P_{\text{atm}} := 1.01325 \cdot 10^5 \text{ Pa}$$

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

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

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

i.e. The total pressure is 3.024 bar.

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

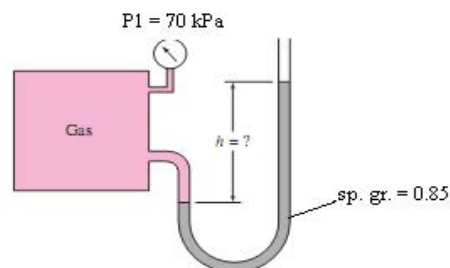


Fig. Prob. 2.6

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

$$\Delta P := 70 \cdot 1000 \text{ Pa} \quad g := 9.81 \text{ m/s}^2$$

$$\rho_{\text{liq}} := 0.85 \cdot 1000 \text{ kg/m}^3$$

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

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

$$\text{i.e. } h = 8.395 \text{ m} \dots \text{height of liquid column} \dots \text{Ans.}$$

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

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

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

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

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

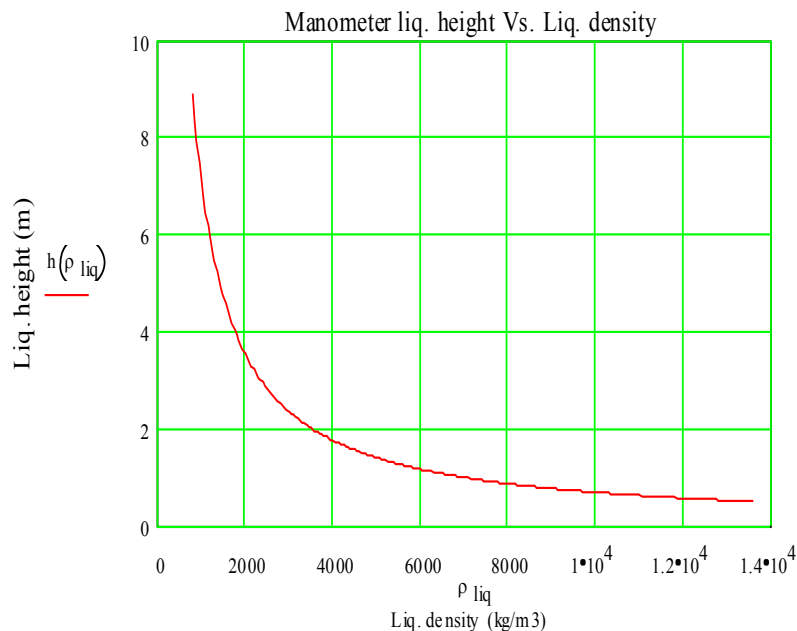


Fig. Prob. 2.6(b)

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

$$h(13600) = 0.525 \quad \text{m.... liq. height with Hg as manometric fluid.}$$

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

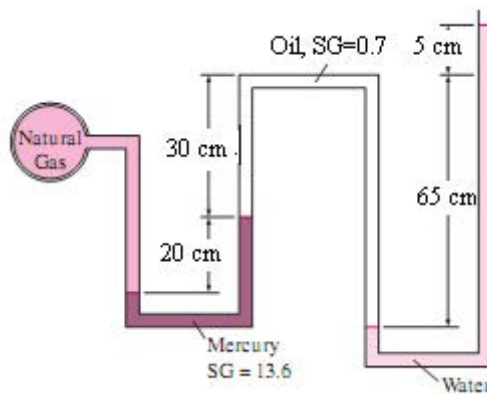
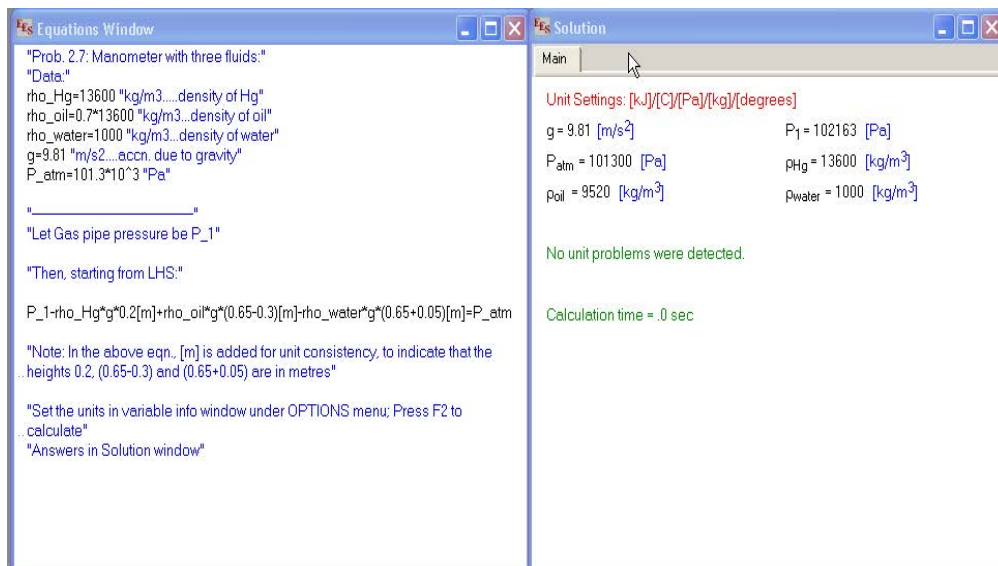


Fig. Prob. 2.7

Right hand end of manometer is open to atmosphere.

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

EES worksheet solution of this problem is shown below:



Thus, the pressure in the gas pipe line is: $P_1 = 102163 \text{ Pa} = 1.02 \text{ bar}$.

Problem 2.8: Change in atm. pressure with the altitude is shown in the following table:

(Ref: http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html)

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

Table 2.7 Atmospheric pressure with Altitude

¹⁾ Sea Level

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

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

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



The advertisement features a background image of a man in a green jacket looking out over a city skyline. The IE Business School logo is in the top left. A badge in the top right states '#1 EUROPEAN BUSINESS SCHOOL FINANCIAL TIMES 2013'. The hashtag #gobeyond is in a white box on the right. The text 'MASTER IN MANAGEMENT' is in a white box. Below it, a paragraph describes the program. A list of three bullet points follows. The slogan 'Because you change, we change with you.' is in italics. At the bottom, contact information and social media icons are provided.

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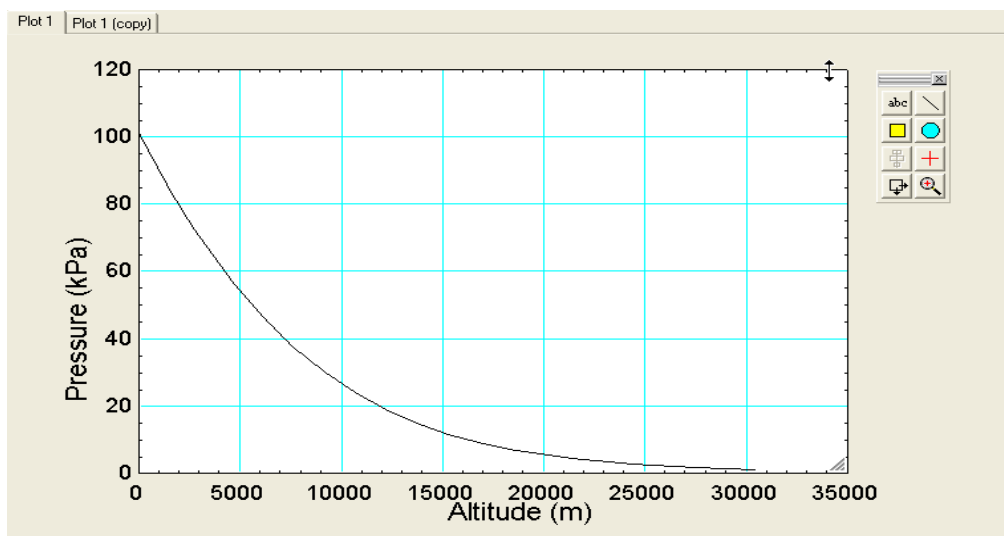
	100 Joules/kg	100 Joules/kg
Row 1	0	101.3
Row 2	153	99.49
Row 3	305	97.63
Row 4	458	95.91
Row 5	610	94.19
Row 6	763	92.46
Row 7	915	90.81
Row 8	1068	89.15
Row 9	1220	87.49
Row 10	1373	85.91
Row 11	1526	84.33
Row 12	1681	81.22
Row 13	2136	78.19
Row 14	2441	75.22
Row 15	2746	72.4
Row 16	3050	69.64
Row 17	4577	57.16
Row 18	6102	46.61
Row 19	7628	37.65
Row 20	9153	30.13
Row 21	10679	23.93
Row 22	12204	18.82
Row 23	13730	14.82
Row 24	15255	11.65
Row 25	16781	9.17
Row 26	18306	7.24
Row 27	21357	4.49
Row 28	24408	2.8

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

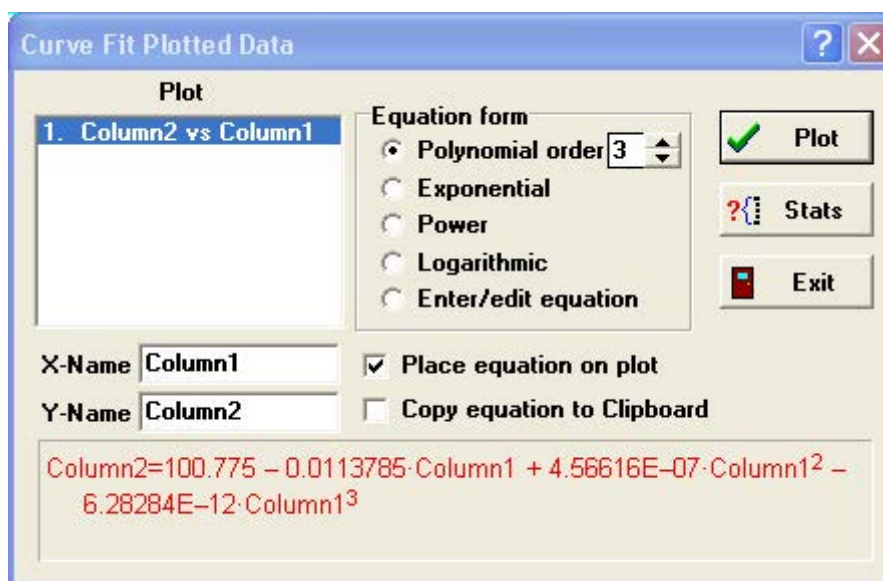
The 'New Plot Setup' dialog window is shown with the following settings:

- Tab Name:** Plot 1
- Description:** (empty)
- Print Description with plot:** ☐
- X-Axis:**
 - Column1
 - Column2
 - Format: A, 0
 - Minimum: 0
 - Maximum: 35000
 - Interval: 5000
 - Linear (selected), Log
 - Grid lines: ☐
- Y-Axis:**
 - Column1
 - Column2
 - Format: A, 4
 - Minimum: 0.0
 - Maximum: 120.0
 - Interval: 20.0
 - Linear (selected), Log
 - Grid lines: ☐
- Table:**
 - Lookup Table
 - Lookup 1
 - First Run: 1
 - Last Run: 30
 - Spline fit: ☐
 - Automatic update: ☐
 - Add legend item: ☐
 - Show array indices: ☐
 - Show error bars: ☐
 - Line: (solid line)
 - Symbol: None
 - Color: (black)
- Buttons:** OK, Cancel

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



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



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

Curve Fit Statistics				
	Value	Std. Error		
a0	1.007751E+02	1.472247E-01	No. points = 30	
a1	-1.137848E-02	7.110074E-05	rms = 4.1945E-01	
a2	4.566159E-07	6.411108E-09	bias = 3.4088E-14	
a3	-6.282845E-12	1.471733E-13	R^2 = 99.99%	
a4			<input type="checkbox"/> Copy to Clipboard	
a5				
a6			<input checked="" type="checkbox"/> OK	

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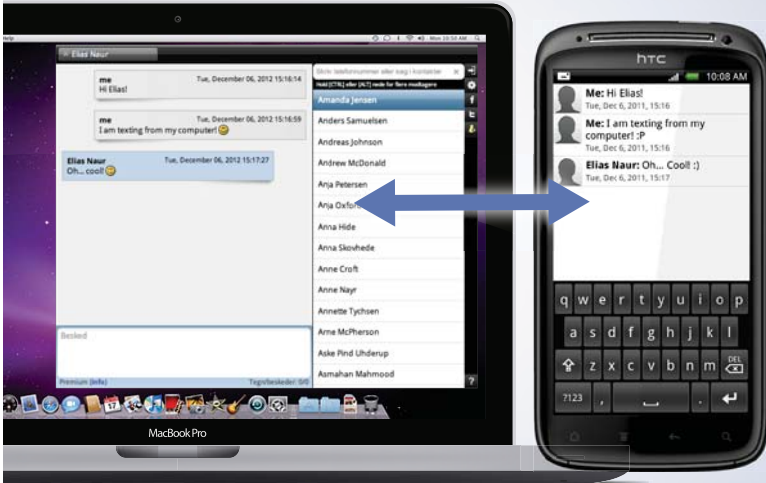
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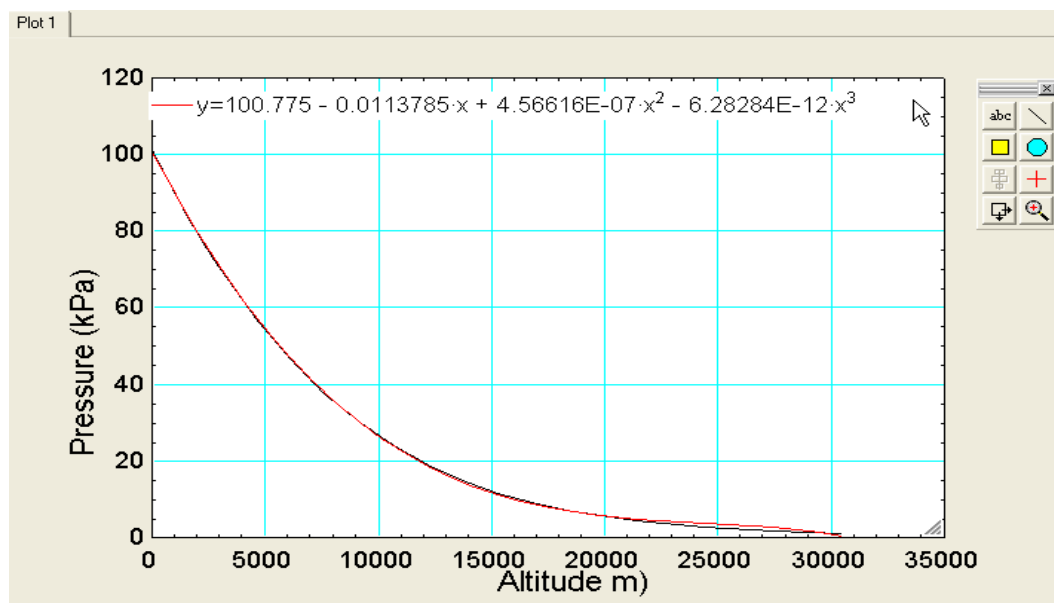
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Press OK in the above screen. Now, click on 'Plot' on the earlier screen and the eqn. is placed on the plot. Right click on the eqn. and format it. Following is the screen shot after formatting:



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

Next, to find the pressure at an altitude of 10000 m: Use the curve fit eqn. In the Equation window of EES, you can type this eqn, substitute for $x = 10000$ and get the value of pressure ($= y$). In the following screen, we have written an EES function using the curve fit eqn. so that pressures can be calculated conveniently for any altitudes, say for $x_1 = 1000$ m, $x_2 = 5000$ m and $x_3 = 10000$ m:

```

EES Equations Window

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

"By curve fit"
FUNCTION Pressure_atm(Altitude)

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

End

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

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

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

```

Now, pressing F2 produces the following Solution:

```
SOLUTION
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
x1 = 1000      x2 = 5000      x3 = 10000      y1 = 89.85
y2 = 54.51     y3 = 26.37
No unit problems were detected.
```

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

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

Let us work out this problem in Mathcad.

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

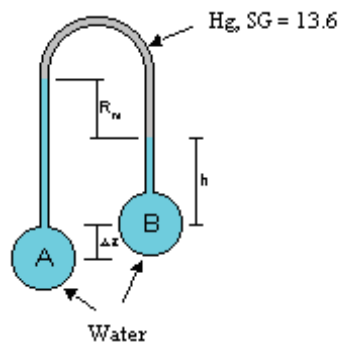


Fig. Prob 2.9

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

$$\rho_{\text{water}} := 1000 \text{ kg/m}^3 \quad \rho_{\text{Hg}} := 13600 \text{ kg/m}^3 \quad g := 9.81 \text{ m/s}^2$$

Find out P_B :

Write down the pressures, starting from bulb A:

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

i.e. $P_B = 1.212 \cdot 10^5 \text{ Pa} \dots \text{Ans.}$

To find the head in metres of water:

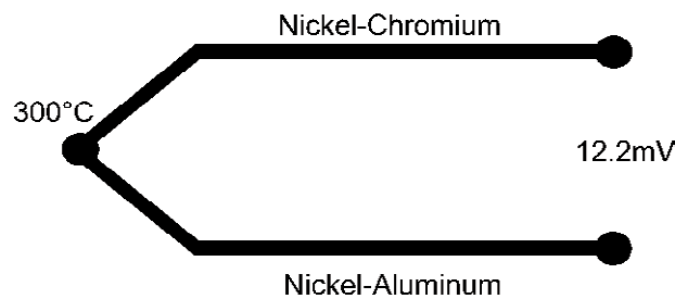
$$P_B = \rho_{\text{water}} \cdot g \cdot \text{head}$$

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

i.e. $\text{head} = 12.357 \text{ m of water} \dots \text{Ans.}$

2.6 Examples of Temperature calculations with Thermocouples:

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



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Thermocouple is a popular device for temperature measurement.

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

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

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

Thermocouples popularly used in industry are:

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

Table 2.8 Thermocouple types

Correct method of connecting a thermocouple is shown below:

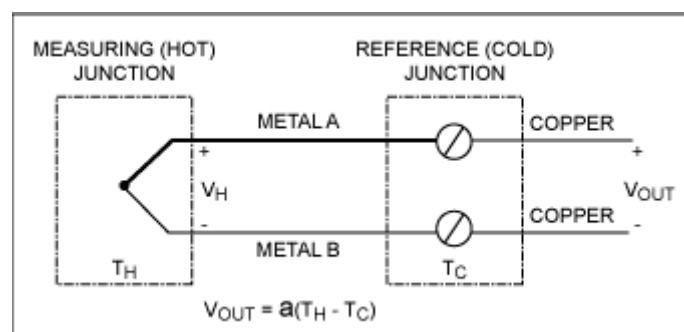


Fig. 2.8 Using Reference junction for thermocouples

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

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

This website presents the following screen:

Download Tables:

Tables of Thermoelectric Voltages and Coefficients for Download	Definitions and Format
<p>Click the desired type to download a table of thermoelectric voltages and coefficients of that type.</p> <p>Click All Thermocouple Types to download a table of thermoelectric voltages and coefficients of all types (B - T).</p> <p>Click Coefficients of All Thermocouple Types to download a table of ONLY coefficients of all types (B - T).</p> <ul style="list-style-type: none"> Type B Type E Type J Type K All Thermocouple Types Type N Type R Type S Type T Coefficients of All Thermocouple Types 	<p>Reference Function</p> <p>Coefficients Definitions</p> <p>Thermoelectric Voltage File Format</p> <p>Coefficients File Format</p>

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NIST **NIST Data Home Page** **ITS-90 Thermocouple** **NIST Online Databases**

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This page was last modified on 04/17/2008 17:12:47.

By clicking at the required type of thermocouple, one can download the look up table for that type. For example, a partial extract (-270 deg.C to 90 deg.C) of the look up table given by NIST for Type E thermocouple in their website is shown below. Note that the table is given in the temperature range: (-270 deg.C to 1000 deg.C).

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

ITS-90 Table for type E thermocouple											
°C	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10
Thermoelectric Voltage in mV											
-270	-9.835										
-260	-9.797	-9.802	-9.808	-9.813	-9.817	-9.821	-9.825	-9.828	-9.831	-9.833	-9.835
-250	-9.718	-9.728	-9.737	-9.746	-9.754	-9.762	-9.770	-9.777	-9.784	-9.790	-9.797
-240	-9.604	-9.617	-9.630	-9.642	-9.654	-9.666	-9.677	-9.688	-9.698	-9.709	-9.718
-230	-9.455	-9.471	-9.487	-9.503	-9.519	-9.534	-9.548	-9.563	-9.577	-9.591	-9.604
-220	-9.274	-9.293	-9.313	-9.331	-9.350	-9.368	-9.386	-9.404	-9.421	-9.438	-9.455
-210	-9.063	-9.085	-9.107	-9.129	-9.151	-9.172	-9.193	-9.214	-9.234	-9.254	-9.274
-200	-8.825	-8.850	-8.874	-8.899	-8.923	-8.947	-8.971	-8.994	-9.017	-9.040	-9.063
-190	-8.561	-8.588	-8.616	-8.643	-8.669	-8.696	-8.722	-8.748	-8.774	-8.799	-8.825
-180	-8.273	-8.303	-8.333	-8.362	-8.391	-8.420	-8.449	-8.477	-8.505	-8.533	-8.561
-170	-7.963	-7.995	-8.027	-8.059	-8.090	-8.121	-8.152	-8.183	-8.213	-8.243	-8.273
-160	-7.632	-7.666	-7.700	-7.733	-7.767	-7.800	-7.833	-7.866	-7.899	-7.931	-7.963
-150	-7.279	-7.315	-7.351	-7.387	-7.423	-7.458	-7.493	-7.528	-7.563	-7.597	-7.632
-140	-6.907	-6.945	-6.983	-7.021	-7.058	-7.096	-7.133	-7.170	-7.206	-7.243	-7.279
-130	-6.516	-6.556	-6.596	-6.636	-6.675	-6.714	-6.753	-6.792	-6.831	-6.869	-6.907
-120	-6.107	-6.149	-6.191	-6.232	-6.273	-6.314	-6.355	-6.396	-6.436	-6.476	-6.516
-110	-5.681	-5.724	-5.767	-5.810	-5.853	-5.896	-5.939	-5.981	-6.023	-6.065	-6.107
-100	-5.237	-5.282	-5.327	-5.372	-5.417	-5.461	-5.505	-5.549	-5.593	-5.637	-5.681
-90	-4.777	-4.824	-4.871	-4.917	-4.963	-5.009	-5.055	-5.101	-5.147	-5.192	-5.237
-80	-4.302	-4.350	-4.398	-4.446	-4.494	-4.542	-4.589	-4.636	-4.684	-4.731	-4.777
-70	-3.811	-3.861	-3.911	-3.960	-4.009	-4.058	-4.107	-4.156	-4.205	-4.254	-4.302
-60	-3.306	-3.357	-3.408	-3.459	-3.510	-3.561	-3.611	-3.661	-3.711	-3.761	-3.811
-50	-2.787	-2.840	-2.892	-2.944	-2.996	-3.048	-3.100	-3.152	-3.204	-3.255	-3.306
-40	-2.255	-2.309	-2.362	-2.416	-2.469	-2.523	-2.576	-2.629	-2.682	-2.735	-2.787
-30	-1.709	-1.765	-1.820	-1.874	-1.929	-1.984	-2.038	-2.093	-2.147	-2.201	-2.255
-20	-1.152	-1.208	-1.264	-1.320	-1.376	-1.432	-1.488	-1.543	-1.599	-1.654	-1.709
-10	-0.582	-0.639	-0.697	-0.754	-0.811	-0.868	-0.925	-0.982	-1.039	-1.095	-1.152
0	0.000	-0.059	-0.117	-0.176	-0.234	-0.292	-0.350	-0.408	-0.466	-0.524	-0.582
ITS-90 Table for type E thermocouple											
°C	0	1	2	3	4	5	6	7	8	9	10
Thermoelectric Voltage in mV											
0	0.000	0.059	0.118	0.176	0.235	0.294	0.354	0.413	0.472	0.532	0.591
10	0.591	0.651	0.711	0.770	0.830	0.890	0.950	1.010	1.071	1.131	1.192
20	1.192	1.252	1.313	1.373	1.434	1.495	1.556	1.617	1.678	1.740	1.801
30	1.801	1.862	1.924	1.986	2.047	2.109	2.171	2.233	2.295	2.357	2.420
40	2.420	2.482	2.545	2.607	2.670	2.733	2.795	2.858	2.921	2.984	3.048
50	3.048	3.111	3.174	3.238	3.301	3.365	3.429	3.492	3.556	3.620	3.685
60	3.685	3.749	3.813	3.877	3.942	4.006	4.071	4.136	4.200	4.265	4.330
70	4.330	4.395	4.460	4.526	4.591	4.656	4.722	4.788	4.853	4.919	4.985
80	4.985	5.051	5.117	5.183	5.249	5.315	5.382	5.448	5.514	5.581	5.648
90	5.648	5.714	5.781	5.848	5.915	5.982	6.049	6.117	6.184	6.251	6.319

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

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

Polynomial function is defined as follows:

Reference Function Coefficients Definitions:

The general form for the emf, E, as a function of t_{90} for all except type K thermocouples is:

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

where E is in mV and t_{90} is in °C. For type K thermocouples above 0°C, there is an additional term to account for a magnetic ordering effect:

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

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

$a_0 = 0.118597600000 \times 10^0$
$a_1 = -0.118343200000 \times 10^{-3}$
$a_2 = 0.126968600000 \times 10^3$

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

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

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


	TYPE E Nickel-10% Chromium(+) Versus Constantan(-)	TYPE J Iron(+) Versus Constantan(-)	TYPE K Nickel-10% Chromium(+) Versus Nickel-5%(-) (Aluminum Silicon)	TYPE R Platinum-13% Rhodium(+) Versus Platinum(-)	TYPE S Platinum-10% Rhodium(+) Versus Platinum(-)	TYPE T Copper(+) Versus Constantan(-)
	-100°C to 1000°C ± 0.5°C	0°C to 760°C ± 0.1°C	0°C to 1370°C ± 0.7°C	0°C to 1000°C ± 0.5°C	0°C to 1750°C ± 1°C	-160°C to 400°C ± 0.5°C
	9th order	5th order	8th order	8th order	9th order	7th order
a ₀	0.104967248	-0.048868252	0.226584602	0.263632917	0.927763167	0.100860910
a ₁	17189.45282	19873.14503	24152.10900	179075.491	169526.5150	25727.94369
a ₂	-282639.0850	-218614.5353	67233.4248	-48840341.37	-31568363.94	-767345.8295
a ₃	12695339.5	11569199.78	2210340.682	1.90002E + 10	8990730663	78025595.81
a ₄	-448703084.6	-264917531.4	-860963914.9	-4.82704E + 12	-1.63565E + 12	-9247486589
a ₅	1.10866E + 10	2018441314	4.83506E + 10	7.62091E + 14	1.88027E + 14	6.97688E + 11
a ₆	-1.76807E + 11		-1.18452E + 12	-7.20026E + 16	-1.37241E + 16	-2.66192E + 13
a ₇	1.71842E + 12		1.38690E + 13	3.71496E + 18	6.17501E + 17	3.94078E + 14
a ₈	-9.19278E + 12		-6.33708E + 13	-8.03104E + 19	-1.56105E + 19	
a ₉	2.06132E + 13				1.69535E + 20	

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

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

where x is in Volts, T is in °C

Table 2.10 NBS polynomial coefficients for Thermocouples



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

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

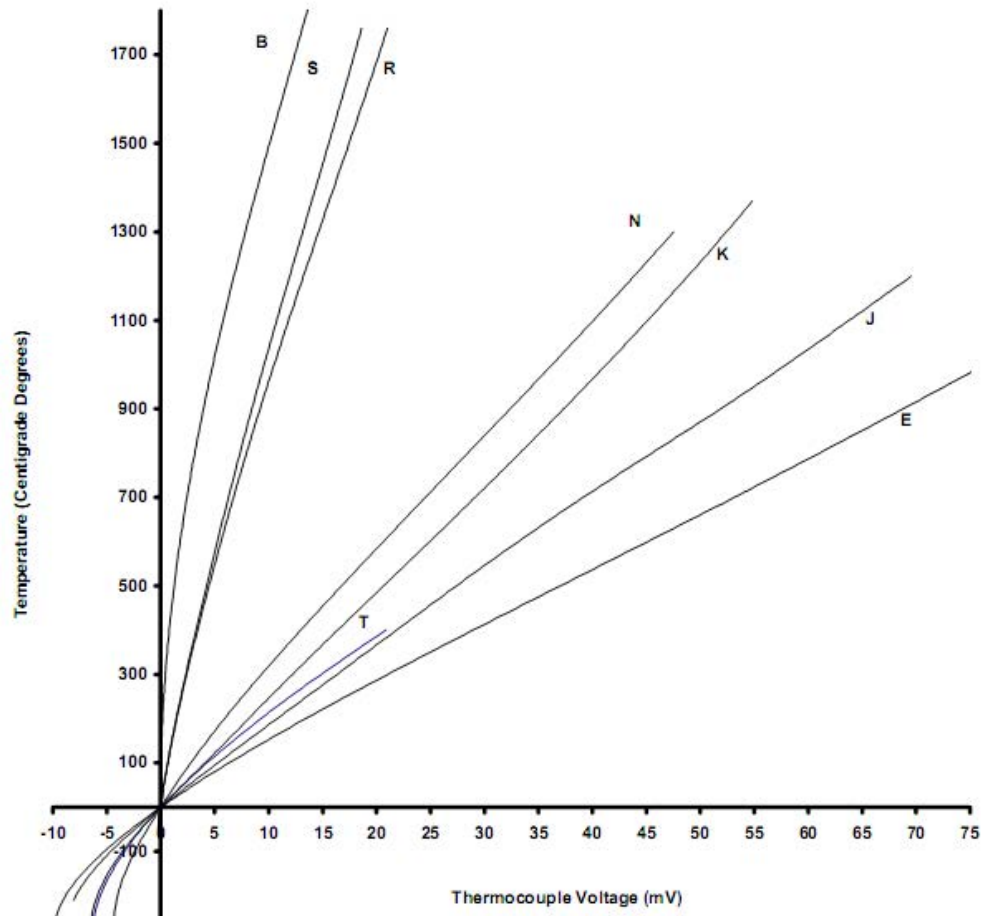


Fig. 2.10 Thermocouple voltage vs temperature for different types of thermocouples

Following problem is worked out in Mathcad:

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

Solution:

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

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

$$\varepsilon(100) = 15 \quad \dots \text{value of } \varepsilon \text{ at } t = 100 \text{ C}$$

$$\varepsilon(50) = 8.75 \quad \dots \text{value of } \varepsilon \text{ at } t = 50 \text{ C}$$

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

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

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

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

We use the 'Solve block' of Mathcad.

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

$$a := 1 \quad b := 1 \quad \dots \text{trial values}$$

Given

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

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

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

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

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

$$T(2.5) = 25.808 \quad \text{C.....Ans.}$$

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

This problem is now solved in EES:

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

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

SOLUTION

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

l = 0 m = 1.04 n = -0.0004 tA = 25

tB = 24.26

No unit problems were detected.

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

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

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

```
"Let the Fahrenheit reading be 'y' and the Centigrade reading be 'x'"
2*x = y "...y is twice x .. by data"
x*9/5 + 32=y "...since both x and y are for the same fluid at the same time, they are equal"
R=y+460 "...deg. R = deg.F + 460"
K=x+273.1 "Kelvin = deg.C + 273.1"
RbyK=R/K "...to verify that R/K = 1.8"
```

SOLUTION

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

K = 433.1 R = 780 RbyK = 1.801 x = 160

y = 320

No unit problems were detected.

Note the answers as: $x = 160 \text{ deg.C}$, $y = 320 \text{ deg.F}$;

$R = 780 \text{ deg. Rankine}$; $K = 433.1 \text{ K}$; ($R/K = 1.8$...verified).

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

Solution is done in EES.

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

```
"We have:
emf = A.T + B.T^2 + C.T^3"

"From data:"

5550 = A*630.74 + B*(630.74)^2 + C*(630.74)^3 "...at 630.74 deg.C"

9150 = A*961.93 + B*(961.93)^2 + C*(961.93)^3 "...at 961.93 deg.C"

10335 = A*1064.3 + B*(1064.3)^2 + C*(1064.3)^3 "...at 1064.3 deg.C"

"When emf = 7300 microvolts:"

7300 = A*T + B*T^2 + C*T^3 "...finds T in deg.C"

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

No unit problems were detected.
```

We note the results:

Polynomial coeffs: $A = 7.142$, $B = 0.002938$ and $C = -4.931\text{E-}07$, and

At $\text{emf} = 7300 \text{ microvolts}$, Temperature $T = 796.2 \text{ deg.C}$

2.7 Constant volume gas thermometer:

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

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

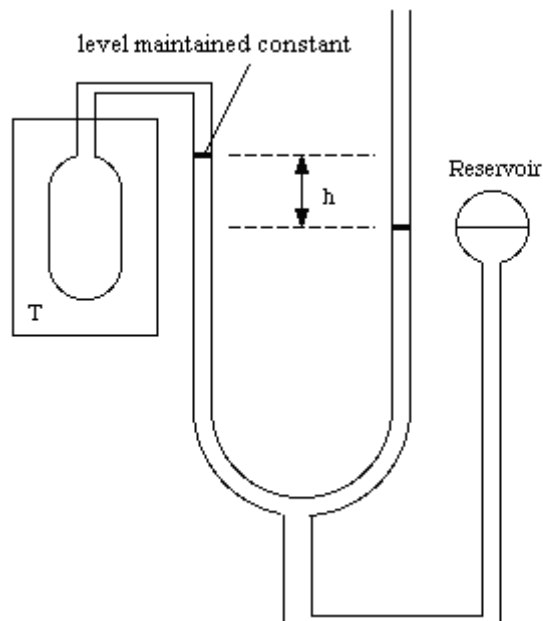


Fig. 2.11 Constant volume gas thermometer

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

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

$$P_{TP} = P_{atm} - \rho \cdot g \cdot h \quad (2.7)$$

where pressures are Pa.

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

Then, applying the Gas Law:

$$\frac{P}{P_{TP}} = \frac{T}{T_{TP}} = \frac{T}{273.16} \quad \dots(2.8)$$

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

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

Solution: We shall solve this problem in EES:

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

Press F2 to get Solutions.

Screen shot of Equations and Solution window are shown below:

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

SOLUTION
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
P_atm = 750          P_T = 645          P_TP = 575          T = 306.41
T_TP = 273.16

No unit problems were detected.
```

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

2.8 Resistance Thermometer Detectors (RTD):

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

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

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

Disadvantages of Pt are:

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

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

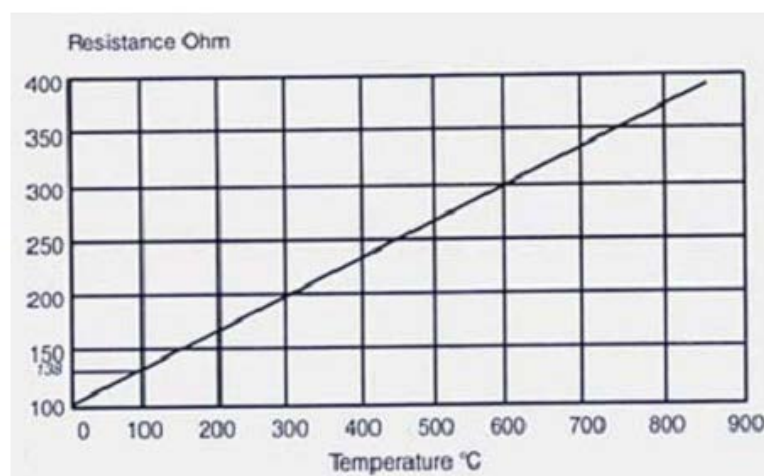


Fig. 2.12 Resistance – Temperature characteristics of Pt-100

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

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

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

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

$$R(t) = R_0 \cdot (1 + A \cdot t + B \cdot t^2) \quad \dots(2.11)$$

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

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

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

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

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

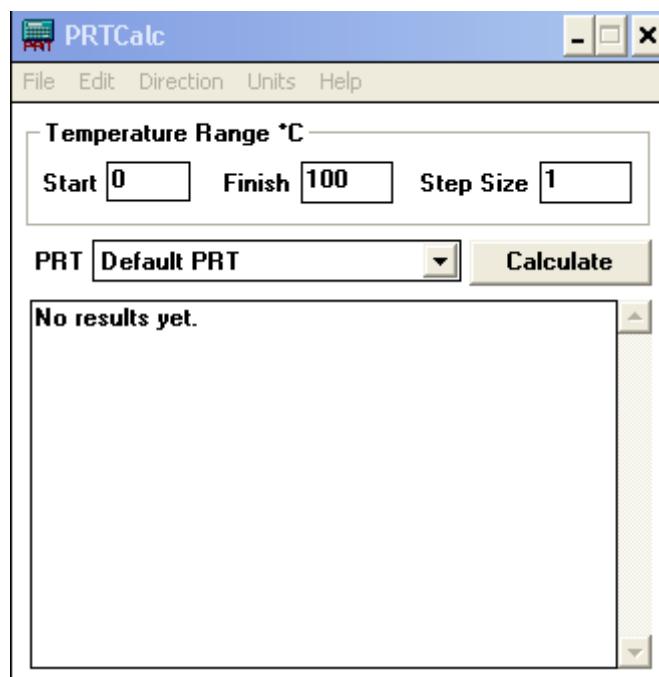
For those who use Pt 100 very often, there is a very versatile free software to make calculations, known as PRTCalc., available for download from <http://www.isotech.co.uk/prtcalc/prtcalc.html>. According to its supplier: “It allows for the accurate conversion of resistance to temperature or temperature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

Important features of PRTCalc are:

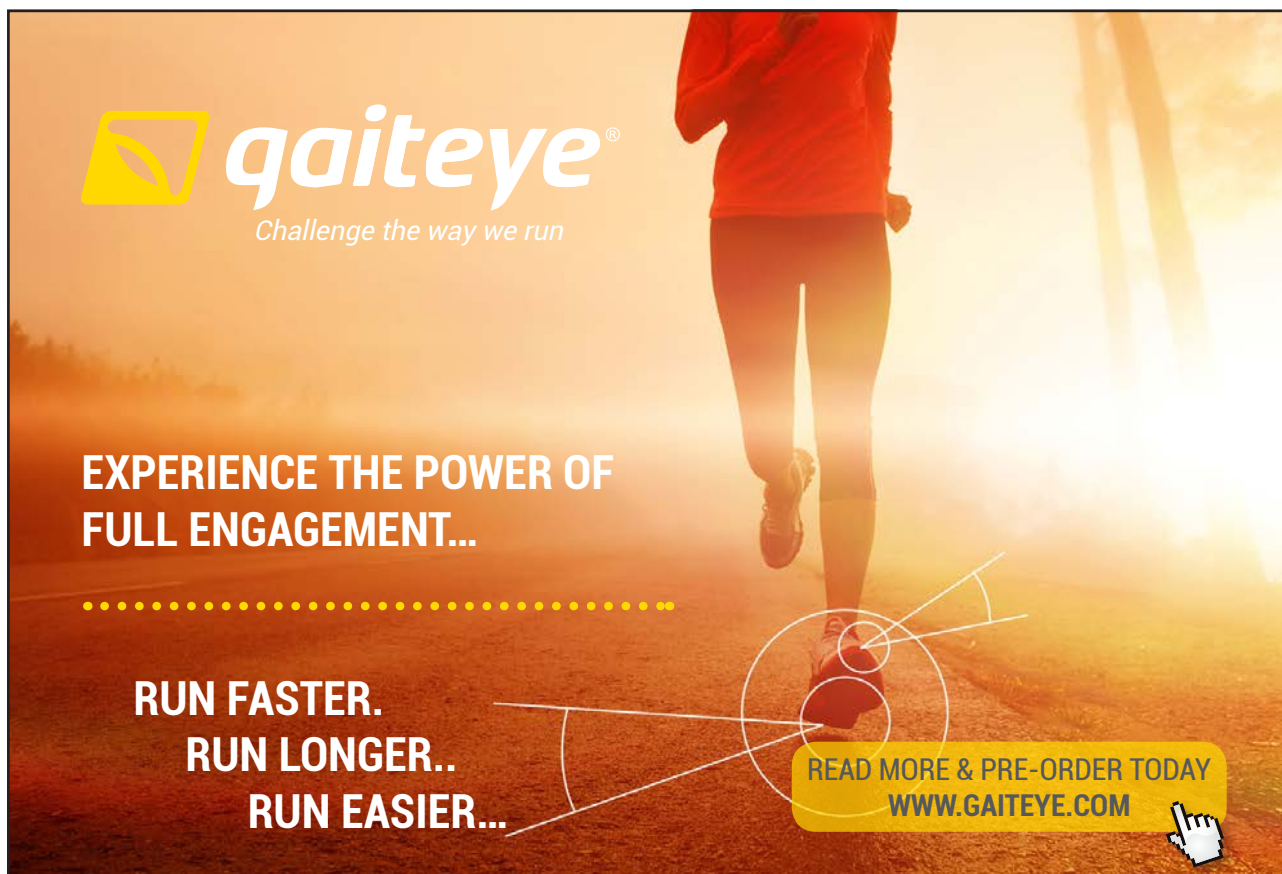
1. Can Generate Large Tables or Single Values
2. Convert Temperature to Resistance with high accuracy
3. Convert Resistance to Temperature to approx. 0.01°C
4. Allows very large lists of data
5. Output Can be Saved as a text file
6. Allows marking and copying of result data
7. Stores coefficients for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

Using PRTCalc:

As you start PRTCalc, following screen is presented:



The screenshot shows the PRTCalc application window. The title bar reads 'PRTCalc'. The menu bar includes 'File', 'Edit', 'Direction', 'Units', and 'Help'. The main interface has a 'Temperature Range °C' section with input fields for 'Start' (0), 'Finish' (100), and 'Step Size' (1). Below this is a 'PRT' dropdown menu set to 'Default PRT' and a 'Calculate' button. A large text area at the bottom displays 'No results yet.'



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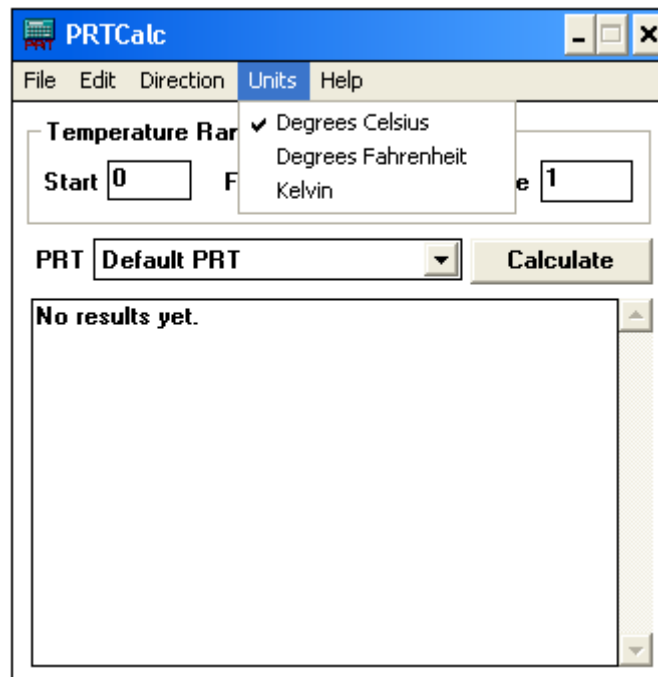
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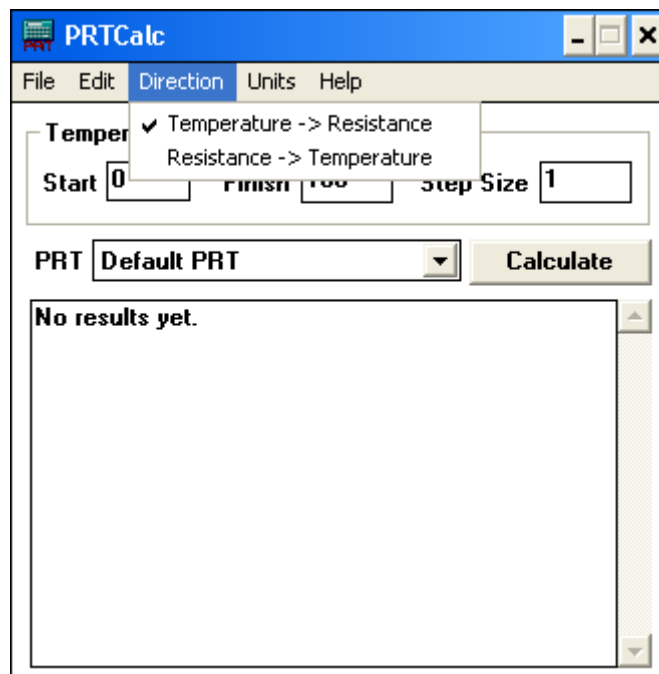
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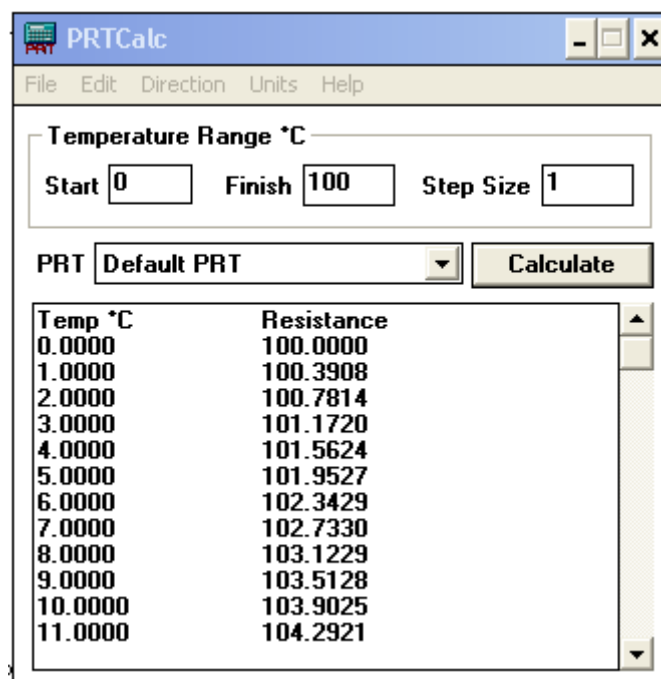
Then, select °C, °F or Kelvin from the **Units** menu:



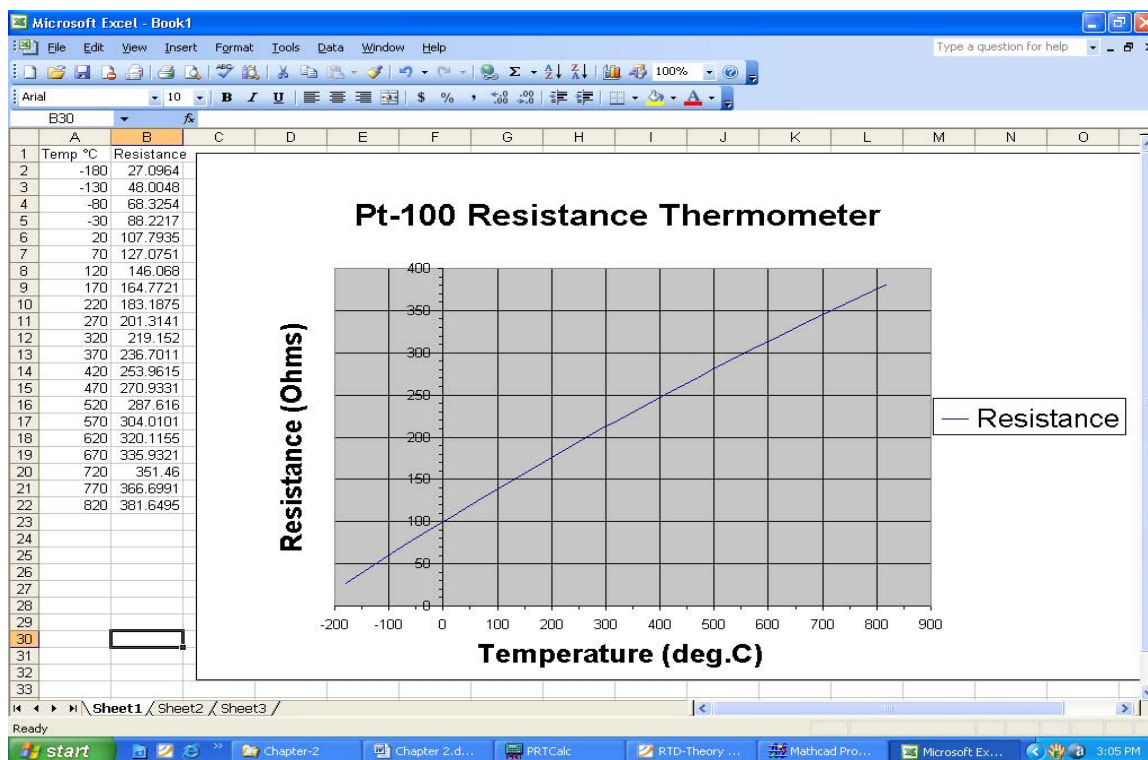
Choose between calculating from resistance to temperature or temperature to resistance from the **Direction** menu:



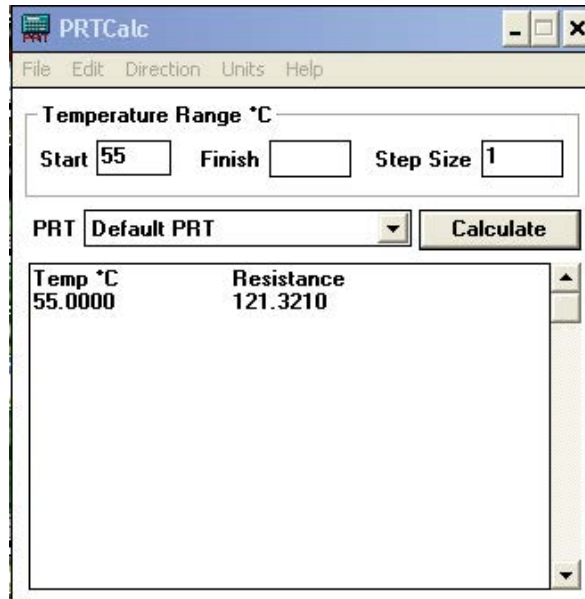
Press 'Calculate' and the table of Temp vs Resistance appears as shown:



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



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



Temp °C	Resistance
55.0000	121.3210

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

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

We shall solve this problem in Mathcad.

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

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

where

$R_0 := 100$	ohms
$A := 3.9083 \cdot 10^{-3}$	deg.C/C
$B := -5.775 \cdot 10^{-7}$	deg.C/C^2
$C := -4.183 \cdot 10^{-12}$	deg.C/C^4

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

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

Given

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

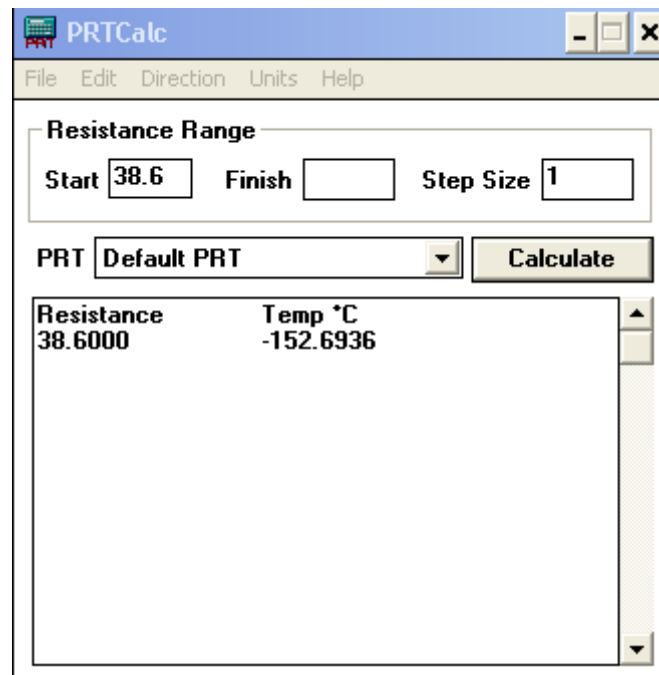
Find(t) = -152.694

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

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

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

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



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

To draw Temp vs Resistance graph for Pt 100:

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

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

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

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

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

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



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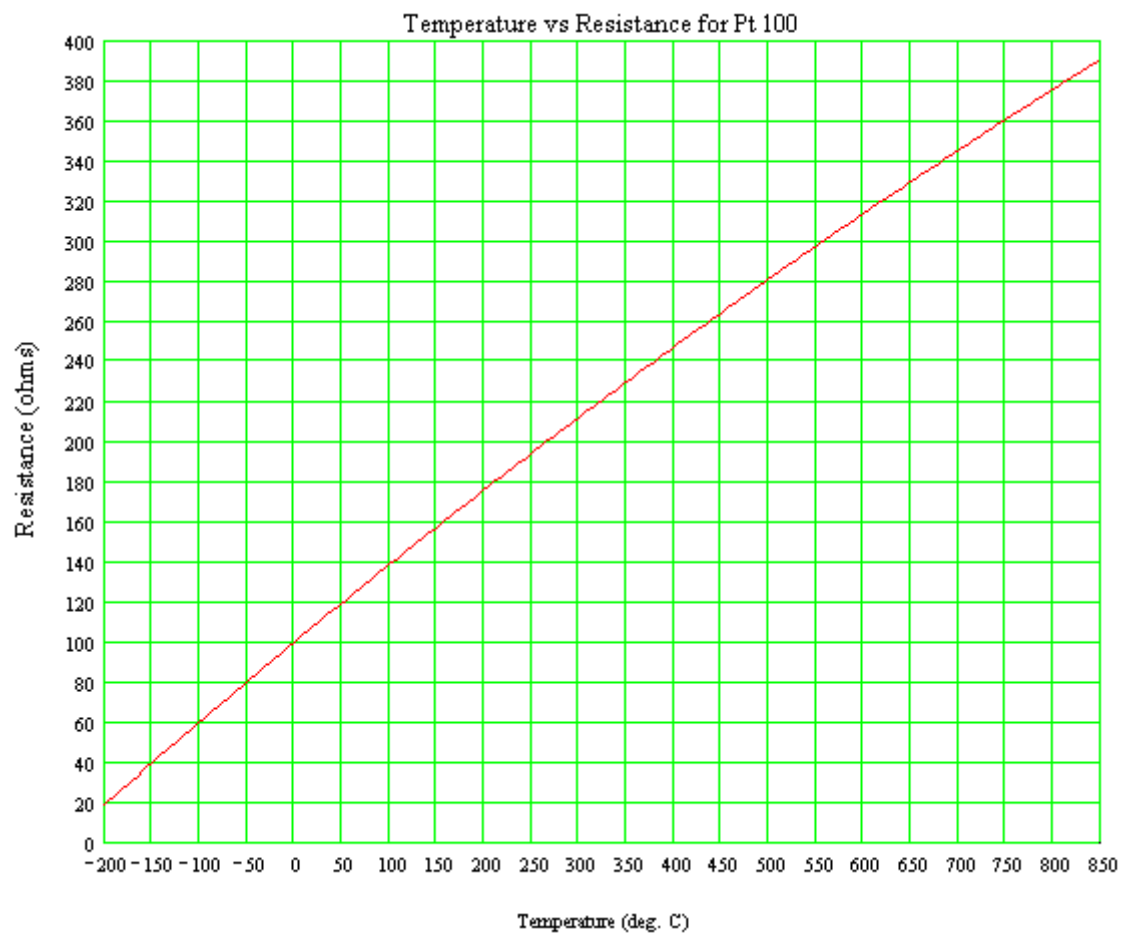


Fig. 2.1 Pt 100 Resistance Thermometer characteristics

2.9 Summary:

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

2.10 References:

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9. www.peaksensors.com
10. www.dataforth.com
11. www.picotech.com
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3 Properties Of Pure Substances

Learning objectives:

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

3.1 Introduction:

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

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

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

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

3.2 Property diagrams for Water:

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

Some sample diagrams are shown below:

3.2.1 T-v diagram: (Ref: 1)

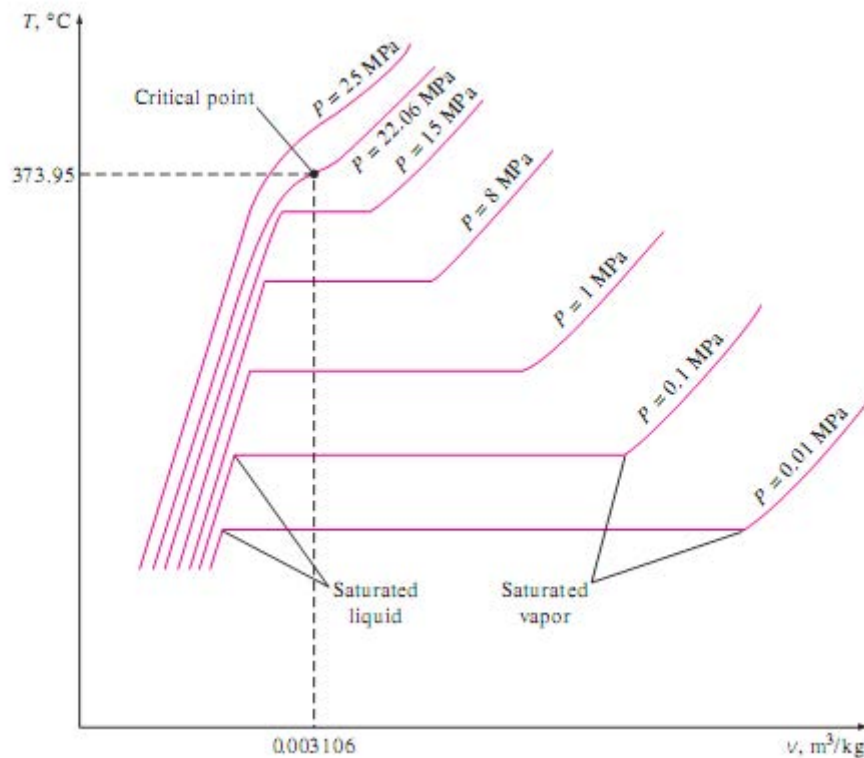


Fig. 3.1 T-v diagram for Water at different pressures

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

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

3.2.2 P-v diagram: (Ref: 1)

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

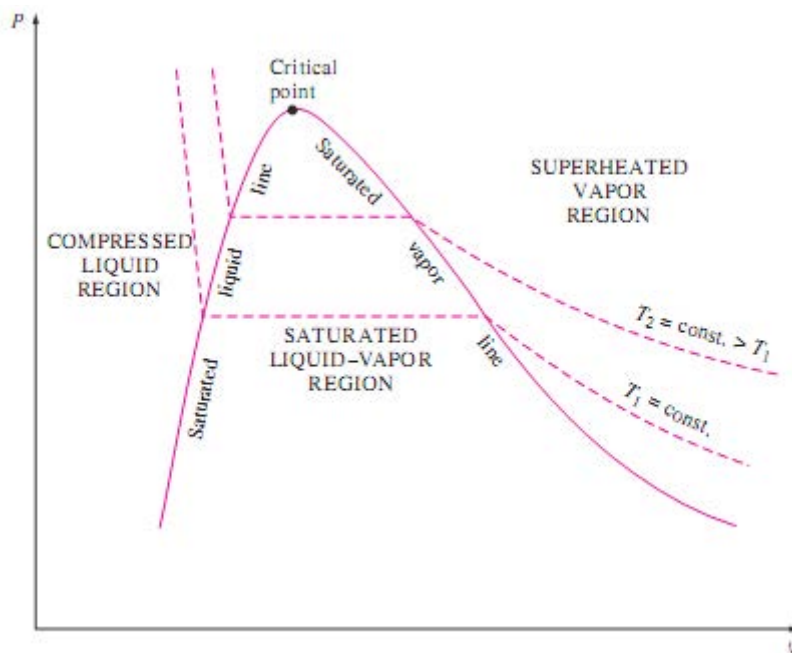


Fig. 3.2 P-v diagram for Pure substance

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

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

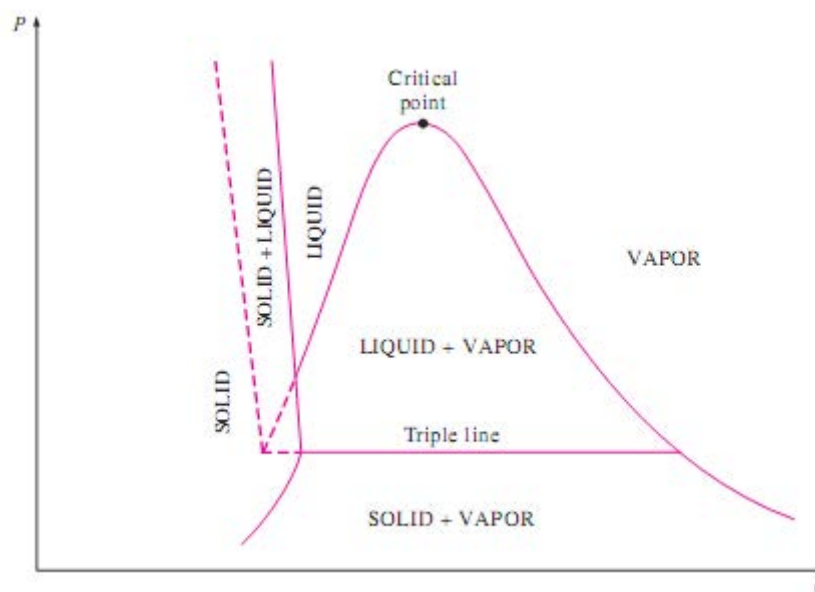


Fig. 3.3 P-v diagram for water (which expands on freezing)

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

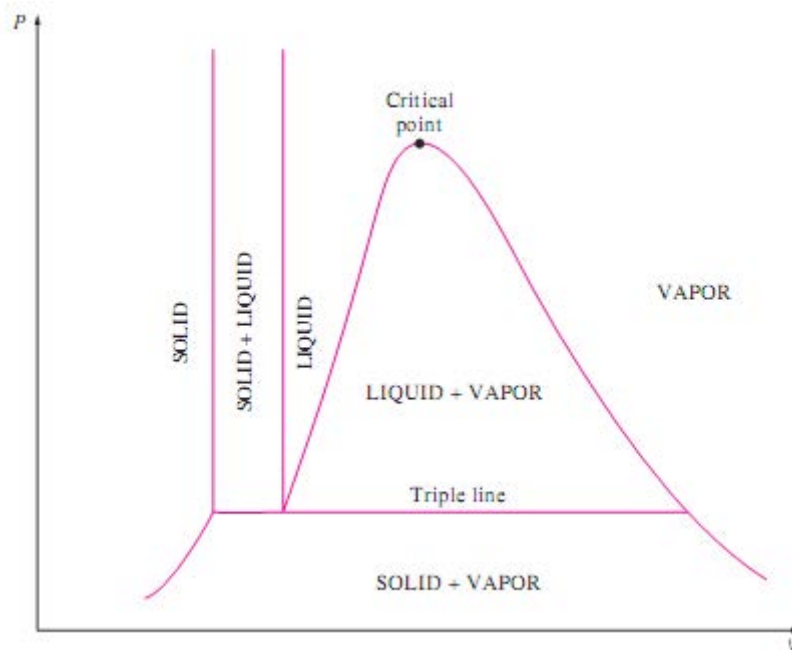


Fig. 3.4 P-v diagram for substances which contract on freezing



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

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

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

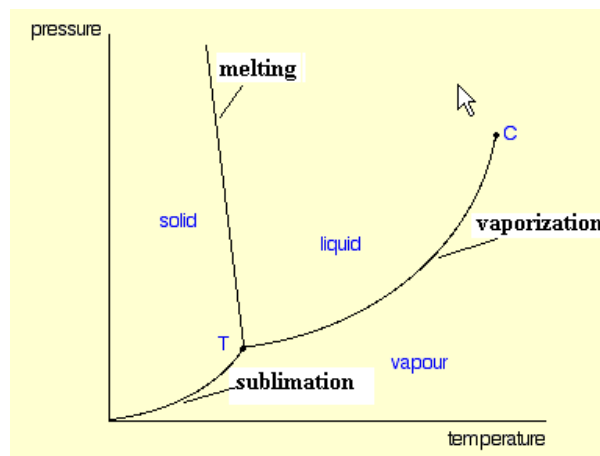


Fig. 3.5a. P-T diagram for water

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

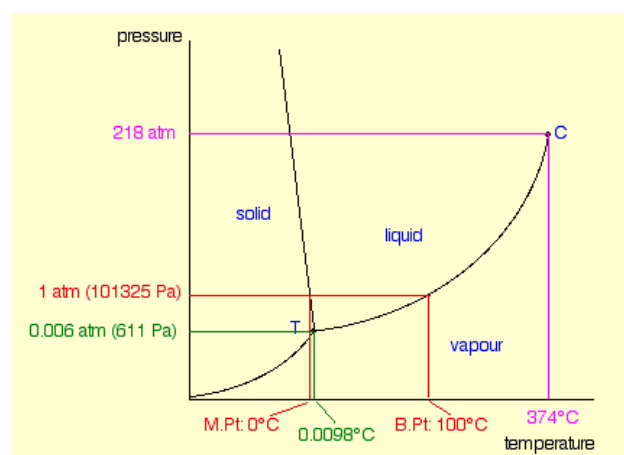


Fig. 3.5b. P-T diagram for water

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

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

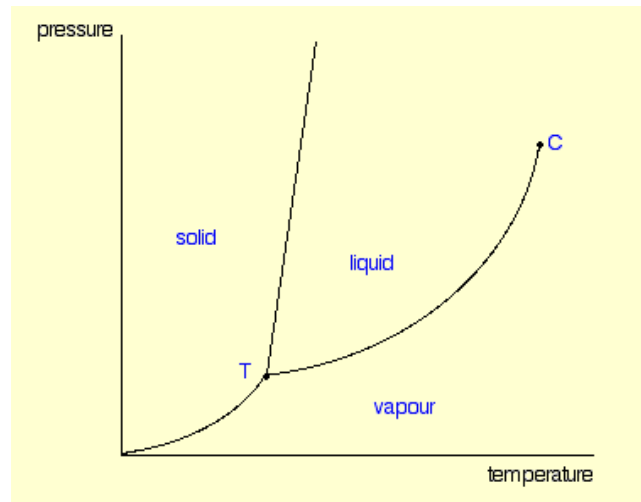


Fig. 3.6 P-T diagram for a substance which contracts on freezing

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

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

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

Table 3.1 Vapor pressure of Ice

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

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

Table 3.2 Vapor pressure of Water

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

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

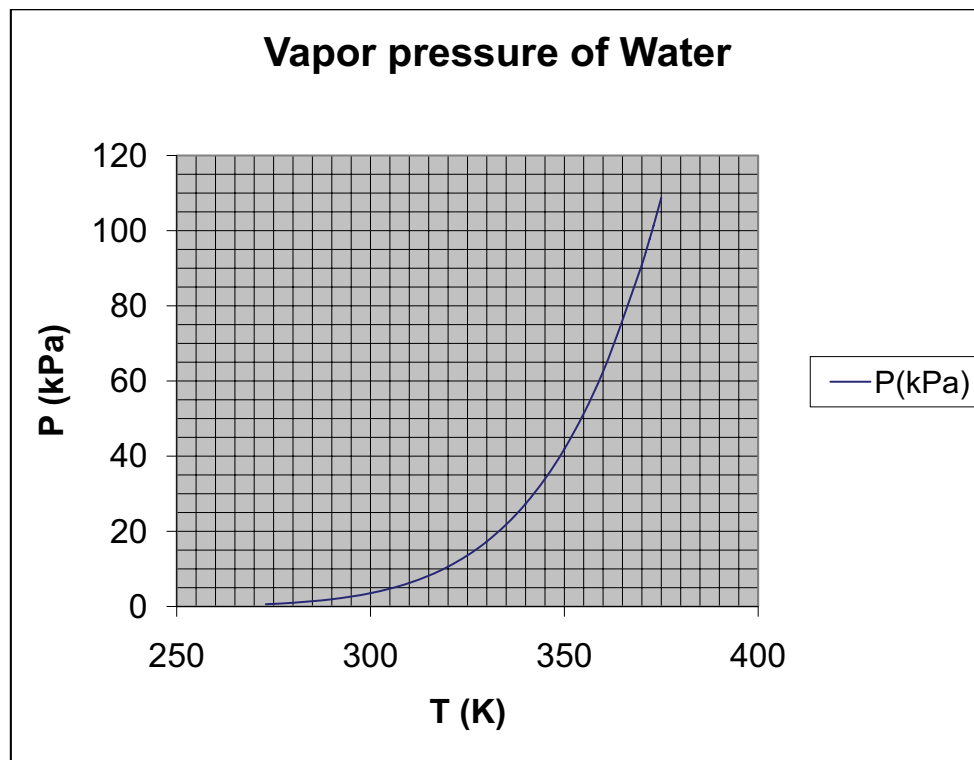


Fig. 3.7 Vapor pressure curve for Water

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

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

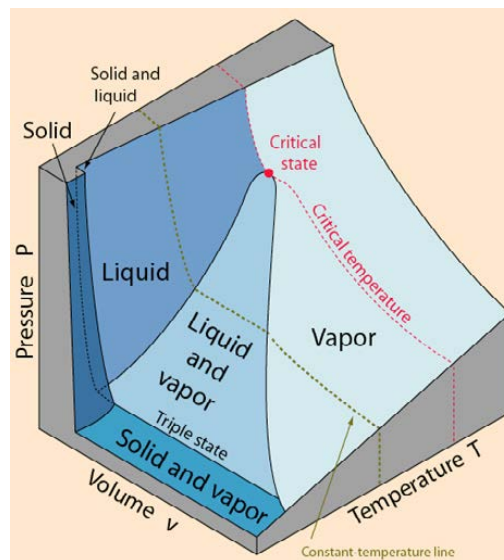


Fig. 3.8 P-v-T surface for Water

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

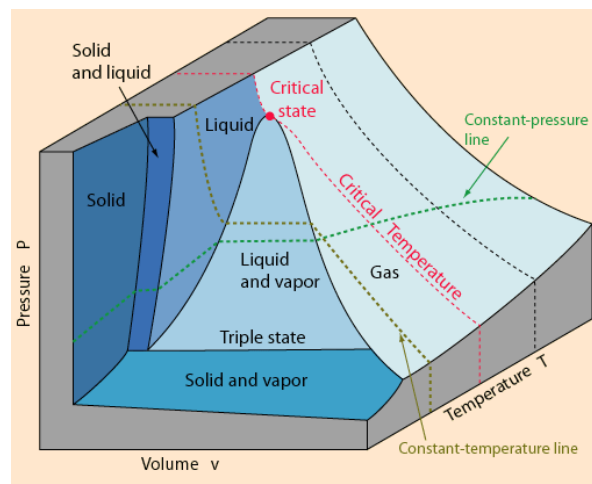


Fig. 3.9 P-v-T surface for a substance that contracts on freezing

3.3 Property Diagrams from Software:

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

3.3.1 Property diagrams using EES:

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

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

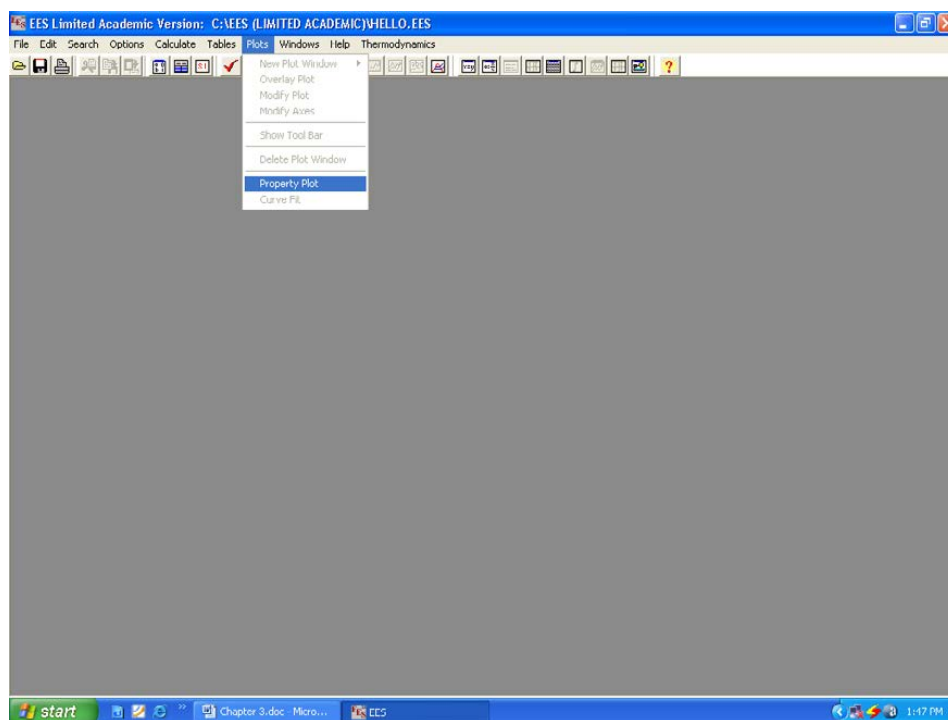


Fig. 3.10a. Drawing Property plot with EES

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

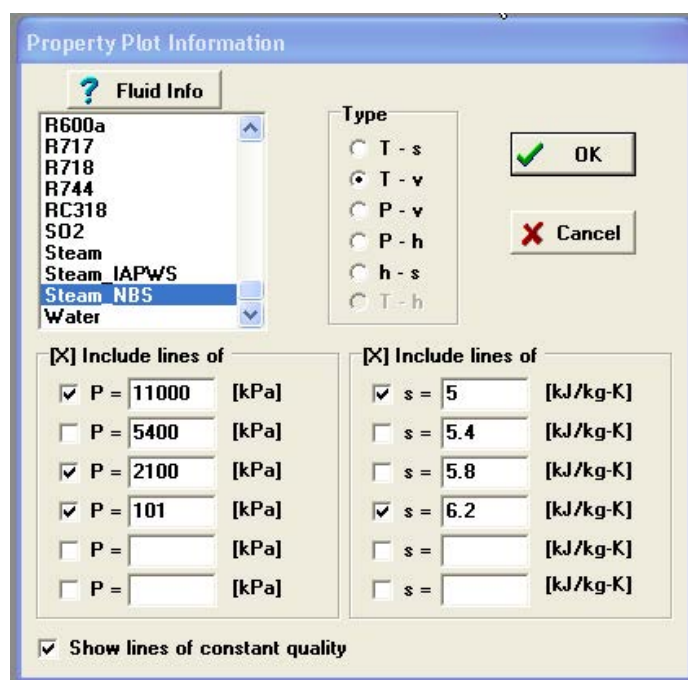


Fig. 3.10b. Drawing Property plot with EES

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

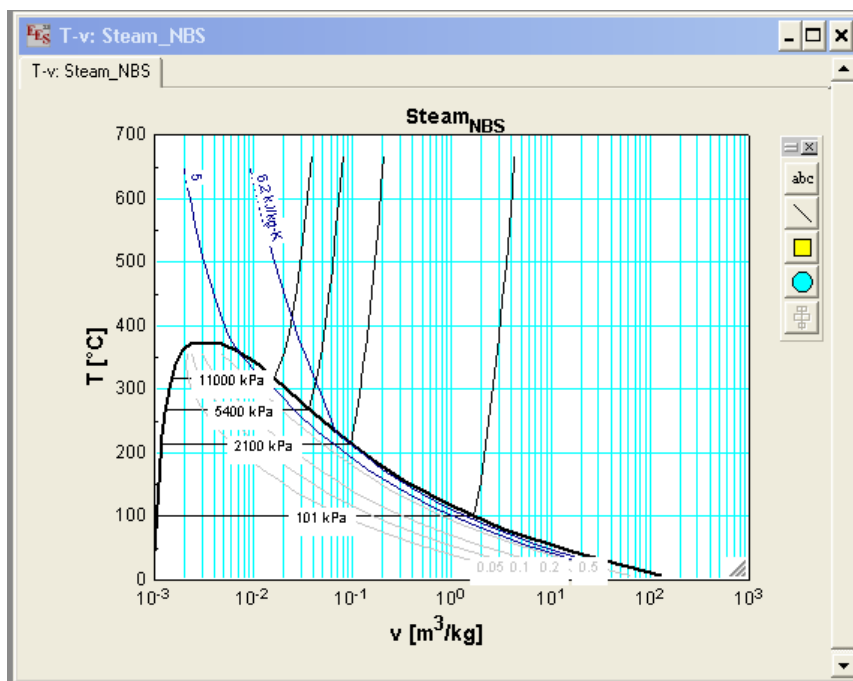


Fig. 3.10c. Drawing Property plot with EES

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

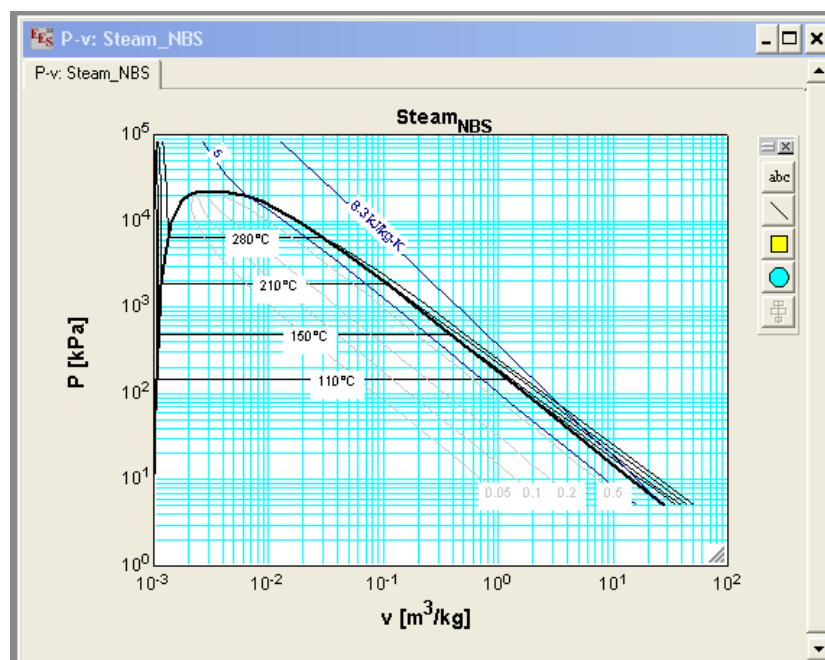


Fig. 3.11 P-v plot for Steam with EES

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

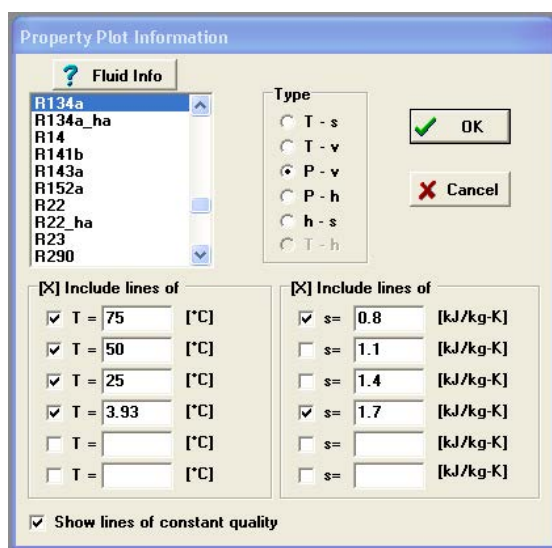


Fig. 3.12a. Drawing P-v plot for R134a with EES

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

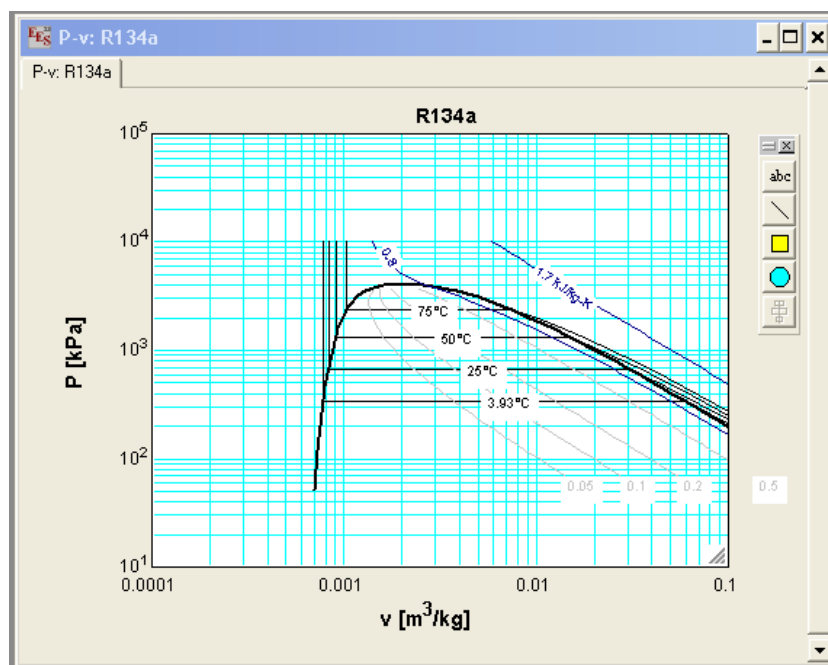


Fig. 3.12b. Drawing P-v plot for R134a with EES

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

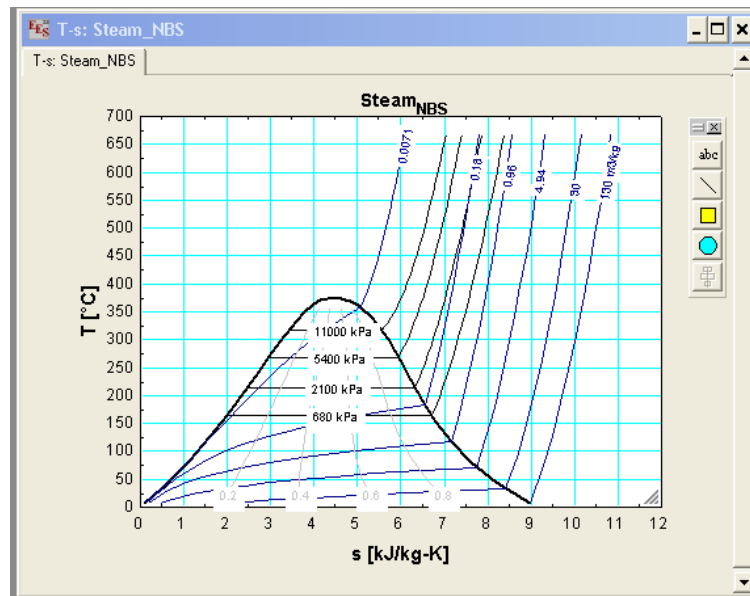


Fig. 3.13 T-s plot for Steam with EES

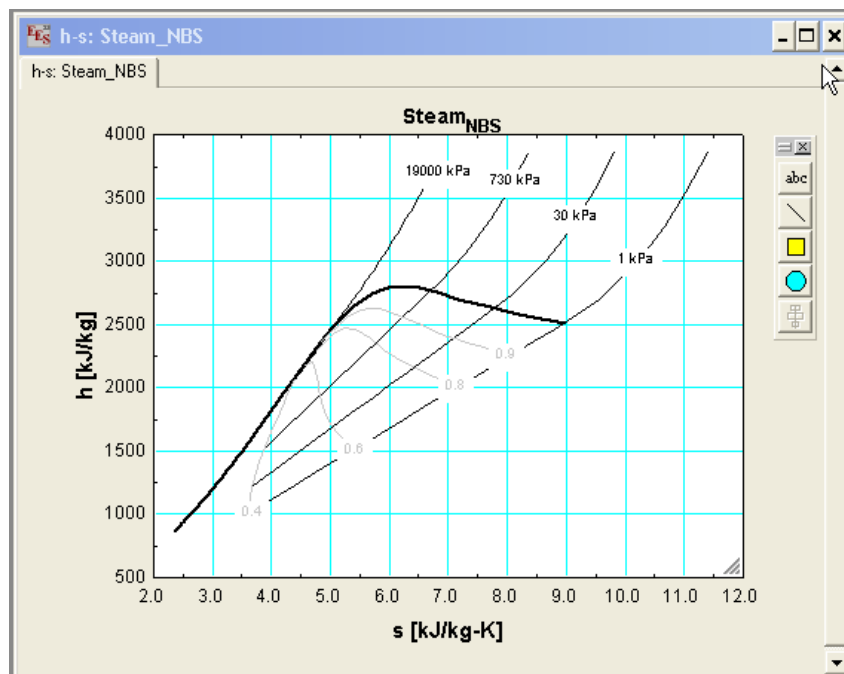


Fig. 3.14a. h-s plot for Steam with EES

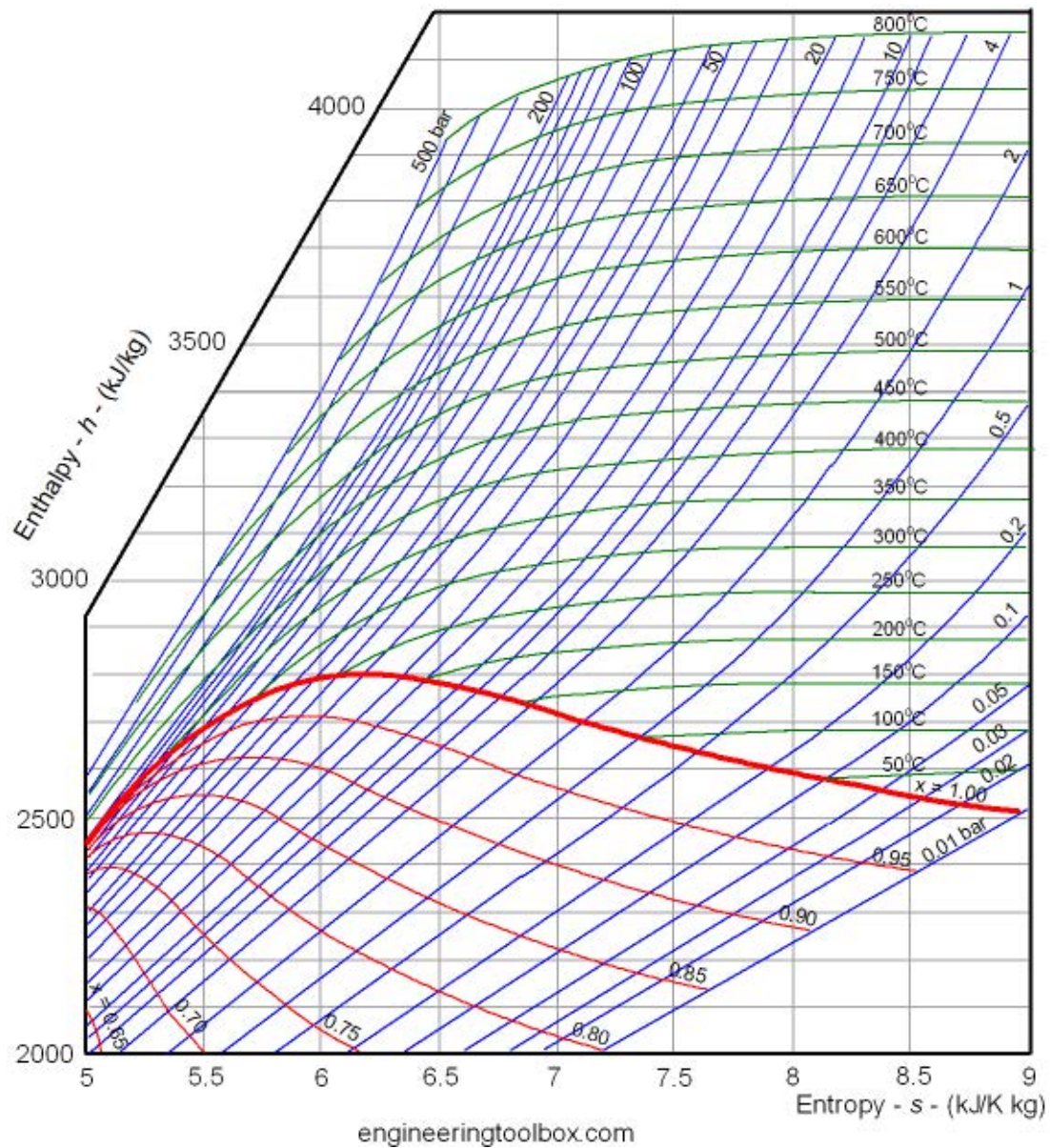


Fig. 3.14b. h-s plot for Steam (from www.Engineeringtoolbox.com)

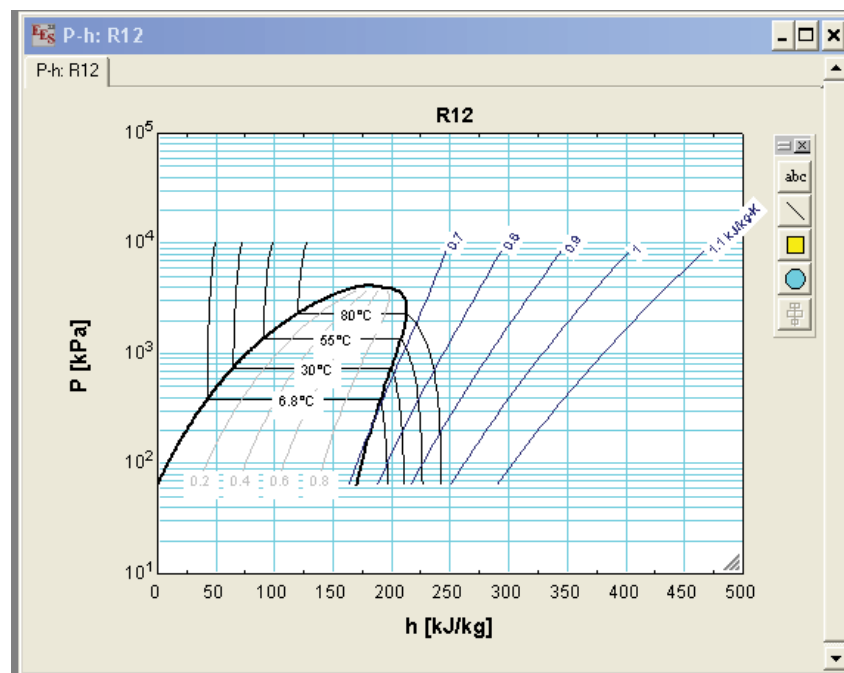


Fig. 3.15a. P-h plot for R12 with EES

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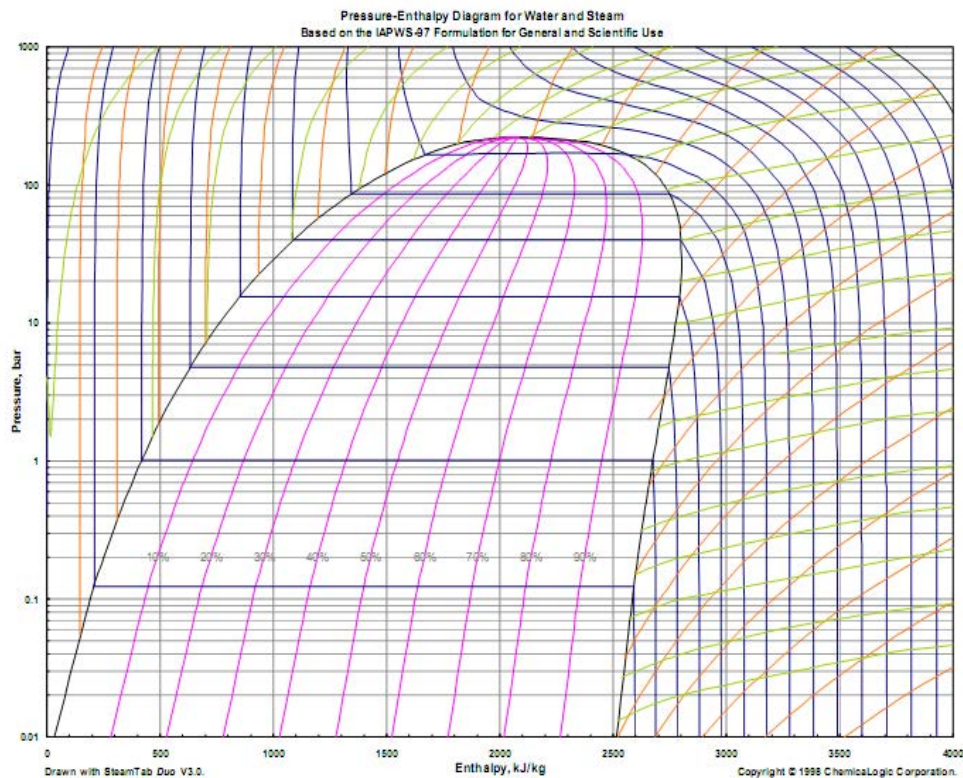


Fig. 3.15a. P-h plot for Steam (from www.ChemicalLogic.com)

3.3.2 Property diagrams using TEST:

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

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

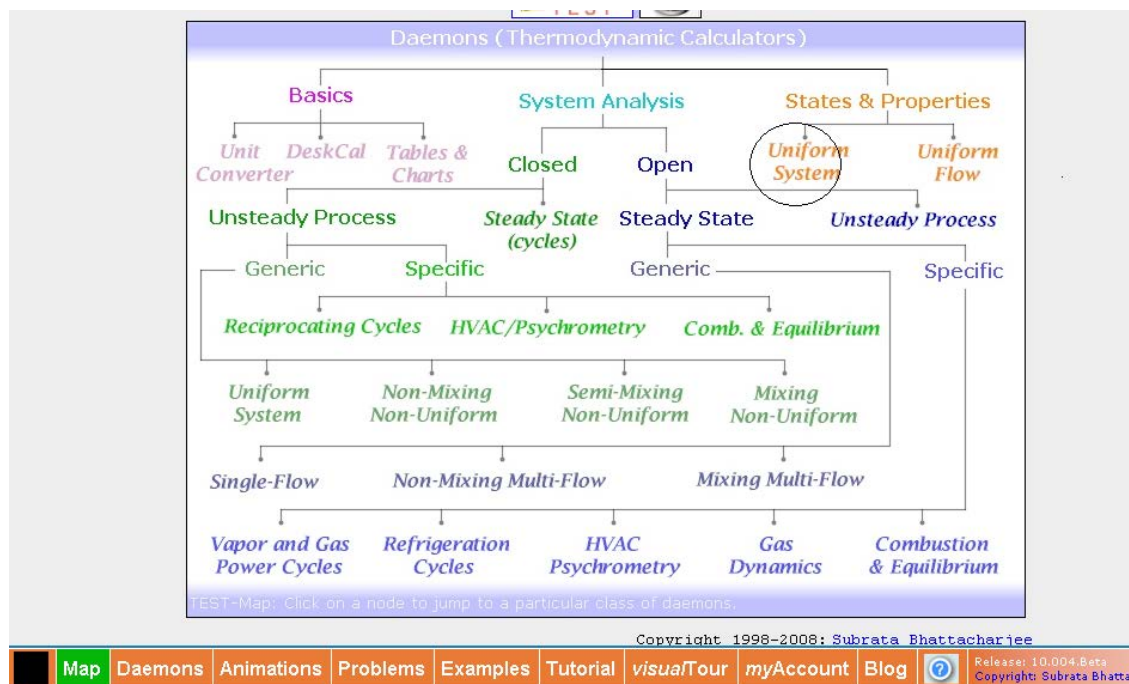


Fig. 3.16a. Drawing P-v plot for H2O with TEST

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

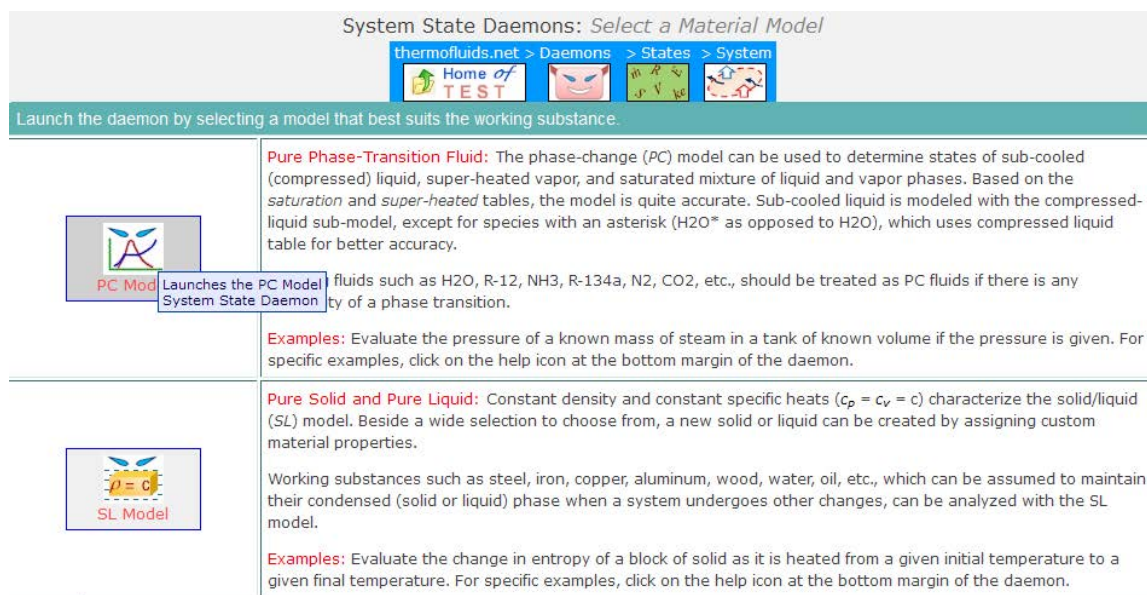


Fig. 3.16b. Drawing P-v plot for H2O with TEST

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

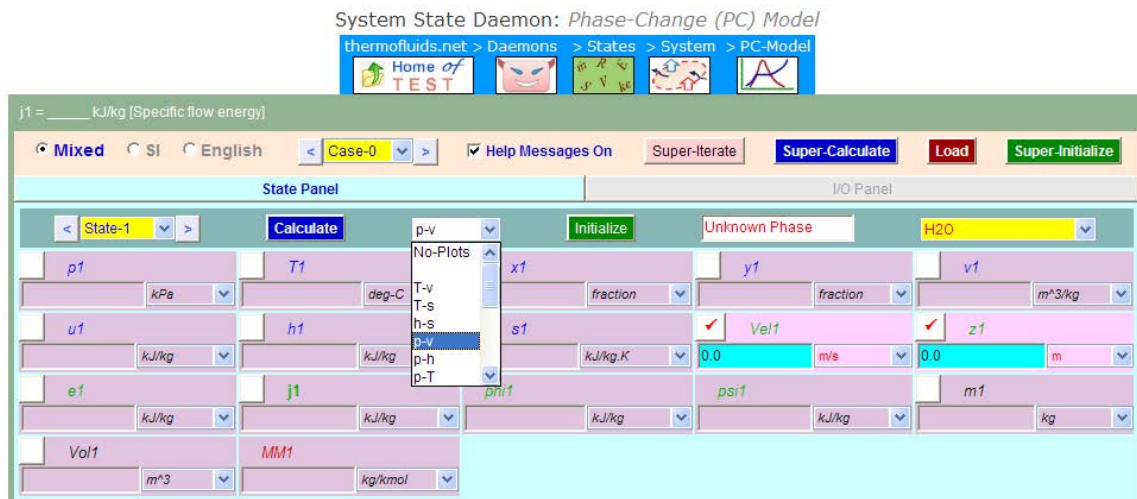


Fig. 3.16c. Drawing P-v plot for H₂O with TEST

Immediately, the P-v plot appears:

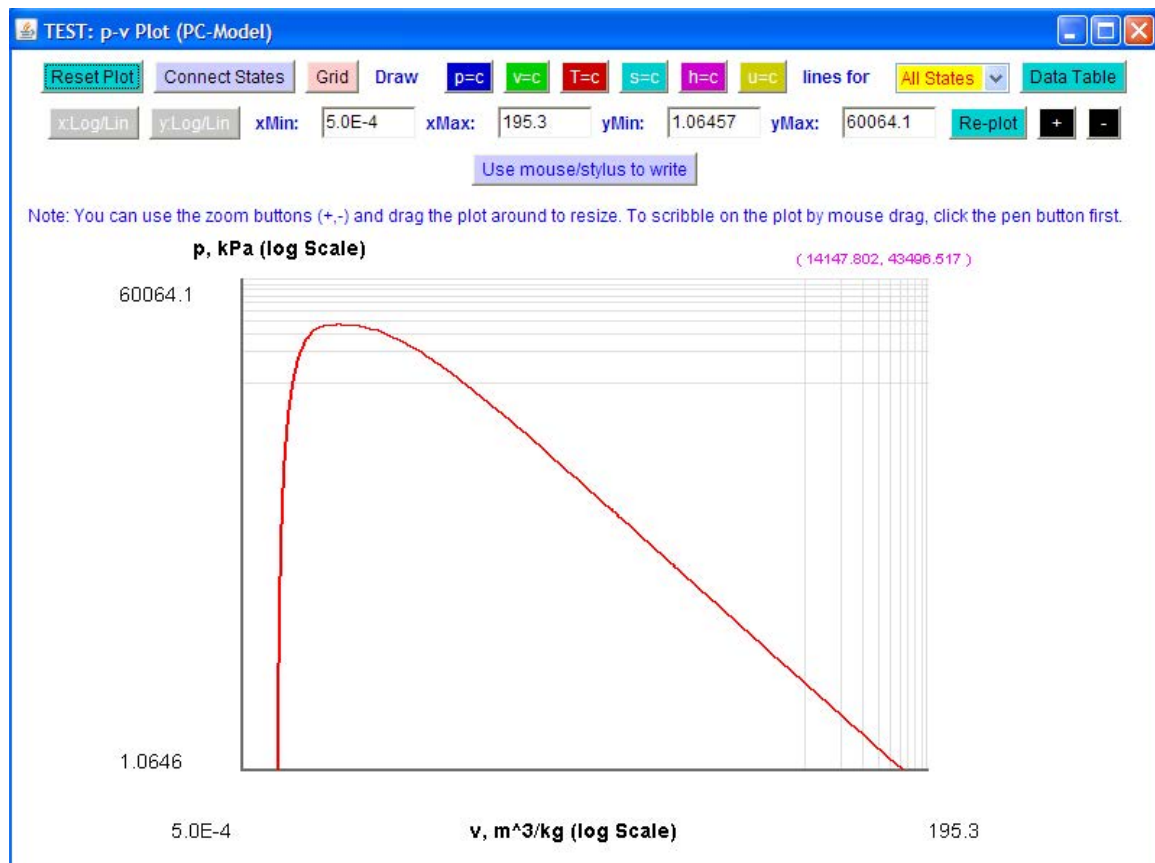


Fig. 3.16d. Drawing P-v plot for H₂O with TEST

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

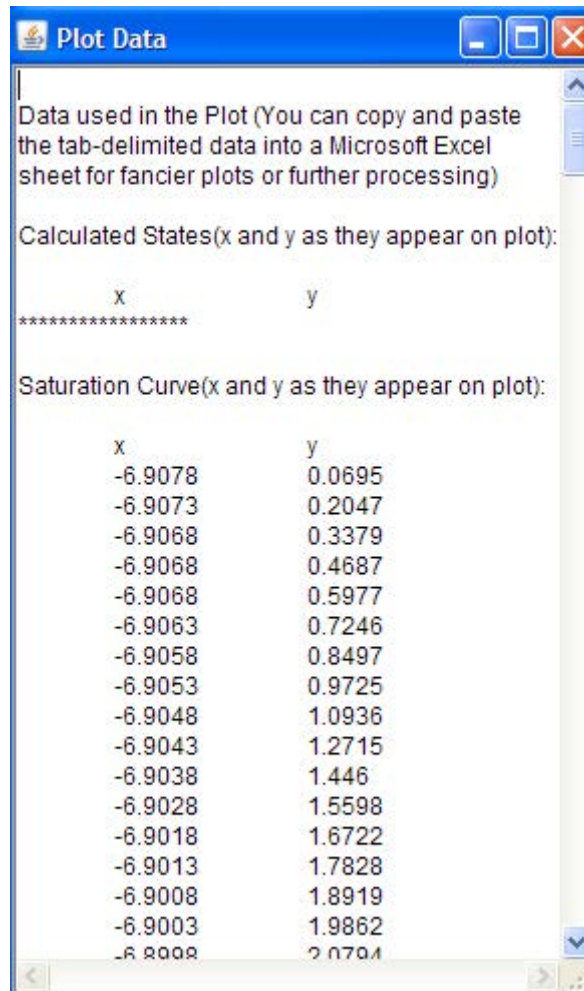


Fig. 3.16e. Drawing P-v plot for H₂O with TEST

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

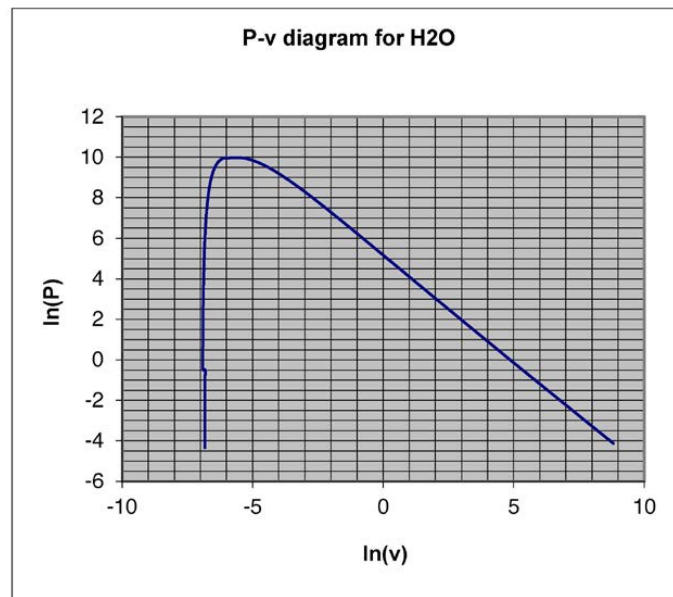


Fig. 3.16f. P-v plot for H₂O drawn in EXCEL with data from TEST

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

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

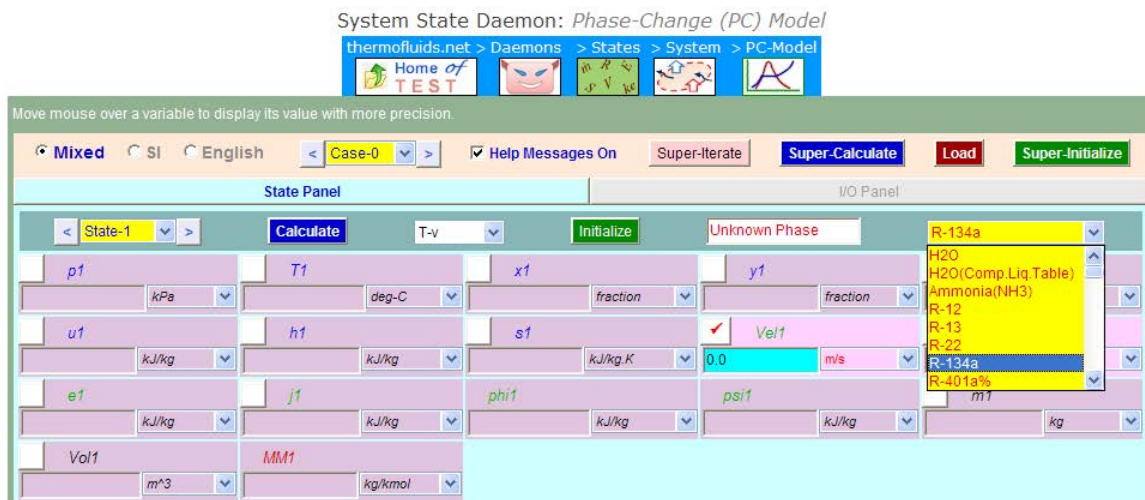


Fig. 3.17a. Drawing T-v plot for R134a with TEST

Immediately following plot appears:

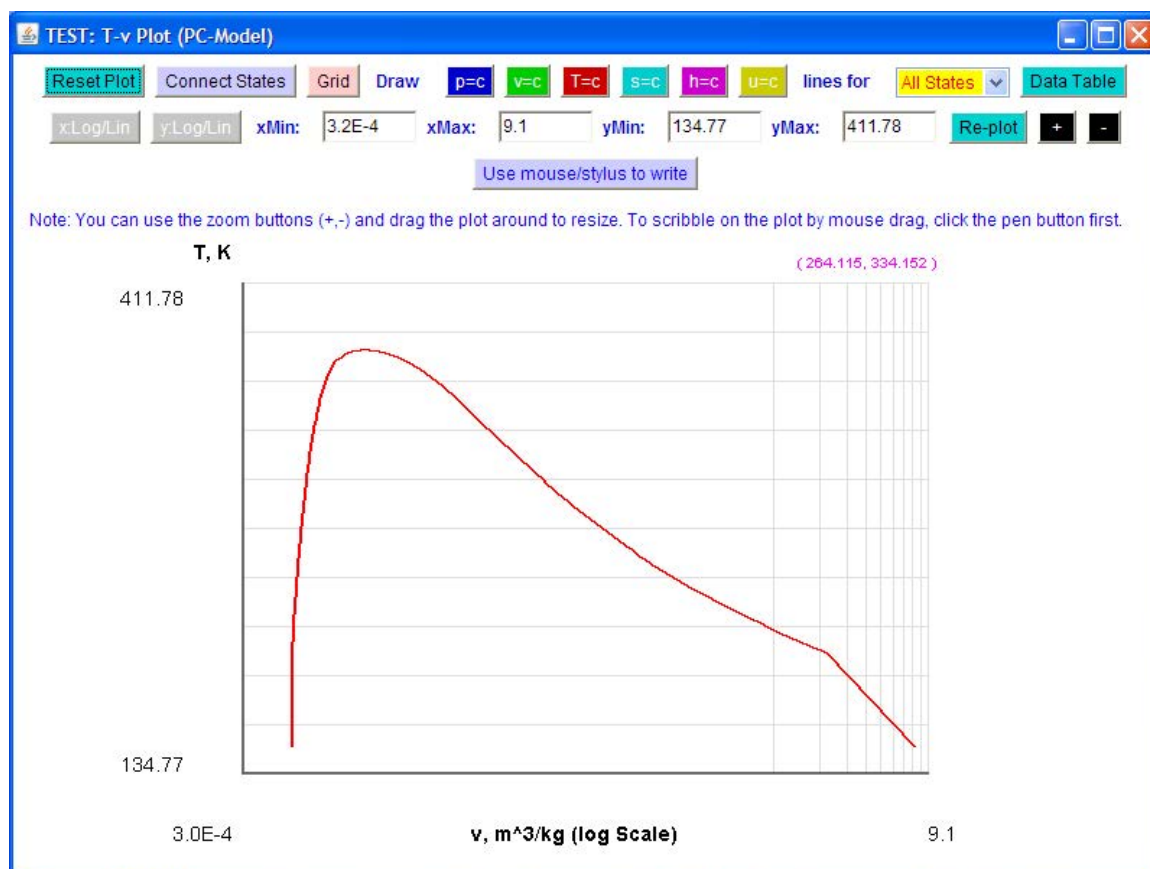


Fig. 3.17b. Drawing T-v plot for R134a with TEST

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

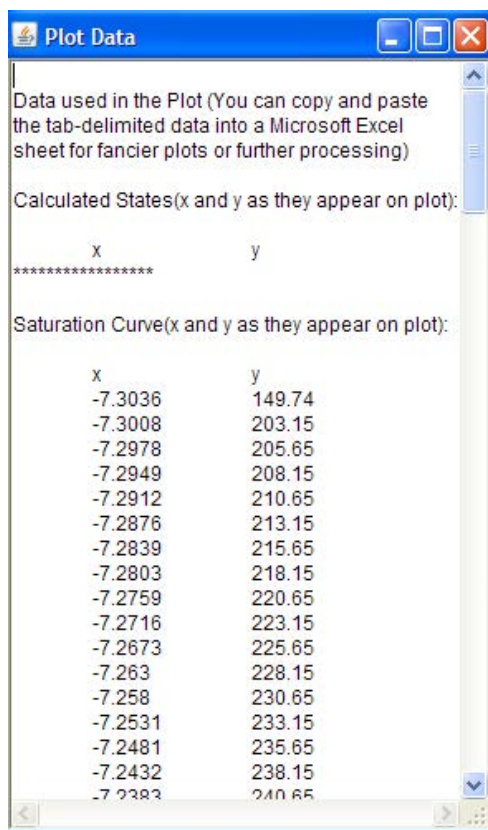


Fig. 3.17c. Plot data for T-v plot for R134a with TEST

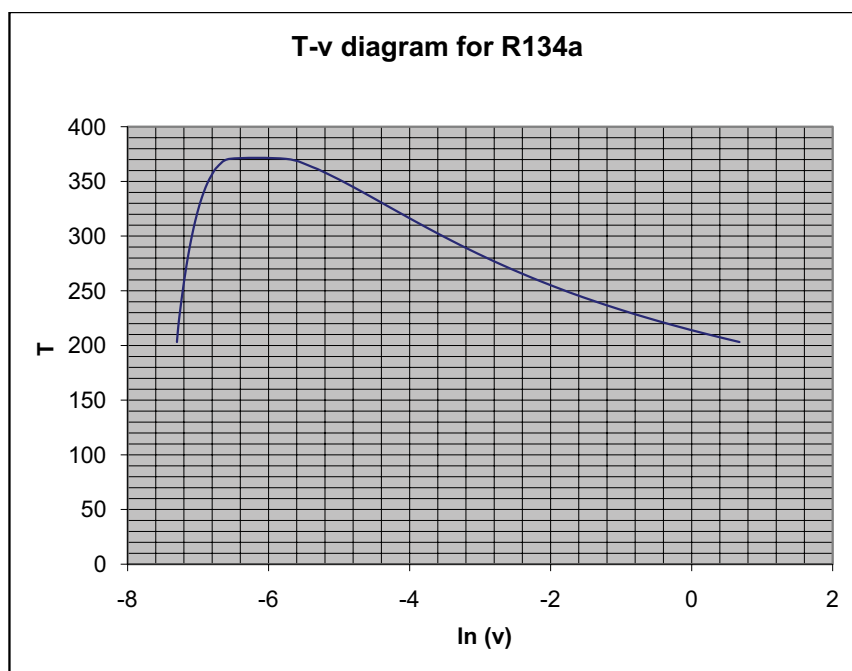


Fig. 3.17d. T-v plot for R134a with EXCEL

3.4 Property values and Tables:

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

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

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

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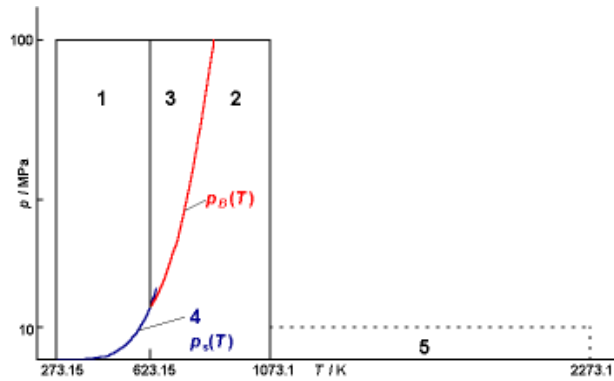


Fig. 3.18a. Five regions for Steam Properties (IAPWS-97)

At this stage, we shall define two quantities:

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

$$h = u + P \cdot v \quad \text{kJ/kg} \dots \dots \dots (3.1)$$

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

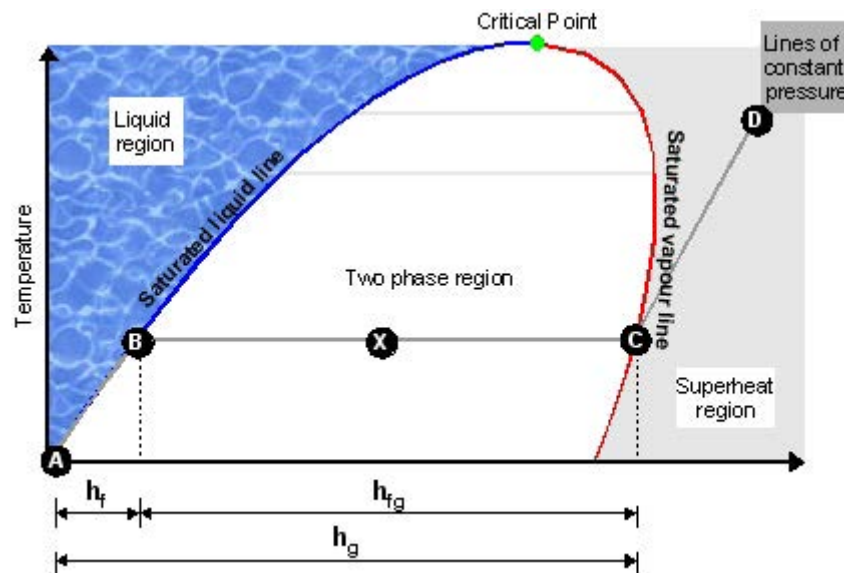


Fig. 3.18b. Five regions for Steam Properties (Ref: www.Steamline.com)

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

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

$$x = \frac{m_g}{m_f + m_g} \quad \dots(3.2)$$

And, quality varies from zero to 1.

Further, specific volume of mixture ‘v’ is given by:

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

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

$$u = u_f + x \cdot u_{fg} \quad \dots(3.4)$$

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

$$s = s_f + x \cdot s_{fg} \quad \dots\dots(3.6)$$

3.4.1 Property values from TEST:

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

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

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

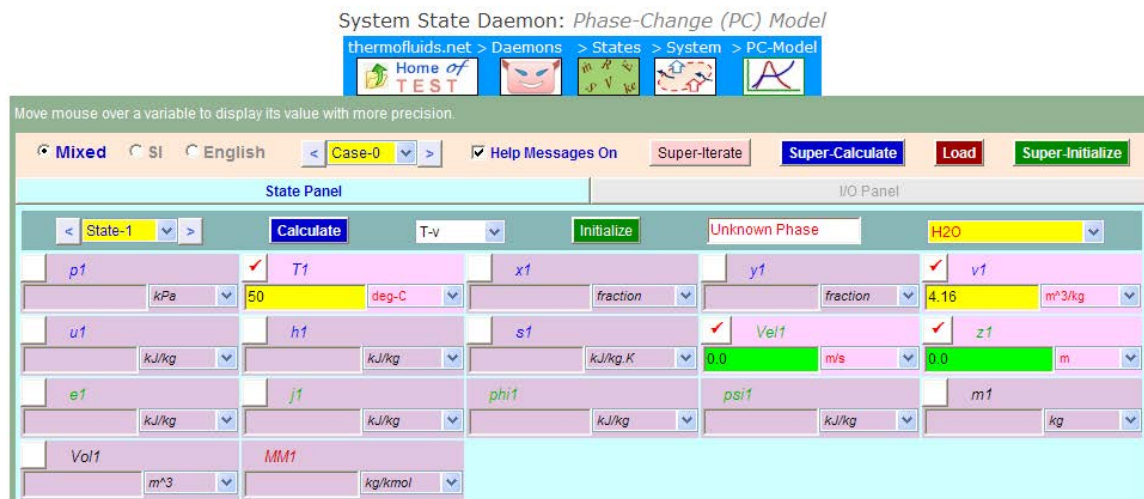


Fig. 3.19a. Finding property values for H₂O with TEST

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After entering the values of T_1 and v_1 , click on 'Calculate' (or, press Enter), and the following screen appears showing all the properties of H₂O:

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

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State Panel I/O Panel

State-1 Calculate T-v Initialize Sat.Mixture: Liq.+Vap. H2O

p_1	12.35001	kPa	T_1	50.0	deg-C	x_1	0.34575	fraction	y_1	0.99984	fraction	v_1	4.16	m ³ /kg
u_1	981.78986	kJ/kg	h_1	1033.1659	kJ/kg	s_1	3.25282	kJ/kg.K	Vel_1	0.0	m/s	z_1	0.0	m
e_1	981.78986	kJ/kg	j_1	1033.1659	kJ/kg	phi_1		kJ/kg	psi_1		kJ/kg	m_1		kg
Vol_1		m ³	MM_1	18.0	kg/kmol									

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

Note that the state is indicated as: (sat. liquid + vapor mixture), with a **'quality'** $x_1 = 0.34575$ and **enthalpy** $h_1 = 1033.1659$ kJ/kg. Other properties such as pressure (p_1), internal energy (u_1), entropy (s_1) etc. can also be read from the above fig.

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

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

Mixed SI English Case-0 Help Messages On Super-Iterate Super-Calculate Load Super-Initialize

State Panel I/O Panel

*****ANALYST: Dr. Muliya; TEST License: Professional*****

Solution logged at: Feb 12, 2014 9:57:52 PM

*****TEST-code: To save the solution, copy the codes generated below into a text file. To reproduce the solution at a later time, launch the daemon (see path name below), paste the saved TEST-code at the bottom of this I/O panel, and click the Load button.

Daemon Path: States>System>PC-Model; v-10.cb01

-----Start of TEST-code-----

```

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

```

-----End of TEST-code-----

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

Mixed SI English Case-0 Help Messages On Super-Iterate Super-Calculate Load Super-Initialize

State Panel I/O Panel

*****DETAILED OUTPUT: All the computed properties and variables are displayed on this block.*****

Evaluated States:

```

# State-1: H2O > Saturated Mixture;
# Given: T1= 50.0 deg-C; v1= 4.16 m^3/kg; Vel1= 0.0 m/s;
# z1= 0.0 m;
# Calculated: p1= 12.35 kPa; x1= 0.3458 fraction; y1= 0.9998 fraction;
# u1= 981.7899 kJ/kg; h1= 1033.1659 kJ/kg; s1= 3.2528 kJ/kg.K;
# e1= 981.7899 kJ/kg; j1= 1033.1659 kJ/kg; MM1= 18.0 kg/kmol;

```

-----Property spreadsheet starts: The following property table can be copied onto a spreadsheet (such as Excel) for further analysis or plots.-----

State	p(kPa)	T(K)	x	v(m ³ /kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg)
# 01	12.35	323.2	0.3	4.16	981.79	1033.17	3.253

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

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

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

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

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

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

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

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

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

Table 3.3b. Properties of H₂O

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Problem 3.1.b: Complete the following Table:

Fluid	P(kPa)	T(deg.C)	v(m ³ /kg)	x	Phase
R-22		10	0.036		
H ₂ O			0.2	0.5	
H ₂ O	50	60			
NH ₃	60	30			
R-134a			0.005	0.5	

Table 3.3c. Properties of Fluids

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

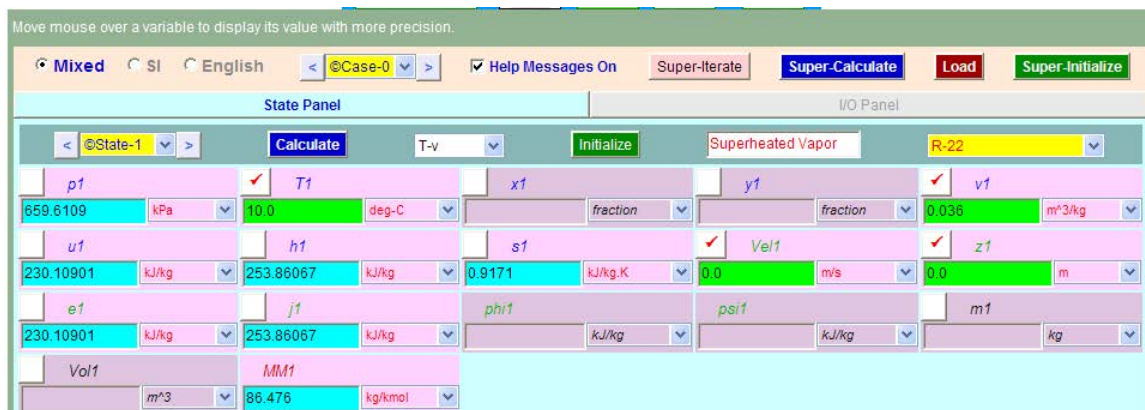


Fig. 3.19d. Finding property values with TEST

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

Fluid	P(kPa)	T(deg.C)	v(m ³ /kg)	x	Phase
R-22	659.61	10	0.036	-	Sup. vapor
H ₂ O	467.99	149.38	0.2	0.5	Sat. mix.
H ₂ O	50	60	0.00102	-	Sub. Liq.
NH ₃	60	30	2.452	-	Sup. vapor
R-134a	2049.62	68.59	0.005	0.5	Sat. mix.

Table 3.3d. Properties of Fluids

3.4.2 Property values from EES:

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

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

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

Table 3.4a. Properties of R-134a

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

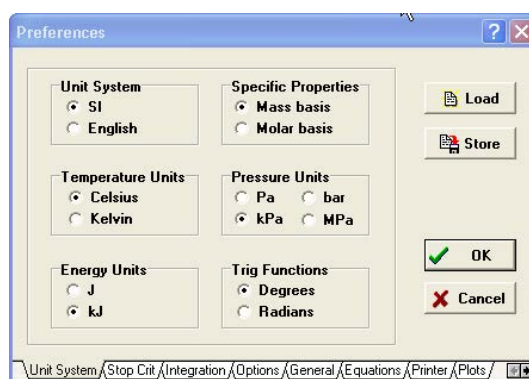


Fig. 3.20a. Properties of R-134a with EES

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

“Properties of R-134a:”

“Data:”

$P[1]=520\text{ kPa}$; $T[1]=-9\text{ deg.C}$

$T[2]=30\text{ deg.C}$; $v[2]=0.022\text{ m}^3/\text{kg}$

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

“Calculate properties for State 1:”

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

“Calculate properties for State 2:”

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

“Calculate properties for State 3:”

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

«Calculate properties for State 4:»

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

“Calculate properties for State 5:”

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

“Calculate properties for State 6:”

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

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

Fig. 3.20b. Array Table



#1

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

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

Table 3.4b. Properties of R-134a

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

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

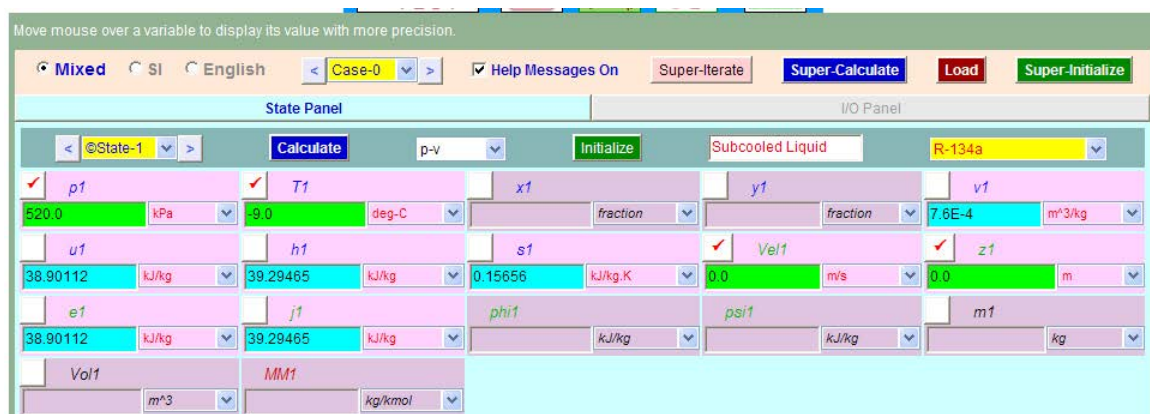


Fig. 3.21(a) Properties of R-134a with TEST

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

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

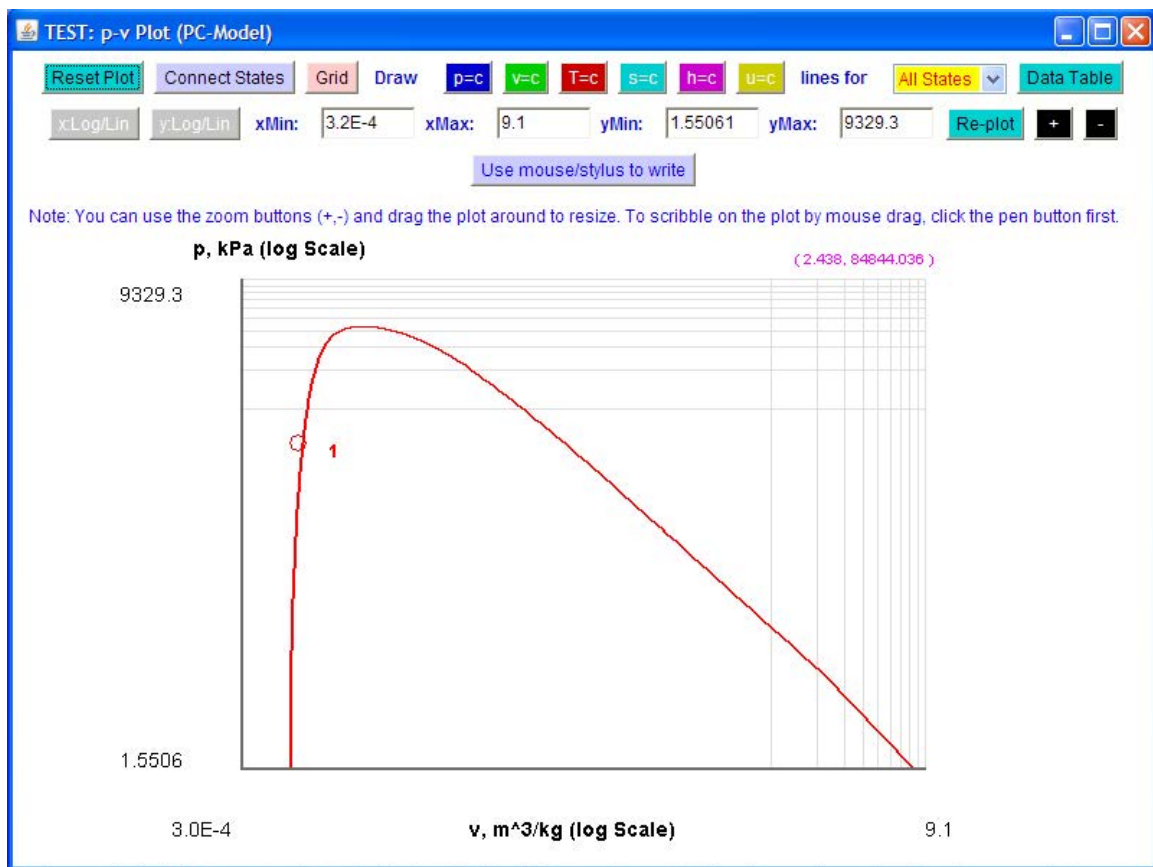


Fig. 3.21(b) State point 1 on the p-v plot for R-134a with TEST

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

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

Compare these values with those obtained using EES.

3.4.3 Property values from 'free' software:

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

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

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

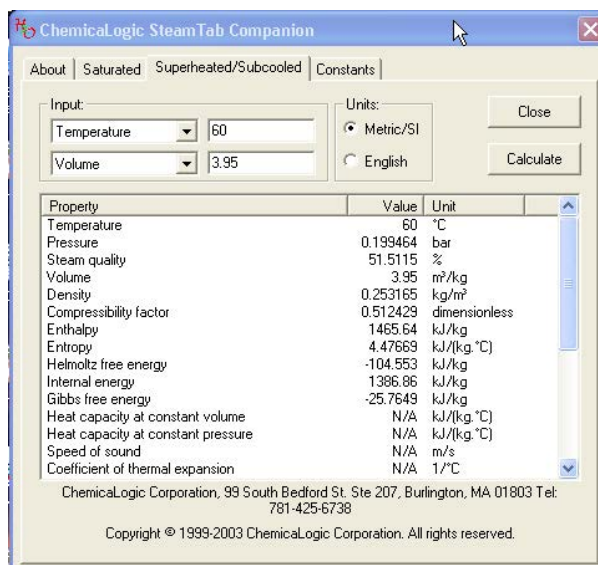


Fig. 3.22a. Properties of Steam with 'SteamTab companion'

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

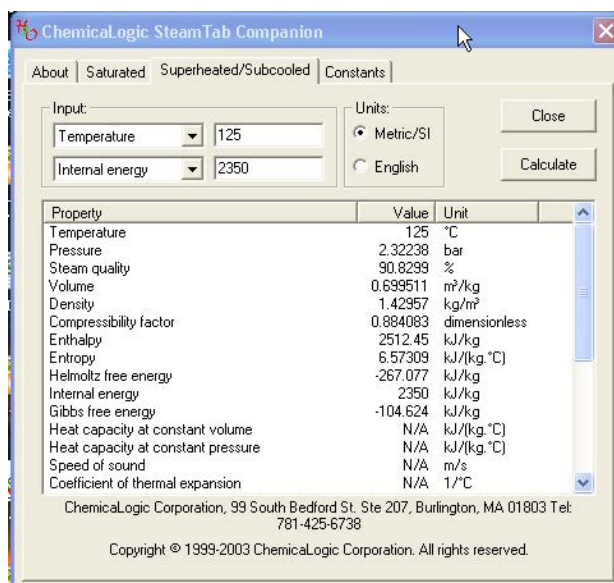


Fig. 3.22b. Properties of Steam from 'SteamTab companion'

Compare these values with the values in Table 3.3 b.

3.4.4 Property values from 'online software':

3.4.4.1 From NIST Website:

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

Thermophysical Properties of Fluid Systems

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

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

SMS from your computer

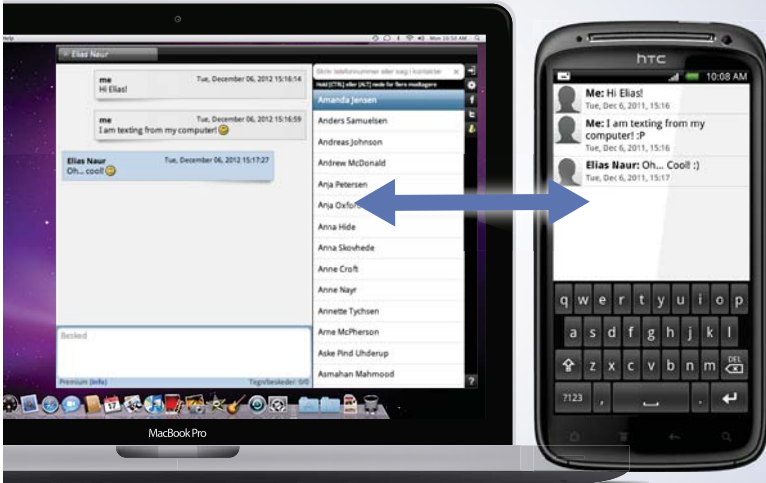
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Please follow the steps below to select the data required.

- Please select the species of interest:
Water
- Please choose the units you wish to use:

Quantity	Units
Temperature	<input type="radio"/> Kelvin <input checked="" type="radio"/> Celsius <input type="radio"/> Fahrenheit <input type="radio"/> Rankine
Pressure	<input type="radio"/> MPa <input checked="" type="radio"/> bar <input type="radio"/> atm <input type="radio"/> torr <input type="radio"/> psia
Density	<input type="radio"/> mol/l <input type="radio"/> mol/m ³ <input type="radio"/> g/ml <input checked="" type="radio"/> kg/m ³ <input type="radio"/> lb-mole/ft ³ <input type="radio"/> lbm/ft ³
Energy	<input type="radio"/> kJ/mol <input checked="" type="radio"/> kJ/kg <input type="radio"/> kcal/mol <input type="radio"/> Btu/lb-mole <input type="radio"/> kcal/g <input type="radio"/> Btu/lbm
Velocity	<input checked="" type="radio"/> m/s <input type="radio"/> ft/s <input type="radio"/> mph
Viscosity	<input type="radio"/> uPa*s <input checked="" type="radio"/> Pa*s <input type="radio"/> cP <input type="radio"/> lbm/ft*s
Surface tension*	<input checked="" type="radio"/> N/m <input type="radio"/> dyn/cm <input type="radio"/> lb/ft <input type="radio"/> lb/in

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

- Choose the desired type of data:
☒ Isothermal properties ☐ Saturation properties — temperature increments
☐ Isobaric properties ☐ Saturation properties — pressure increments
☐ Isochoric properties
- Please select the desired standard state convention:
Default for fluid
- Press to Continue

Fig. 3.23a. Properties of Water from NIST

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

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

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

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

Isothermal Properties for Water

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

- Enter temperature in selected units:
200 (Acceptable range: 0.01 to 1001.9 C)
- Enter pressure range and increment in selected units:

P _{Low}	1	(min value: 0.0 bar)
P _{High} *	20	
P _{Increment}	1	

* The maximum pressure limit is the lowest of the following values:
☐ 10000.000 bar
☐ The pressure at which a density of 1332. kg/m³ is reached.

- Check here if you want to use the display applet (requires Java capable browser) ☒
- Press for Data

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Fig. 3.23b. Properties of Water from NIST

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

Isothermal Properties for Water

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

Fluid Data

Isothermal Data for T = 200.00 C

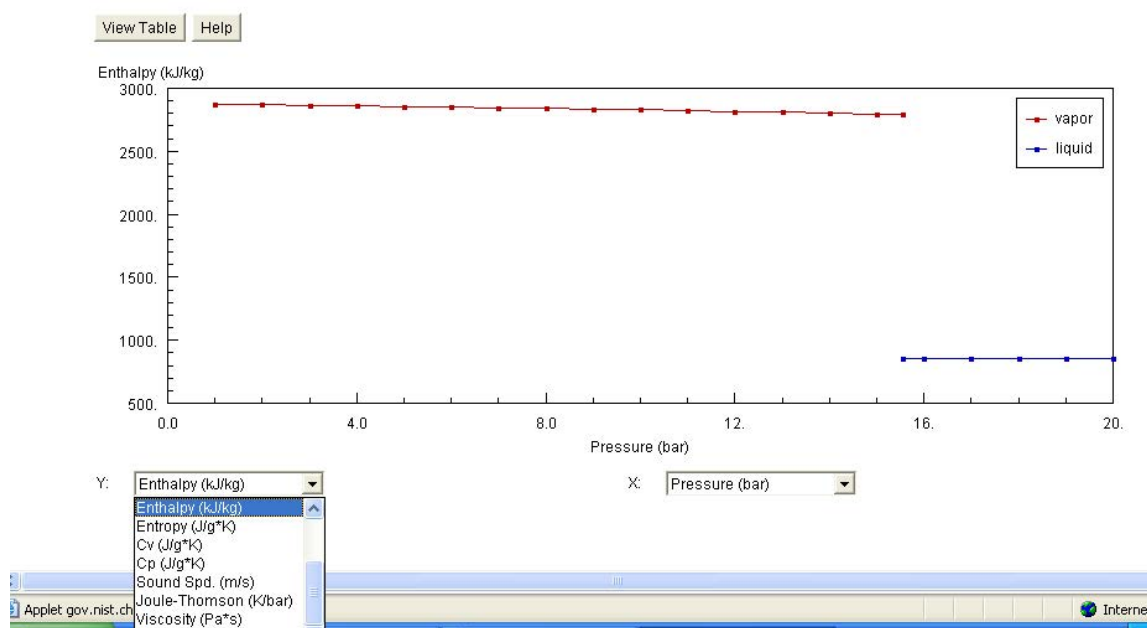


Fig. 3.23c. Properties of Water from NIST

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

Fluid Data

Isothermal Data for T = 200.00 C

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

Fig. 3.23d. Properties of Water from NIST

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

Reference States

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

Additional fluid data

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

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

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

Fluid Data

Data on Saturation Curve

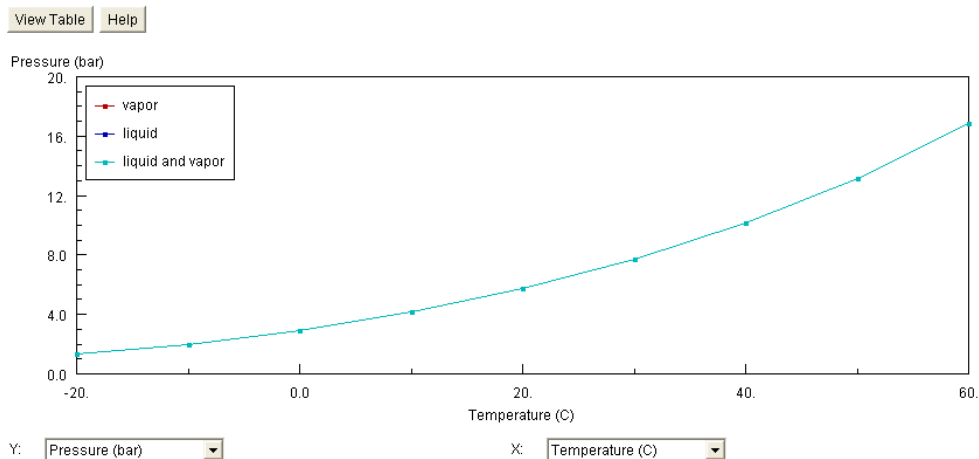


Fig. 3.24a. Properties of R134a from NIST

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Liquid Phase Data

Data on Saturation Curve

Temperature (C)	Pressure (bar)	Density (kg/m ³)	Volume (m ³ /kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g °K)	Cv (J/g °K)	Cp (J/g °K)	Sound Spd. (m/s)	Joule-Thomson (K/bar)	Viscosity (Pa·s)	Therm. Cond. (W/m·K)	Surf. Tension (N/m)	Phase
-20.000	1.3273	1358.3	0.00073623	173.54	173.64	0.90025	0.85511	1.2930	713.79	-0.024277	0.00034758	0.10107	0.014513	liquid
-10.000	2.0060	1327.1	0.00075351	186.55	186.70	0.95065	0.86688	1.3156	667.63	-0.020962	0.00030355	0.096491	0.013019	liquid
0.0000	2.9280	1294.8	0.00077233	199.77	200.00	1.0000	0.87909	1.3410	621.65	-0.016946	0.00026653	0.092013	0.011560	liquid
10.000	4.1461	1261.0	0.00079305	213.25	213.58	1.0485	0.89177	1.3704	575.69	-0.011998	0.00023487	0.087618	0.010138	liquid
20.000	5.7171	1225.3	0.00081610	227.00	227.47	1.0962	0.90501	1.4049	529.61	-0.0057783	0.00020737	0.083284	0.0087555	liquid
30.000	7.7020	1187.5	0.00084213	241.07	241.72	1.1435	0.91890	1.4465	483.24	0.0022299	0.00018313	0.078992	0.0074170	liquid
40.000	10.166	1146.7	0.00087204	255.52	256.41	1.1905	0.93363	1.4984	436.43	0.012848	0.00016145	0.074716	0.0061268	liquid
50.000	13.179	1102.3	0.00090719	270.43	271.62	1.2375	0.94945	1.5661	388.96	0.027461	0.00014177	0.070427	0.0048906	liquid
60.000	16.818	1052.9	0.00094979	285.91	287.50	1.2848	0.96683	1.6602	340.49	0.048608	0.00012361	0.066091	0.0037161	liquid

Fig. 3.24b. Properties of R134a from NIST

Vapor Phase Data

Data on Saturation Curve

Temperature (C)	Pressure (bar)	Density (kg/m ³)	Volume (m ³ /kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g °K)	Cv (J/g °K)	Cp (J/g °K)	Sound Spd. (m/s)	Joule-Thomson (K/bar)	Viscosity (Pa·s)	Therm. Cond. (W/m·K)	Phase
-20.000	1.3273	6.7845	0.14739	366.99	386.55	1.7413	0.70464	0.81580	146.28	4.2261	9.9995e-06	0.0098164	vapor
-10.000	2.0060	10.041	0.099590	372.69	392.66	1.7334	0.73222	0.85435	146.89	3.7110	1.0362e-05	0.010655	vapor
0.0000	2.9280	14.428	0.069309	378.31	398.60	1.7271	0.76082	0.89723	146.94	3.2952	1.0726e-05	0.011514	vapor
10.000	4.1461	20.226	0.049442	383.82	404.32	1.7221	0.79042	0.94546	146.38	2.9569	1.1099e-05	0.012402	vapor
20.000	5.7171	27.780	0.035997	389.17	409.75	1.7180	0.82103	1.0007	145.15	2.6813	1.1488e-05	0.013335	vapor
30.000	7.7020	37.535	0.026642	394.30	414.82	1.7145	0.85273	1.0655	143.16	2.4576	1.1907e-05	0.014336	vapor
40.000	10.166	50.085	0.019966	399.13	419.43	1.7111	0.88575	1.1445	140.34	2.2778	1.2373e-05	0.015446	vapor
50.000	13.179	66.272	0.015089	403.55	423.44	1.7072	0.92049	1.2461	136.55	2.1358	1.2917e-05	0.016734	vapor
60.000	16.818	87.379	0.011444	407.38	426.63	1.7024	0.95766	1.3868	131.66	2.0267	1.3587e-05	0.018326	vapor

Fig. 3.24c. Properties of R134a from NIST

3.4.4.2 From Mathpad Website:[Ref:8]

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

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

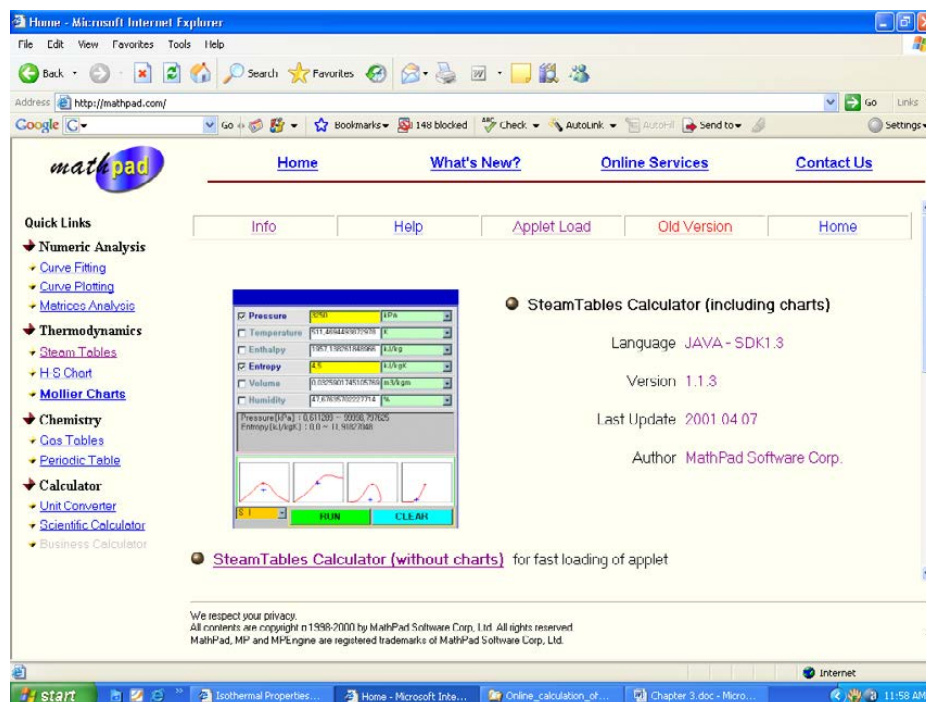


Fig. 3.25a. Properties of H₂O from Mathpad

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

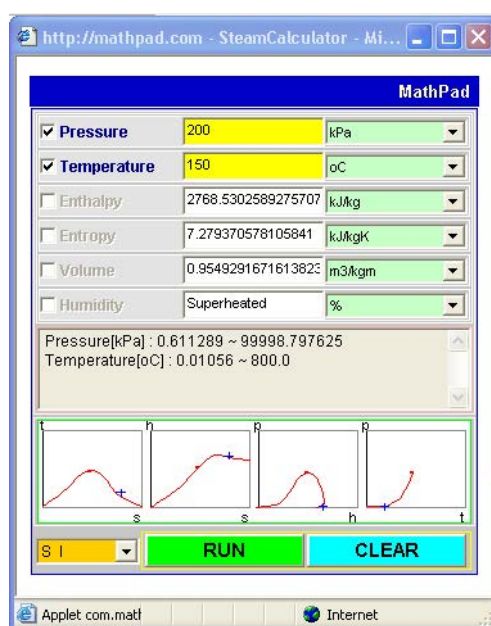


Fig. 3.25b. Properties of H₂O from Mathpad

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

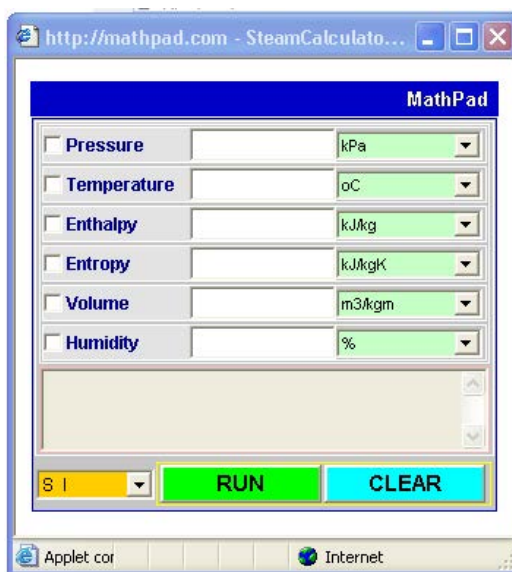


Fig. 3.25c. Properties of H₂O from Mathpad

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

The screenshot shows a web browser window with the address bar displaying "http://www.mathpad.com - SteamCal...". The main content area is titled "MathPad" and contains a form for calculating the properties of water. The form has several input fields with checkboxes and dropdown menus for units. The "Pressure" and "Enthalpy" fields are checked and highlighted in yellow, with values of 200 and 2700 respectively. The other fields are unchecked and show calculated values. Below the input fields, a text box displays the available ranges for Pressure and Enthalpy. At the bottom, there is a "S I" dropdown menu, a green "RUN" button, and a blue "CLEAR" button. The status bar at the bottom shows "Applet cor" and "Internet".

Property	Value	Unit
<input checked="" type="checkbox"/> Pressure	200	kPa
<input type="checkbox"/> Temperature	120.230941358499	oC
<input checked="" type="checkbox"/> Enthalpy	2700	kJ/kg
<input type="checkbox"/> Entropy	7.11083788206084	kJ/kgK
<input type="checkbox"/> Volume	0.87867138621688	m ³ /kgm
<input type="checkbox"/> Humidity	0.28572412035273	-

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

S I RUN CLEAR

Fig. 3.25d. Properties of H₂O from Mathpad

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

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

WS

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

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

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

Joule-Thomson coefficient, JT	-	-	$t-p$ $p-t$	-
All property	p, t h, s p, h p, s t, h	-	-	-

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

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

Updated August 25, 2008

Fig. 3.26. Properties of H2O from MPEI

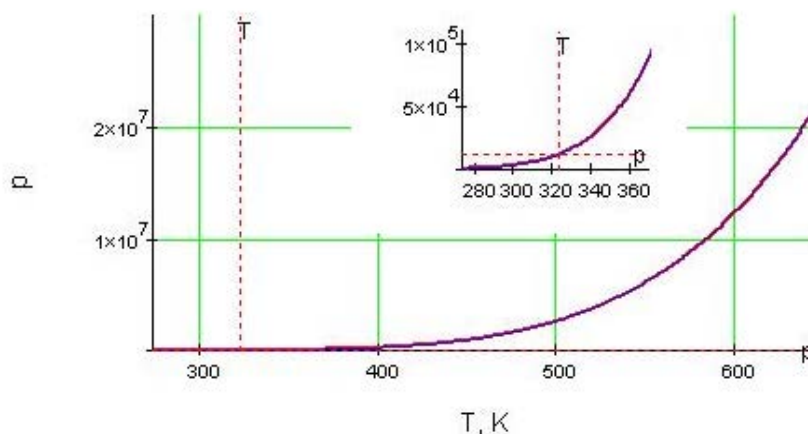
As an example of its use, let us calculate the properties of sat. water and steam with chart as a function of temperature (t). Click on the appropriate button on the page as shown and enter 50 deg.C for t; following results and plots appear:


Water/Steam properties at saturated line [IAPWS-IF97](#)
[Свойства воды и водяного пара на линии насыщения](#)

Temperature := °C

0.01 °C - 373.946 °C

$p := \text{wspPST}(T) = 0.01235 \text{ MPa}$ = 0.1219 atm = 1.7914 psi








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Энтальпия Enthalpy

$$h' := \text{wspHSWT}(T) = 209.336 \text{ kJ/kg}$$

$$h' = 49.999 \text{ kcal/kg}$$

$$h' = 89.998 \text{ Btu/lb}$$

$$h'' := \text{wspHSST}(T) = 2591.31 \text{ kJ/kg}$$

$$h'' = 618.924 \text{ kcal/kg}$$

$$h'' = 1114.063 \text{ Btu/lb}$$

$$r := \text{wspRST}(T) = 2381.974 \text{ kJ/kg}$$

$$r = 568.925 \text{ kcal/kg}$$

$$r = 1024.065 \text{ Btu/lb}$$

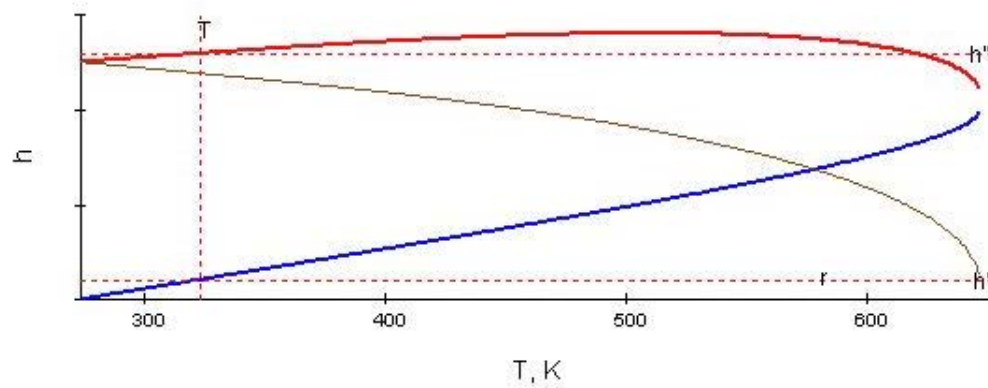


Fig. 3.27 a,b. Properties of H₂O from MPEI

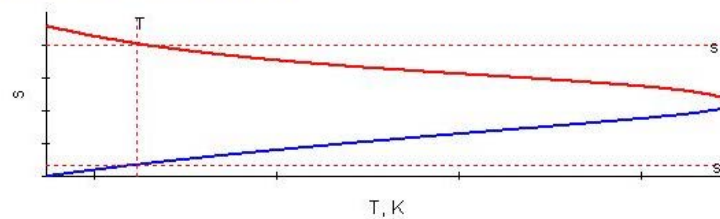
Энтропия Entropy

$$s' := \text{wspSSWT}(T) = 0.70379 \text{ kJ/(kg K)}$$

$$s' = 0.1681 \text{ Btu/(lb } ^\circ\text{R)} \text{ or kcal/(kg } ^\circ\text{C)}$$

$$s'' := \text{wspSSST}(T) = 8.07491 \text{ kJ/(kg K)}$$

$$s'' = 1.92866 \text{ Btu/(lb } ^\circ\text{R)} \text{ or kcal/(kg } ^\circ\text{C)}$$

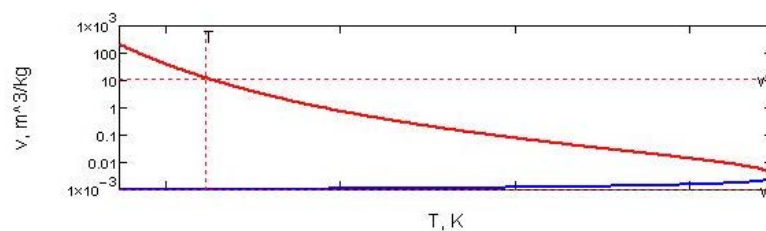


$$v' := \text{wspVSWT}(T) = 1.01214 \times 10^{-3} \text{ m}^3/\text{kg}$$

$$v' = 0.016213 \text{ ft}^3/\text{lb}$$

$$v'' := \text{wspVSST}(T) = 12.02786 \text{ m}^3/\text{kg}$$

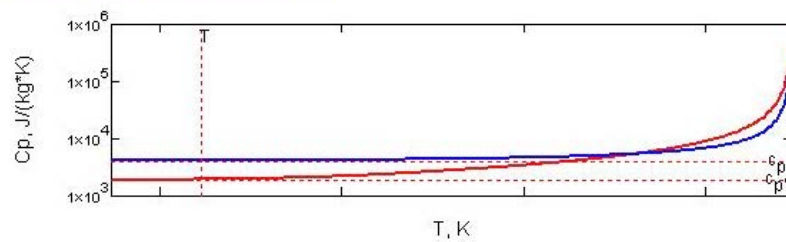
$$v'' = 192.667901 \text{ ft}^3/\text{lb}$$



Удельная изобарная теплоемкость Specific isobaric heat capacity-----

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

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



Удельная изохорная теплоемкость Specific isochoric heat capacity-----

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

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

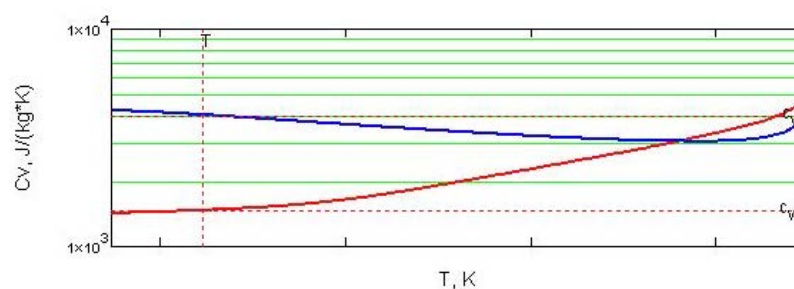
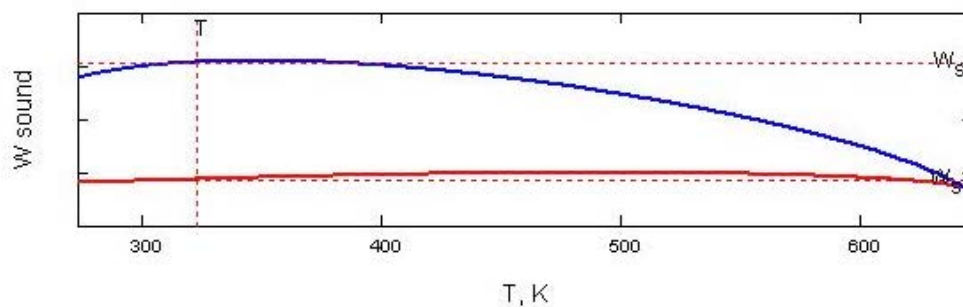


Fig. 3.27 c,d,e,f. Properties of H2O from MPEI

Скорость звука Sound speed-----

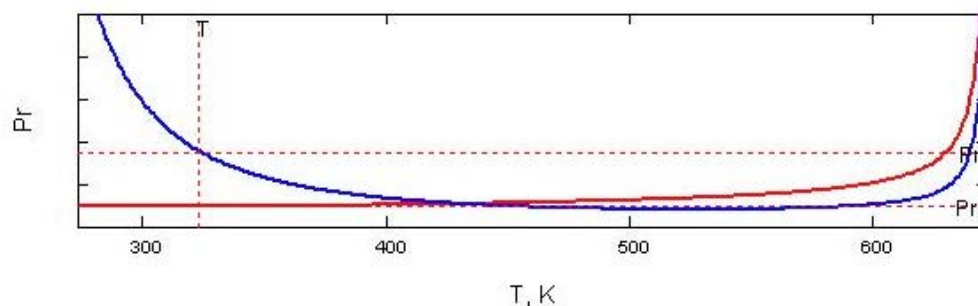
$$W_{S'} := \text{wspWSWT}(T) = 1545.176 \text{ m/s} \quad W_{S'} = 5562.632 \text{ km/h}$$

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



Число Прандтля Prandtl number-----

$$Pr' := \text{wspPRANDTLESWT}(T) = 3.56658 \quad Pr' := \text{wspPRANDTLESST}(T) = 1.01036$$



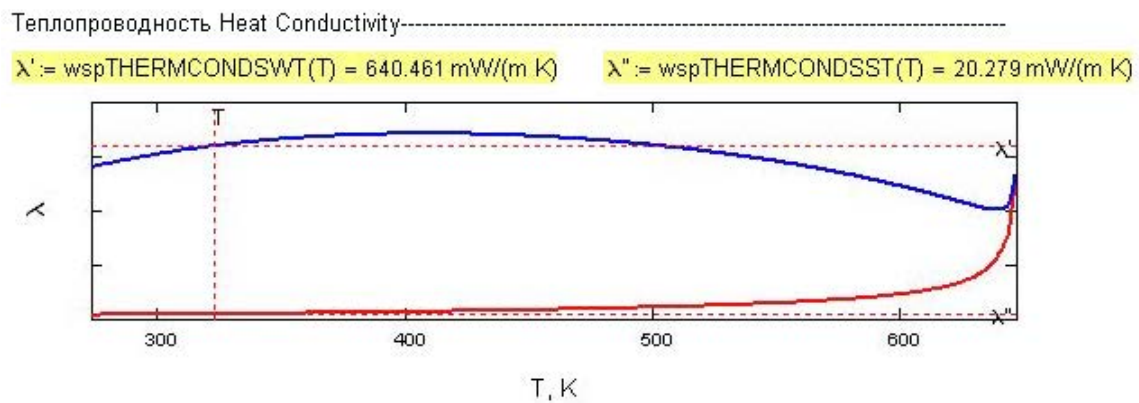


Fig. 3.27 g,h,i. Properties of H₂O from MPEI

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3.4.4.4 From Spirax Sarco Website:[Ref:14]

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

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

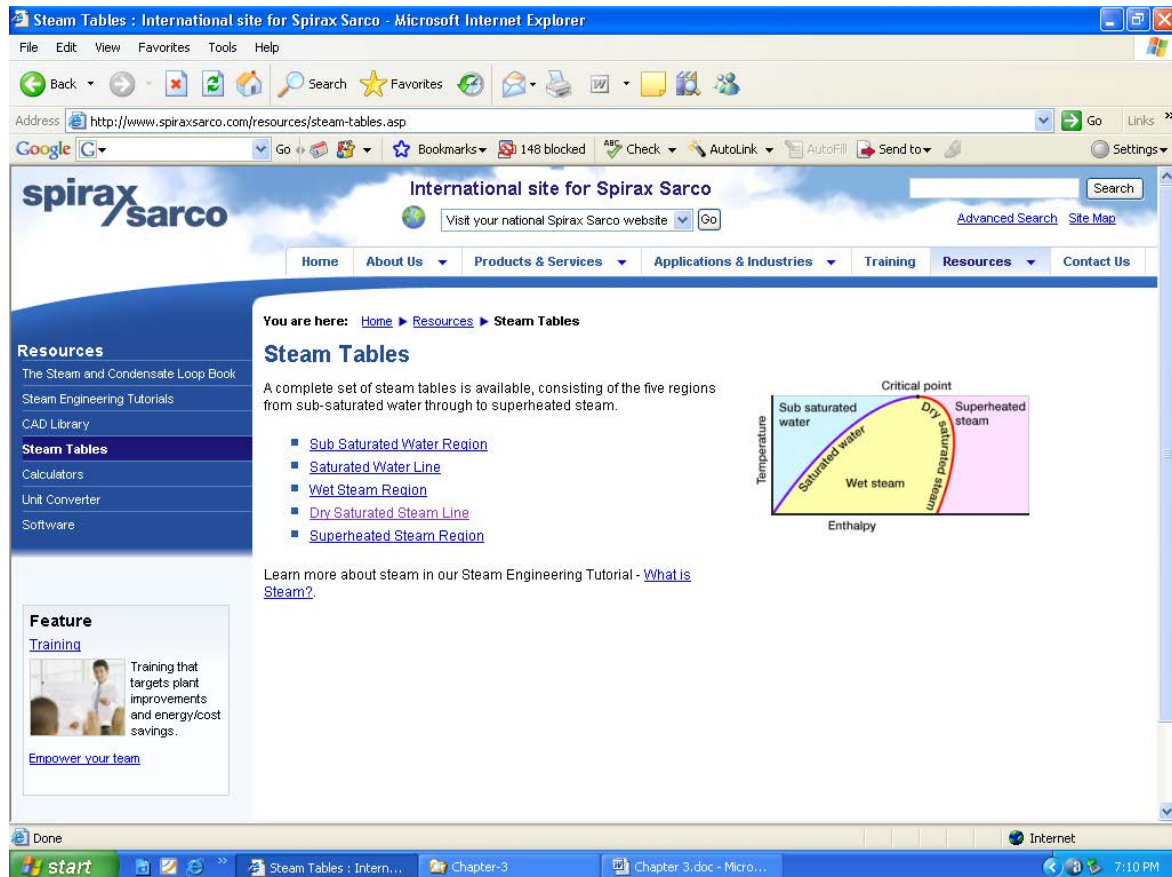


Fig. 3.28a. Properties of H₂O from Spirax Sarco

We can get steam tables in any of the five regions by clicking on the appropriate link. Let us click on the wet steam region:

International site for Spirax Sarco

Visit your national Spirax Sarco website Go

Advanced Search Site Map

Home About Us Products & Services Applications & Industries Training Resources Contact Us

You are here: Home > Resources > Steam Tables > Wet Steam Region

Wet Steam Region - Steam Table

The wet steam region (also known as the two-phase region) depicts all values of steam in its wet condition. Its boundaries are the saturated water line and the dry saturated steam line.

The addition of heat to steam at any point in the wet steam region causes the steam to dry, but always at the same temperature. The drier the steam, the closer it is to the dry saturated steam line.

Learn more about steam in our tutorial - [What is Steam?](#)

Set your [preferences](#) for these steam tables.

Steam Tables

- Sub Saturated Water Region
- Saturated Water Line
- Wet Steam Region**
- Dry Saturated Steam Line
- Superheated Steam Region

Temperature-Enthalpy Diagram

The diagram shows the relationship between Temperature and Enthalpy for water and steam. Key regions include Sub saturated water, Saturated water, Wet steam, Dry steam, and Superheated steam. The Critical point is marked at the end of the saturated water line.

Inputs

Output: Saturation Pressure and Dryness

☒ Single Value ☐ Table

Saturation Pressure: Enter Value kPa (kN/m²) absolute

Dryness: Enter Value %

Calculate Reset Print

Outputs

Saturation Temperature	<input type="text"/>	°C
Specific Enthalpy of Water (h_f)	<input type="text"/>	kJ/kg
Specific Enthalpy of Evaporation of Wet Steam	<input type="text"/>	kJ/kg
Specific Enthalpy of Wet Steam (h)	<input type="text"/>	kJ/kg
Density of Wet Steam	<input type="text"/>	kg/m ³
Specific Volume of Wet Steam (v)	<input type="text"/>	m ³ /kg
Specific Entropy of Water (s_f)	<input type="text"/>	kJ/kg K
Specific Entropy of Evaporation of Wet Steam	<input type="text"/>	kJ/kg K
Specific Entropy of Wet Steam (s)	<input type="text"/>	kJ/kg K
Specific Heat of Water ($c_{p,f}$)	<input type="text"/>	kJ/kg K
Specific Heat of Wet Steam ($c_{p,w}$)	<input type="text"/>	kJ/kg K
Specific Heat of Wet Steam ($c_{p,g}$)	<input type="text"/>	kJ/kg K
Dynamic Viscosity of Water	<input type="text"/>	Pa s
Dynamic Viscosity of Steam	<input type="text"/>	Pa s

Fig. 3.28b. Properties of H₂O from Spirax Sarco

Note that you can get output for a single point (state) or you can generate a table for a set of states. Let us get property at a single point. Input can be pressure and quality (dryness) or other combinations which can be chosen from the widget. For now, enter $P_{sat} = 200$ kPa and dryness = 80%. Press 'Calculate'. You get:

Inputs		
Output	Saturation Pressure and Dryness	
	<input checked="" type="radio"/> Single Value	<input type="radio"/> Table
Saturation Pressure	200	kPa (kN/m ²) absolute
Dryness	80	%
<input type="button" value="Calculate"/> <input type="button" value="Reset"/> <input type="button" value="Print"/>		
Saturation Temperature	120.241	°C
Specific Enthalpy of Water (h_f)	504.836	kJ/kg
Specific Enthalpy of Evaporation of Wet Steam	1761.39	kJ/kg
Specific Enthalpy of Wet Steam (h)	2266.23	kJ/kg
Density of Wet Steam	1.41064	kg/m ³
Specific Volume of Wet Steam (v)	0.708896	m ³ /kg
Specific Entropy of Water (s_f)	1.53042	kJ/kg K
Specific Entropy of Evaporation of Wet Steam	4.47747	kJ/kg K
Specific Entropy of Wet Steam (s)	6.00789	kJ/kg K
Specific Heat of Water (c_p)	4.24911	kJ/kg K
Specific Heat of Wet Steam ($c_{p,v}$)	1.99547	kJ/kg K
Specific Heat of Wet Steam ($c_{p,p}$)	2.55115	kJ/kg K
Dynamic Viscosity of Water	2.31623E-04	Pa s
Dynamic Viscosity of Steam	1.29635E-05	Pa s

Fig. 3.28c. Properties of H₂O from Spirax Sarco

3.4.5 Property Tables:

Many times, values of properties are required in a tabular form for reference. Tables can be obtained in the given range immediately from some of these software.

3.4.5.1 Property table from NIST:

This has already been explained under article 3.4.4. Advantage of NIST website is that you can get property table and several types of plots not only for Water but also for a very large number of fluids. So, it is a very useful site and should always be kept in mind while looking for properties of substances.

3.4.5.2 Property table from Spirax Sarco:

Click on <http://www.spiraxsarco.com/resources/steam-tables.asp>). Then click on Superheated region. Select the Inputs as Superheated temperature and pressure, and Outputs as Table:

International site for Spirax Sarco

Search

Visit your national Spirax Sarco website

Go

Advanced Search Site Map

Home About Us Products & Services Applications & Industries Training Resources Contact Us

You are here: Home > Resources > Steam Tables > Superheated Steam Region

Superheated Steam Region - Steam Table

The superheated steam region depicts steam at a temperature higher than its saturation temperature. Should saturated steam be heated at constant pressure, its temperature will rise, producing superheated steam.

Learn more about steam in our tutorial - [What is Steam?](#)

Set your [preferences](#) for these steam tables.

Steam Tables

- Sub Saturated Water Region
- Saturated Water Line
- Wet Steam Region
- Dry Saturated Steam Line
- Superheated Steam Region**

Feature Training

Training that targets plant improvements and energy/cost savings.

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Inputs: Superheat Temperature And Pressure

Output: ☐ Single Value ☒ Table

Superheat Temperature: From 250 °C To 400 °C Steps of 10 °C

Pressure: 300 kPa (kN/m²) absolute

Calculate Reset Print

Phase Diagram: A Temperature-Enthalpy diagram showing the phase regions of water: Sub saturated water, Saturated water, Wet steam, Dry saturated steam, and Superheated steam. The Critical point is marked at the end of the saturated steam line.

Fig. 3.29a. Properties of H₂O from Spirax Sarco

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Enter the values for temperature range and pressure. Click on 'Calculate'. We get:

Superheat Temp	Pressure	Saturation Temp	Degrees Superheat	Specific Enthalpy of Water (h_f)	Specific Enthalpy of Evaporation (h_{fg})	Specific Enthalpy of Superheated Steam	Density of Steam	Specific Volume of Steam (v)	Specific Entropy of Water (s_f)	Specific Entropy of Evaporation (s_{fg})	Specific Entropy of Superheated Steam	Specific Heat of Steam (c_p)	Specific Heat of Steam (c_p)	Speed of sound	Dynamic Viscosity of Steam	Isentropic Coefficient	Compressibility Factor of Steam
°C	kPa (kN/m ²) absolute	°C	°C	kJ/kg	kJ/kg	kJ/kg	kg/m ³	m ³ /kg	kJ/kg K	kJ/kg K	kJ/kg K	kJ/kg K	kJ/kg K	m/s	Pa s		
250	300	133.555	116.445	561.645	2163.67	2967.12	1.25576	0.796333	1.67217	5.31999	7.51577	1.54207	2.03376	558.303	1.82E-05	1.30468	0.989458
260	300	133.555	126.445	561.645	2163.67	2987.46	1.23124	0.812192	1.67217	5.31999	7.55428	1.54458	2.03376	563.605	1.86E-05	1.30363	0.990235
270	300	133.555	136.445	561.645	2163.67	3007.8	1.20771	0.828013	1.67217	5.31999	7.59208	1.5476	2.03456	568.831	1.90E-05	1.30255	0.990339
280	300	133.555	146.445	561.645	2163.67	3028.15	1.18511	0.8438	1.67217	5.31999	7.62921	1.5506	2.03603	573.985	1.94E-05	1.30146	0.991575
290	300	133.555	156.445	561.645	2163.67	3048.52	1.16339	0.859556	1.67217	5.31999	7.66571	1.55488	2.03808	579.071	1.98E-05	1.30035	0.992154
300	300	133.555	166.445	561.645	2163.67	3068.91	1.14249	0.875285	1.67217	5.31999	7.7016	1.55902	2.04063	584.093	2.03E-05	1.29923	0.992682
310	300	133.555	176.445	561.645	2163.67	3089.34	1.12235	0.890989	1.67217	5.31999	7.73692	1.56345	2.04363	589.052	2.07E-05	1.2981	0.993164
320	300	133.555	186.445	561.645	2163.67	3109.79	1.10294	0.90667	1.67217	5.31999	7.7717	1.56811	2.047	593.953	2.11E-05	1.29697	0.993695
330	300	133.555	196.445	561.645	2163.67	3130.25	1.08421	0.922332	1.67217	5.31999	7.80656	1.57299	2.05071	598.797	2.15E-05	1.29583	0.994201
340	300	133.555	206.445	561.645	2163.67	3150.8	1.06613	0.937975	1.67217	5.31999	7.83971	1.57806	2.05471	603.586	2.19E-05	1.29468	0.994725
350	300	133.555	216.445	561.645	2163.67	3171.37	1.04866	0.953601	1.67217	5.31999	7.87238	1.58329	2.05888	608.323	2.24E-05	1.29354	0.995242
360	300	133.555	226.445	561.645	2163.67	3191.98	1.03177	0.969212	1.67217	5.31999	7.9058	1.58868	2.06348	613.009	2.28E-05	1.29239	0.995760
370	300	133.555	236.445	561.645	2163.67	3212.64	1.01542	0.98481	1.67217	5.31999	7.93817	1.5942	2.0682	617.647	2.32E-05	1.29124	0.996273
380	300	133.555	246.445	561.645	2163.67	3233.35	0.999606	1.00039	1.67217	5.31999	7.97012	1.59985	2.0731	622.238	2.36E-05	1.29009	0.996785
390	300	133.555	256.445	561.645	2163.67	3254.1	0.984284	1.01597	1.67217	5.31999	8.00165	1.6056	2.07818	626.783	2.40E-05	1.28894	0.997297
400	300	133.555	266.445	561.645	2163.67	3274.91	0.969434	1.03153	1.67217	5.31999	8.0328	1.61145	2.08341	631.283	2.44E-05	1.28779	0.997809

Fig. 3.29b. Properties of H2O from Spirax Sarco

3.4.5.3 Property table from TEST:

Go to TEST – Map and click on ‘Tables & Charts’:

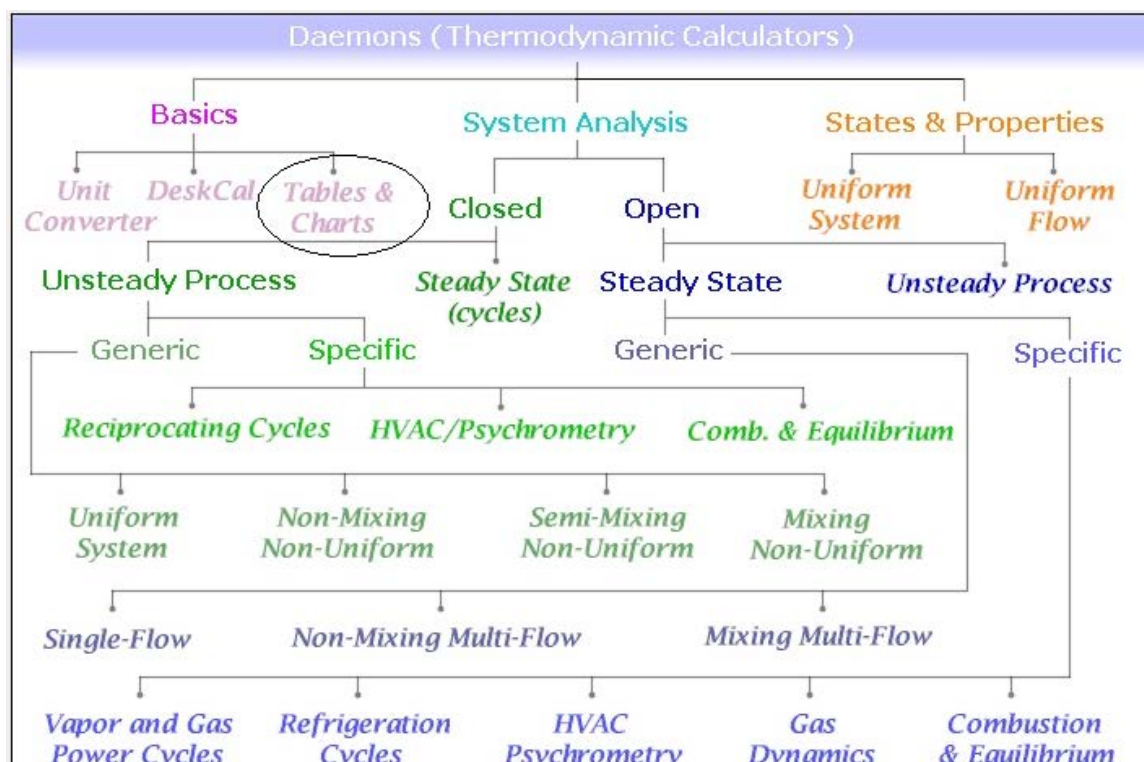


Fig. 3.30a. Property Table of H2O from TEST

We get:

Thermodynamic Lookup Tables: Evaluate Properties Manually and Verify Using Daemons								
<div>thermofluids.net > Daemons > Basics > Tables</div> <div> Home TEST SL Daemon PC Daemon PG Daemon IG Daemon RG Daemon MA Daemon n-IG Non-mixing IG</div>								
Click on a table icon for a traditional chart or table and the daemon icon for a smart table.								
Table-A (SL Model)		 Table A-1	 Table A-2	Material properties ($c_p = c_v$ and $v = 1/\rho$) of solids and liquids upon which the SL (solid/liquid) model is built. In the state daemon, simply select the working substance and click Calculate to display the material properties.				
Table-B (PC Model)		H2O	 Table B-1	 Table B-2	 Table B-3	 Table B-4	 Table B-5	Saturation and superheated tables for phase-change (PC) fluids. In the PC daemon, select the working fluid (from more than 60 fluids), enter two independent thermodynamic properties (say, p and h : all thermodynamic properties are colored blue) to obtain all other properties.
		R-134a	 Table B-6	 Table B-7	R-22	 Table B-8	 Table B-9	
		R-12	 Table B-10	 Table B-11	Ammonia (NH ₃)	 Table B-12	 Table B-13	
		N2	 Table B-14	 Table B-15	Propane (C ₃ H ₈)	 Table B-16	 Table B-17	
Table-C (PG Model)		 Table C-1	Material properties - c_p , c_v , R , k , etc. - upon which the perfect gas (PG) model is built. In the PG state daemon, select the working fluid and click Calculate to display the material properties.					
Table-D (IG Model)		 Table D-1	 Table D-2	Polynomial relation and tabular data for c_p as a function of absolute temperature T . To obtain c_p from the IG daemon, select the gas, enter a temperature, and click Calculate. You may also obtain the temperature by entering a value for c_p .				
		 Table D-3	 Table D-4	 Table D-5	 Table D-6	 Table D-7	Ideal gas (IG) tables for several gases. In the IG daemon, you will find a much wider selection of gases. Select a gas, enter two independent thermodynamic properties and click Calculate for a complete state.	
		 Table D-8	 Table D-9	 Table D-10	 Table D-11	 Table D-12		
		 Table D-13	 Table D-14	 Table D-15				
Table-E (RG Model)		 Table E-1	Critical properties of various fluids used in the real gas (RG) model. In the RG daemon, select the fluid and click Calculate to display all the material properties including the critical properties.					
		Lee-Kesler Charts	 Table E-2	 Table E-3	 Table E-4	Compressibility charts used in the real gas (RG) model. Lee-Kesler charts are based on ideal fluid assumption and Nelson-Obert charts are based on average data. In the RG daemon, select a model by using the LK or NO radio button, select a fluid, enter two independent thermodynamic properties, and click Calculate to obtain the complete state.		
		Nelson-Obert Charts	 Table E-5	 Table E-6	 Table E-7			
		BWR Coefficients	 Table E-8	Constants used in Benedict-Webb-Rubin (BWR) equation of state.				
Table-F (MA Model)		 Table F-1	Traditional psychrometric chart for moist air. The MA (moist air) daemon handles other moist gases beside air. After selecting the gas, enter the known thermodynamic (blue) properties to calculate the rest.					
Table-G (Thermo-Chem Tables)				 Table G-1	 Table G-2	 Table G-3	Formation enthalpies, heating values, and equilibrium constants tables. Use the n-IG mixture daemon to obtain component and mixture properties, combustion daemon to find heating values, and the chemical equilibrium daemon to find equilibrium constant.	









Table-H (Gas-Dynamics Tables)	 Gas Dynamics Daemon	 Table H-1	 Table H-2	 Table H-3	Isentropic, normal-shock, and barometric (variation of properties with altitude) table. In the gas dynamics daemon, select a gas and click Calculate to populate the isentropic, normal-shock, delta-theta (oblique shock), and Prandtl-Meyer table (expansion fan) in the table panel.
Table-I (Conversion Table)	 Unit Converter Daemon	 Table I-1	Handy unit conversion table in a pdf file. An enhanced version of the unit conversion daemon is available as a free Android app with an intuitive spinning wheel interface. Search for Engineering Unit Converter app in Google Play.		
Table-J (Equation Sheet)	 Engineering Calculator	 Table J-1	Frequently used equations for property evaluation and system analysis for manual solution in a compact pdf file. Launch the calculator daemon (appears in a pop-up window) for quick engineering calculations.		

Fig. 3.30b. Property Table of H₂O from TEST

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Click on desired Table. For example, click on Tsat-H2O. We get Sat. water-Temp-Table:

Table-B.2, PC Model, H₂O: **Saturation Temperature Table**



Saturated Water (H2O)--Temperature Table									
deg-C	kPa	Spec. Volume m ³ /kg		Internal Energy kJ/kg		Enthalpy kJ/kg		Entropy kJ/kg·K	
Temp.	Sat. press.	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor
T °C	p _{sat} @T	v _f	v _g	u _f	u _g	h _f	h _g	s _f	s _g
0.01	0.6113	0.001000	206.14	0.00	2375.3	0.01	2501.4	0.0000	9.1562
5	0.8721	0.001000	147.12	20.97	2382.3	20.98	2510.6	0.0761	9.0257
10	1.2276	0.001000	106.38	42.00	2389.2	42.01	2519.8	0.1510	8.9008
15	1.7051	0.001001	77.93	62.99	2396.1	62.99	2528.9	0.2245	8.7814
20	2.339	0.001002	57.79	83.95	2402.9	83.96	2538.1	0.2966	8.6672
25	3.169	0.001003	43.36	104.88	2409.8	104.89	2547.2	0.3674	8.5580
30	4.246	0.001004	32.89	125.78	2416.6	125.79	2556.3	0.4369	8.4533
35	5.628	0.001006	25.22	146.67	2423.4	146.68	2565.3	0.5053	8.3531
40	7.384	0.001008	19.52	167.56	2430.1	167.57	2574.3	0.5725	8.2570
45	9.593	0.001010	15.26	188.44	2436.8	188.45	2583.2	0.6387	8.1648
50	12.349	0.001012	12.03	209.32	2443.5	209.33	2592.1	0.7038	8.0763
55	15.758	0.001015	9.568	230.21	2450.1	230.23	2600.9	0.7679	7.9913
60	19.940	0.001017	7.671	251.11	2456.6	251.13	2609.6	0.8312	7.9096
65	25.03	0.001020	6.197	272.02	2463.1	272.06	2618.3	0.8935	7.8310
70	31.19	0.001023	5.042	292.95	2469.6	292.98	2626.8	0.9549	7.7553
75	38.58	0.001026	4.131	313.90	2475.9	313.93	2634.7	1.0155	7.6824
80	47.39	0.001029	3.407	334.86	2482.2	334.91	2635.3	1.0753	7.6122
85	57.83	0.001033	2.828	355.84	2488.4	355.90	2651.9	1.1343	7.5445
90	70.14	0.001036	2.361	376.85	2494.5	376.92	2660.1	1.1925	7.4791
95	84.55	0.001040	1.982	397.88	2500.6	397.96	2668.1	1.2500	7.4159
T °C	p _{sat} @T MPa	v _f	v _g	u _f	u _g	h _f	h _g	s _f	s _g
100	0.10135	0.001044	1.6729	418.94	2506.5	419.04	2676.1	1.3069	7.3549
105	0.12082	0.001048	1.4194	440.02	2512.4	440.15	2683.8	1.3630	7.2958
110	0.14327	0.001052	1.2102	461.14	2518.1	461.30	2691.5	1.4185	7.2387
115	0.16906	0.001056	1.0366	482.30	2523.7	482.48	2699.0	1.4734	7.1833
120	0.19853	0.001060	0.8919	503.50	2529.3	503.71	2706.3	1.5276	7.1296
125	0.2321	0.001065	0.7706	524.74	2534.6	524.99	2713.5	1.5813	7.0775
130	0.2701	0.001070	0.6685	546.02	2539.9	546.31	2720.5	1.6344	7.0269
135	0.3130	0.001075	0.5822	567.35	2545.0	567.69	2727.3	1.6870	6.9777
140	0.3613	0.001080	0.5089	588.74	2550.0	589.13	2733.9	1.7391	6.9299
145	0.4154	0.001085	0.4463	610.18	2554.9	610.63	2740.3	1.7907	6.8833
150	0.4758	0.001091	0.3928	631.68	2559.5	632.20	2746.5	1.8418	6.8379
155	0.5431	0.001096	0.3468	653.24	2564.1	653.84	2752.4	1.8925	6.7935
160	0.6178	0.001102	0.3071	674.87	2568.4	675.55	2758.1	1.9427	6.7502
165	0.7005	0.001108	0.2727	696.56	2572.5	697.34	2763.5	1.9925	6.7078
170	0.7917	0.001114	0.2428	718.33	2576.5	719.21	2768.7	2.0419	6.6663
175	0.8920	0.001121	0.2168	740.17	2580.2	741.17	2773.6	2.0909	6.6256
180	1.0021	0.001127	0.19405	762.09	2583.7	763.22	2778.2	2.1396	6.5857

185	1.1227	0.001134	0.17409	784.10	2587.0	785.37	2782.4	2.1879	6.5465
190	1.2544	0.001141	0.15654	806.19	2590.0	807.62	2786.4	2.2359	6.5079
195	1.3978	0.001149	0.14105	828.37	2592.8	829.98	2790.0	2.2835	6.4698
200	1.5538	0.001157	0.12736	850.65	2595.3	852.45	2793.2	2.3309	6.4323
205	1.7230	0.001164	0.11521	873.04	2597.5	875.04	2796.0	2.3780	6.3952
210	1.9062	0.001173	0.10441	895.53	2599.5	897.76	2798.5	2.4248	6.3585
215	2.104	0.001181	0.09479	918.14	2601.1	920.62	2800.5	2.4714	6.3221
220	2.318	0.001190	0.08619	940.87	2602.4	943.62	2802.1	2.5178	6.2861
225	2.548	0.001199	0.07849	963.73	2603.3	966.78	2803.3	2.5639	6.2503
230	2.795	0.001209	0.07158	986.74	2603.9	990.12	2804.0	2.6099	6.2146
235	3.060	0.001219	0.06537	1009.89	2604.1	1013.62	2804.2	2.6558	6.1791
240	3.344	0.001229	0.05976	1033.21	2604.0	1037.32	2803.8	2.7015	6.1437
245	3.648	0.001240	0.05471	1056.71	2603.4	1061.23	2803.0	2.7472	6.1083
250	3.973	0.001251	0.05013	1080.39	2602.4	1085.36	2801.5	2.7927	6.0730
255	4.319	0.001263	0.04598	1104.28	2600.9	1109.73	2799.5	2.8383	6.0375
260	4.688	0.001276	0.04221	1128.39	2599.0	1134.37	2796.9	2.8838	6.0019
265	5.081	0.001289	0.03877	1152.74	2596.6	1159.28	2793.6	2.9294	5.9662
270	5.499	0.001302	0.03564	1177.36	2593.7	1184.51	2789.7	2.9751	5.9301
275	5.942	0.001317	0.03279	1202.25	2590.2	1210.07	2785.0	3.0208	5.8938
280	6.412	0.001332	0.03017	1227.46	2586.1	1235.99	2779.6	3.0668	5.8571
285	6.909	0.001348	0.02777	1253.00	2581.4	1262.31	2773.3	3.1130	5.8199
290	7.436	0.001366	0.02557	1278.92	2576.0	1289.07	2766.2	3.1594	5.7821
295	7.993	0.001384	0.02354	1305.20	2569.9	1316.30	2758.1	3.2062	5.7437
300	8.581	0.001404	0.02167	1332.00	2563.0	1344.00	2749.0	3.2534	5.7045
305	9.202	0.001425	0.019948	1359.30	2555.2	1372.40	2738.7	3.3010	5.6643
310	9.856	0.001447	0.018350	1387.10	2546.4	1401.30	2727.3	3.3493	5.6230
315	10.547	0.001472	0.016867	1415.50	2536.6	1431.00	2714.5	3.3982	5.5804
320	11.274	0.001499	0.015488	1444.60	2525.5	1461.50	2700.1	3.4480	5.5362
330	12.845	0.001561	0.012996	1505.30	2498.9	1525.30	2665.9	3.5507	5.4417
340	14.586	0.001638	0.010797	1570.30	2464.6	1594.20	2622.0	3.6594	5.3357
350	16.513	0.001740	0.008813	1641.90	2418.4	1670.60	2563.9	3.7777	5.2112
360	18.651	0.001893	0.006945	1725.20	2351.5	1760.50	2481.0	3.9147	5.0526
370	21.03	0.002213	0.004925	1844.00	2228.5	1890.50	2332.1	4.1106	4.7971
374.14	22.09	0.003155	0.003155	2029.60	2029.6	2099.30	2099.3	4.4298	4.4298

Fig. 3.30c. Property Table of H₂O from TEST

Similarly, we can get compressed water tables and Tables for R134a.

3.4.5.4 Property table from free software WSProps:

This software is from www.Sourceforge.net. As you start WSProps, go to File-New and following window appears:

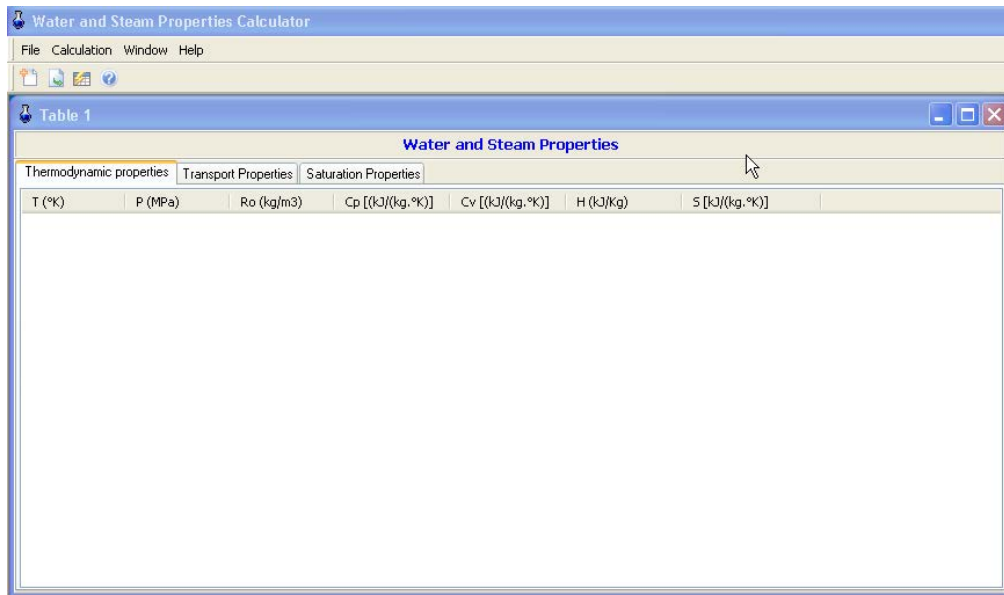


Fig. 3.31a. Property Table of H₂O from WSProps

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First set the Units by going to Calculation-Run. Set the Units as shown below:



Fig. 3.31b. Property Table of H₂O from WSProps

Next, press the calculation tab.

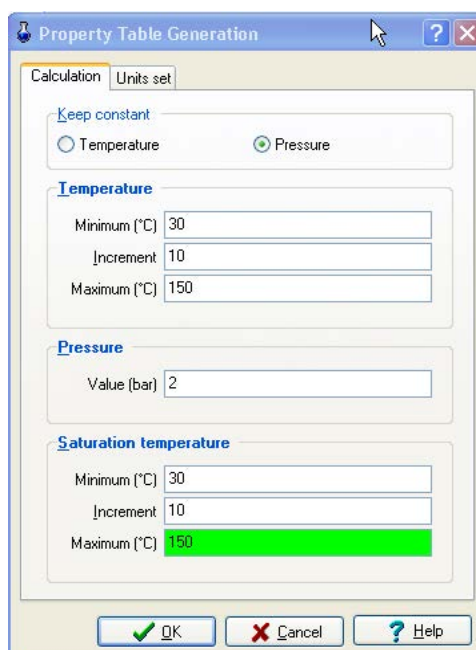
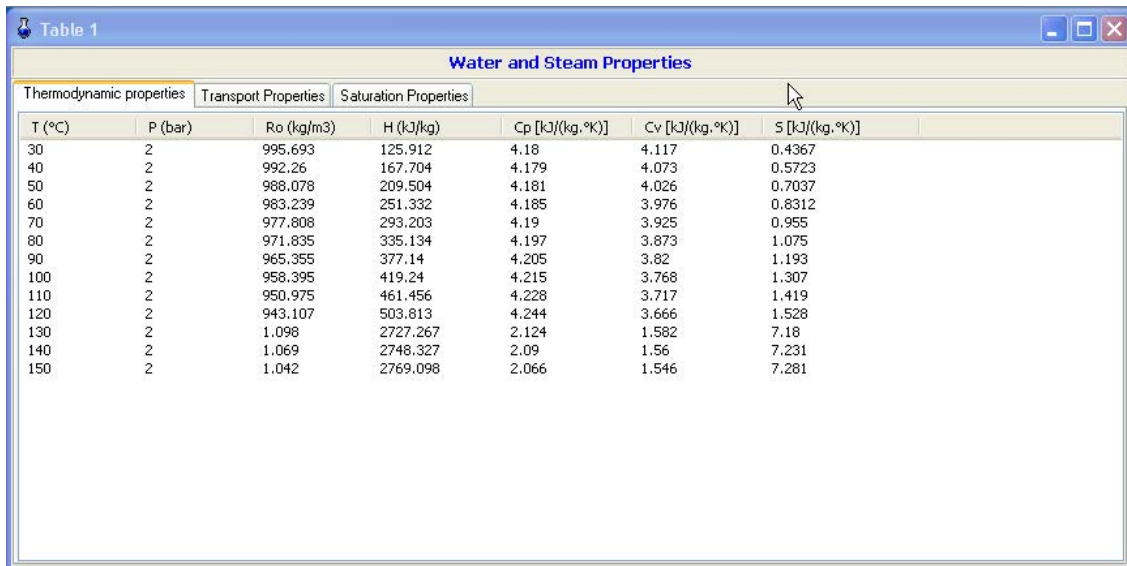


Fig. 3.31c. Property Table of H₂O from WSProps

Enter the Temperature range and pressure values as shown above and click OK.

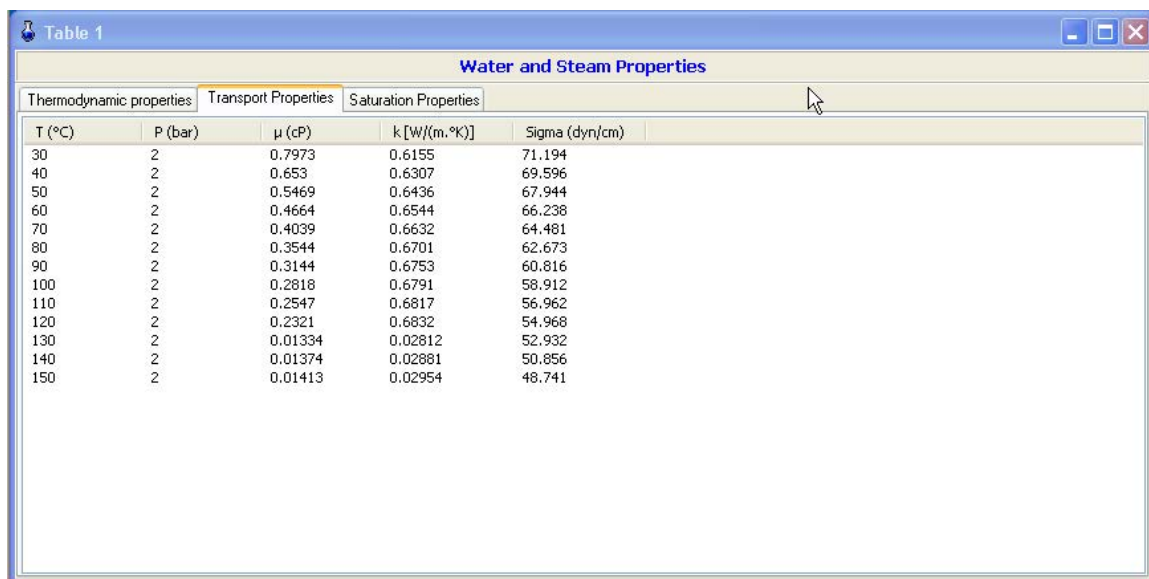
We get:



Water and Steam Properties						
Thermodynamic properties						
T (°C)	P (bar)	Ro (kg/m ³)	H (kJ/kg)	Cp [kJ/(kg.°K)]	Cv [kJ/(kg.°K)]	S [kJ/(kg.°K)]
30	2	995.693	125.912	4.18	4.117	0.4367
40	2	992.26	167.704	4.179	4.073	0.5723
50	2	988.078	209.504	4.181	4.026	0.7037
60	2	983.239	251.332	4.185	3.976	0.8312
70	2	977.808	293.203	4.19	3.925	0.955
80	2	971.835	335.134	4.197	3.873	1.075
90	2	965.355	377.14	4.205	3.82	1.193
100	2	958.395	419.24	4.215	3.768	1.307
110	2	950.975	461.456	4.228	3.717	1.419
120	2	943.107	503.813	4.244	3.666	1.528
130	2	1.098	2727.267	2.124	1.582	7.18
140	2	1.069	2748.327	2.09	1.56	7.231
150	2	1.042	2769.098	2.066	1.546	7.281

Fig. 3.31d. Property Table of H₂O from WSProps

Thermodynamic properties, Transport properties and saturation properties are obtained by clicking on the respective tabs:



Water and Steam Properties				
Transport Properties				
T (°C)	P (bar)	μ (cP)	k [W/(m.°K)]	Sigma (dyn/cm)
30	2	0.7973	0.6155	71.194
40	2	0.653	0.6307	69.596
50	2	0.5469	0.6436	67.944
60	2	0.4664	0.6544	66.238
70	2	0.4039	0.6632	64.481
80	2	0.3544	0.6701	62.673
90	2	0.3144	0.6753	60.816
100	2	0.2818	0.6791	58.912
110	2	0.2547	0.6817	56.962
120	2	0.2321	0.6832	54.968
130	2	0.01334	0.02812	52.932
140	2	0.01374	0.02881	50.856
150	2	0.01413	0.02954	48.741

Fig. 3.31e. Property Table of H₂O from WSProps

Water and Steam Properties							
Thermodynamic properties		Transport Properties		Saturation Properties			
T (K)	Pvp (bar)	RoL (kg/m ³)	RoV (kg/m ³)	HL (kJ/kg)	HV (kJ/kg)	SL [kJ/(kg.°K)]	SV [kJ/(kg.°K)]
303.15	0.004247	995.602	0.03041	125.734	2555.727	0.4368	8.453
313.15	0.007385	992.17	0.05124	167.534	2573.615	0.5724	8.256
323.15	0.01235	987.991	0.08315	209.344	2591.344	0.7038	8.075
333.15	0.01995	983.154	0.1304	251.183	2608.879	0.8313	7.908
343.15	0.0312	977.728	0.1984	293.066	2626.162	0.9551	7.754
353.15	0.04742	971.761	0.2937	335.012	2643.123	1.076	7.611
363.15	0.07018	965.291	0.4239	377.038	2659.683	1.193	7.479
373.15	0.1014	958.347	0.5981	419.163	2675.76	1.307	7.355
383.15	0.1434	950.948	0.8268	461.409	2691.273	1.419	7.239
393.15	0.1987	943.108	1.122	503.802	2706.139	1.528	7.13
403.15	0.2703	934.836	1.497	546.368	2720.277	1.635	7.027
413.15	0.3615	926.136	1.967	589.139	2733.607	1.739	6.93
423.15	0.4762	917.01	2.548	632.147	2746.047	1.842	6.837

Fig. 3.31f. Property Table of H₂O from WSProps



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3.5 Example Problems:

Let us work out a few problems to illustrate the use of these software.

Problem 3.3. Find the enthalpy and entropy of steam when the pressure is 2 MPa and specific volume is 0.09 m³/kg. [VTU, 2005]

Solution: If this problem has to be solved using conventional steam tables, tedious interpolation will be required. But, the problem is solved very easily with TEST:

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). Substance 'H₂O' is automatically selected. Select P1 and v1 and enter the values given. Take care to select proper units. See Fig. 3.34a below:

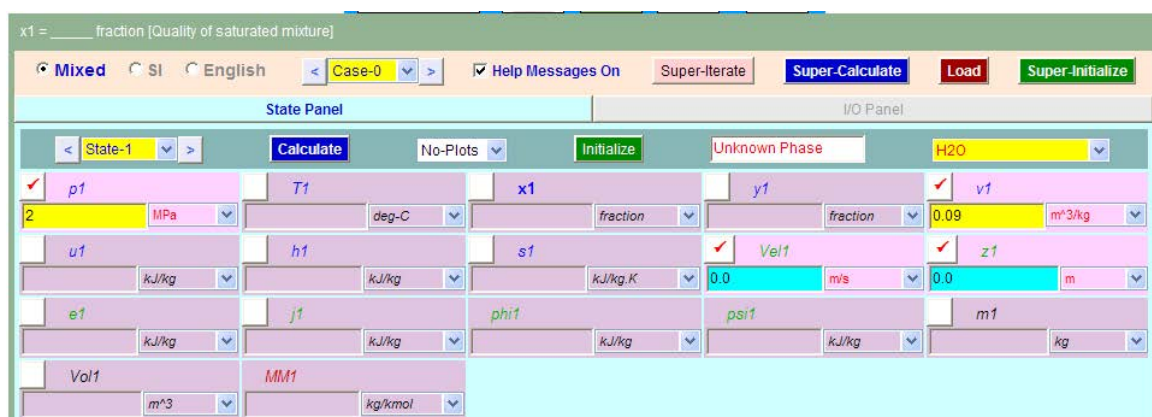


Fig. 3.32a. Properties of H₂O from TEST

Now, click 'Calculate' and immediately all the results are displayed, as shown below:



Fig. 3.32b. Properties of H₂O from TEST

Read the result as: $h_1 = 2614.85 \text{ kJ/kg}$, and $s_1 = 5.96 \text{ kJ/kg.K}$, and the state is: sat. mixture with quality (i.e. dryness fraction) = 0.902.

By clicking on the T-s plot widget, you can locate the state on the T-s diagram too, as shown Fig. 3.34c and 3.34d below:

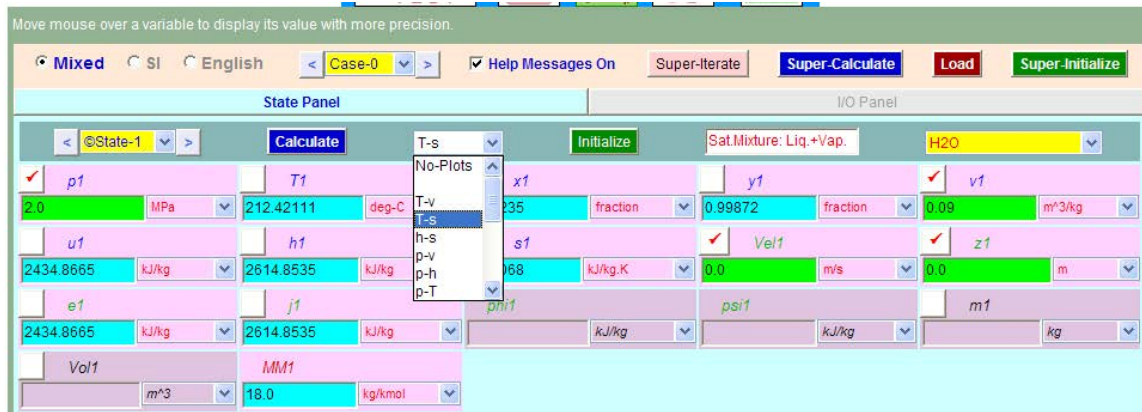


Fig. 3.32c. Properties of H2O from TEST

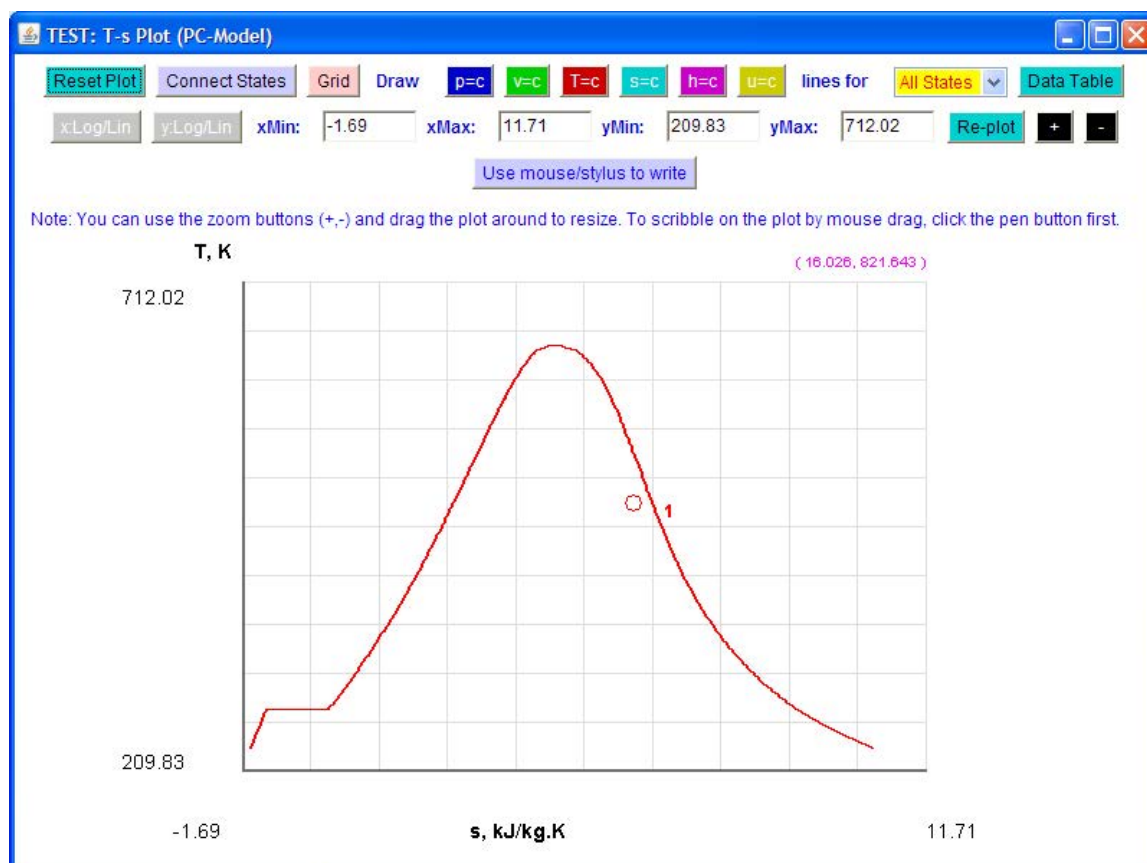


Fig. 3.32d. Properties of H2O from TEST – (T-s) plot

Problem 3.4. A rigid container is filled with steam at 600 kPa and 200 deg.C. At what temperature the steam begins to condense when it is cooled? Determine the corresponding pressure. [VTU, 2004]

Solution: Container is 'rigid' – means that the volume remains constant. Let us solve this problem in TEST. Let state 1 be at 600 kPa and 200 deg.C.

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). Substance 'H2O' is automatically selected. Select P1 and 1 and enter the values given. Take care to select proper units. Click 'Calculate' and all properties at state 1 are presented. See Fig. 3.35a below:

State Panel

Calculate T-s Initialize Superheated Vapor H2O

p_1	600.0	kPa	T_1	200.0	deg-C	x_1		fraction	y_1		fraction	v_1	0.35201	m ³ /kg
u_1	2638.8906	kJ/kg	h_1	2850.0974	kJ/kg	s_1	6.96645	kJ/kg.K	Vel_1	0.0	m/s	z_1	0.0	m
e_1	2638.8906	kJ/kg	j_1	2850.0974	kJ/kg	ϕ_1		kJ/kg	ψ_1		kJ/kg	m_1		kg
Vol_1		m ³	MM_1	18.0	kg/kmol									

Fig. 3.33a. Properties of H2O from TEST – State 1

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Next, select State 2. Since State 2 is saturated vapor (when condensation just begins), 'quality' $x_2 = 1$. Also, since volume remains constant, $v_2 = v_1$. Enter these values of x_2 and v_2 as shown, and click 'Calculate'. You get the following result:



Fig. 3.33b. Properties of H2O from TEST – State 2

Note that condensation occurs at $T_2 = 154.39$ deg.C and the corresponding pressure $P_2 = 534.49$ kPa. And if we need the amount of heat rejected, it is equal to $(u_2 - u_1)$, since volume is constant; and $(u_2 - u_1) = (2563.46 - 2638.89) = -75.43$ kJ/kg. (-ve sign indicates that heat is rejected.).

Next, states 1 and 2 can be shown on a T-s diagram. Choose T-s on the Plots widget and the plot appears as shown below. Press 'Connect states', click ' $v = c$ ' tab to produce the const. volume line, and adjust xmin, xmax, ymin and ymax as shown:

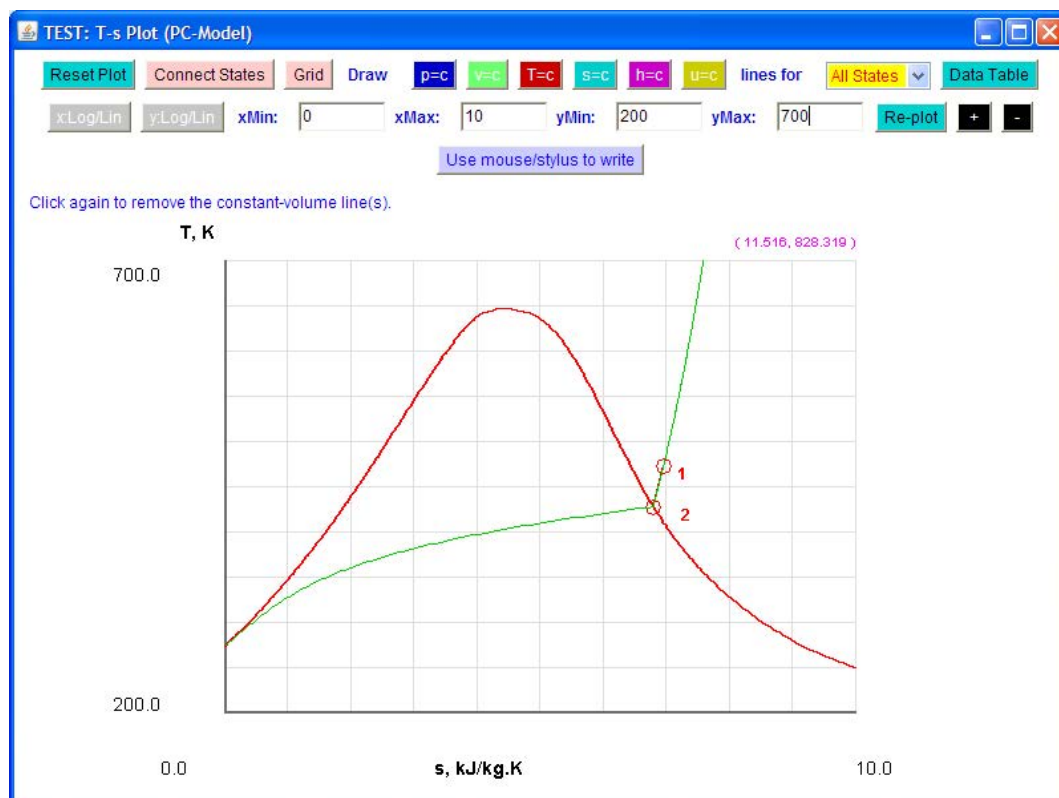


Fig. 3.33c. Properties of H2O from TEST – (T-s) plot

Note that constant volume line passes through states 1 and 2, as it should.

Problem 3.5. A pressure cooker contains 1.5 kg of steam at 5 bar pressure and 0.8 dry. Find the quantity of heat which must be rejected so that the quality of steam becomes 0.4 dry.... [VTU, 2003]

Solution: Again, TEST is very convenient to solve this problem.

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at $P_1 = 5$ bar, $m_1 = 1.5$ kg, $x_1 = 0.8$. Enter these values and press 'Calculate'. All properties at state 1 are presented immediately:



Fig. 3.34a. Properties of H2O from TEST – State 1

Next, enter parameters for state 2, i.e. $m_2 = m_1$, $x_2 = 0.4$, $v_2 = v_1$; Press 'Calculate' and we get:



Fig. 3.34b. Properties of H2O from TEST – State 2

Since volume is constant, heat rejected =

$$(u_2 - u_1) = (1331.263 - 2176.8577) \text{ kJ/kg} \times 1.5 \text{ kg} = -1268.4 \text{ kJ. (-ve sign indicates that heat is rejected.)}$$

Alternatively:

Let us solve this problem in EES. In the Equation window of EES, enter the equations and press F2 for solution. We get:

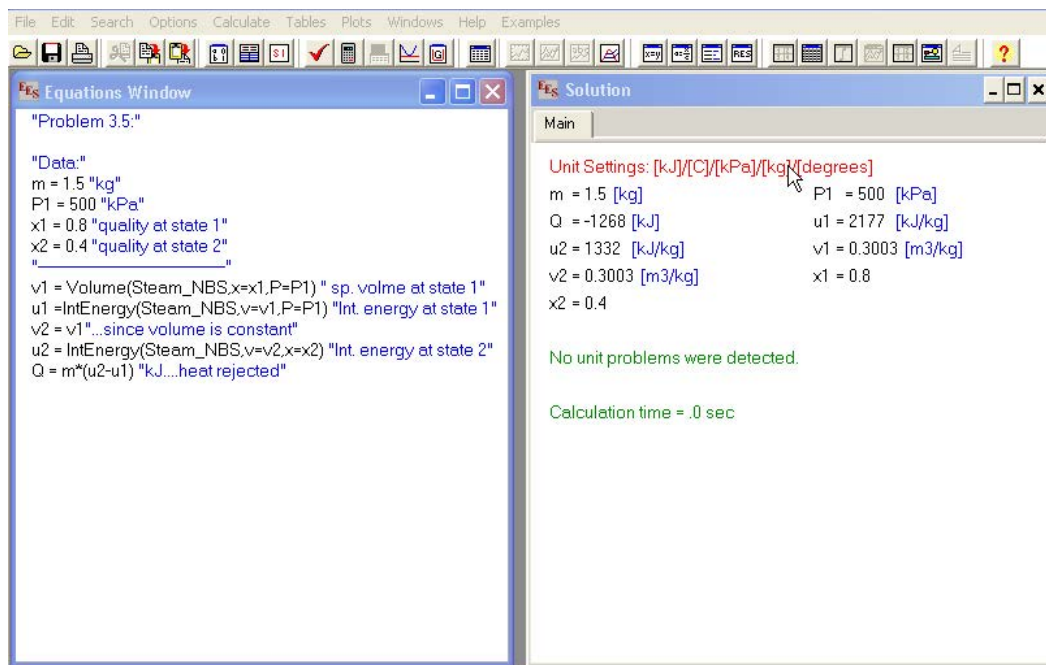


Fig. 3.34c. Properties of H₂O from EES

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Problem 3.6: A rigid vessel contains 1 kg of wet steam at a pressure of 0.15 MPa. When the mixture is heated, the state passes through the critical point. Determine:

- i. the volume of the vessel
- ii. mass of liquid and vapor initially in the vessel
- iii. temperature of the mixture when the pressure has risen to 3 MPa, and
- iv. the heat transfer required to produce the final state (iii)...[VTU, 2004]

Solution:

Note two points:

- i. Since 1 kg of wet steam passes through the critical point in a closed vessel, it is clear that the volume must be equal to critical volume = 0.003155 m³/kg.
- ii. Specific volume of wet steam is given by:

$$v = v_f + x \cdot v_{fg}$$

$$\text{i.e. } v = v_f + x \cdot (v_g - v_f)$$

$$\text{i.e. } v = (1 - x) \cdot v_f + x \cdot v_g$$

$$\text{i.e. } v \approx x \cdot v_g \quad \dots \text{approx} \dots (3.7) \quad \text{since } x \ll 1$$

Therefore, for a constant volume process, we can write, approximately:

$$x_1 \cdot v_{g1} = x_2 \cdot v_{g2} \quad \dots (3.8)$$

Where x_1, x_2 are the dryness fraction values at state 1 and state 2 respectively.

First let us solve this problem with TEST:

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at $P_1 = 0.15$ MPa, $m_1 = 1.0$ kg, $v_1 = 0.003155$ m³/kg. Enter these values and press 'Calculate'. All properties at state 1 are presented immediately:

Fig. 3.35a. Properties of H2O from TEST

Note that internal energy $u_1 = 470.563$ kJ/kg and quality $x_1 = 0.00181$.

Next, calculate for state 2, with $v_2 = v_1$ and $P_2 = 3$ MPa. We get the following screen, where we note that $u_2 = 1052.0969$ kJ/kg, and $T_2 = 233.9$ deg.C

Fig. 3.35b. Properties of H2O from TEST

For completeness, draw the T-v plot too. As explained earlier, select the T-v plot and the plot appears immediately. Draw the $v = \text{const.}$ line by clicking $v = c$ tab (see fig. below). Note that constant volume line connecting states 1 and 2 passes through the critical point.



Fig. 3.35c. T-v plot for H₂O from TEST

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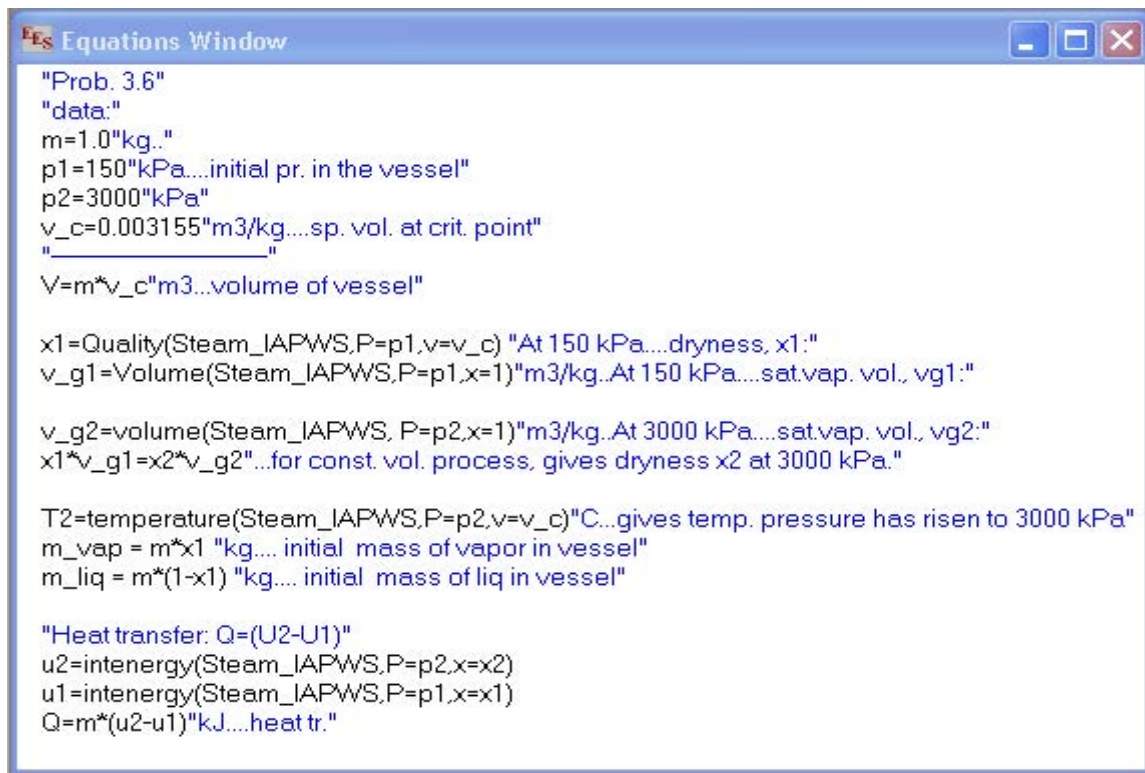
Therefore, the solution is:

- volume of the vessel = 0.003155 m^3
- mass of liquid and vapor initially in the vessel: By definition, 'quality' is the mass fraction of vapor present in the mixture. So, since the total mass is 1 kg, we have: mass of vapor = $x_1 = 0.00181 \text{ kg}$, and mass of liquid = $(1 - x_1) = 0.9982 \text{ kg}$.
- temperature of the mixture when the pressure has risen to 3 MPa = $T_2 = 233.9 \text{ deg.C}$, and
- the heat transfer required to produce the final state 2: $Q = (u_2 - u_1) = 581.53 \text{ kJ}$.

Alternatively:

Let us solve this problem with EES:

Write down the equations in the Equations window, as shown below. Read the comments against each eqn.



```

"Prob. 3.6"
"data:"
m=1.0"kg.."
p1=150"kPa....initial pr. in the vessel"
p2=3000"kPa"
v_c=0.003155"m3/kg....sp. vol. at crit. point"
"_____ "
V=m*v_c"m3...volume of vessel"

x1=Quality(Steam_IAPWS,P=p1,v=v_c) "At 150 kPa....dryness, x1:"
v_g1=Volume(Steam_IAPWS,P=p1,x=1)"m3/kg..At 150 kPa....sat.vap. vol., vg1:"

v_g2=volume(Steam_IAPWS, P=p2,x=1)"m3/kg..At 3000 kPa....sat.vap. vol., vg2:"
x1*v_g1=x2*v_g2"...for const. vol. process, gives dryness x2 at 3000 kPa."

T2=temperature(Steam_IAPWS,P=p2,v=v_c)"C...gives temp. pressure has risen to 3000 kPa"
m_vap = m*x1 "kg.... initial mass of vapor in vessel"
m_liq = m*(1-x1) "kg.... initial mass of liq in vessel"

"Heat transfer: Q=(U2-U1)"
u2=intenergy(Steam_IAPWS,P=p2,x=x2)
u1=intenergy(Steam_IAPWS,P=p1,x=x1)
Q=m*(u2-u1)"kJ....heat tr."
  
```

Fig. 3.36a. Properties of H₂O from EES

Now, press F2 to calculate. Following results appear:

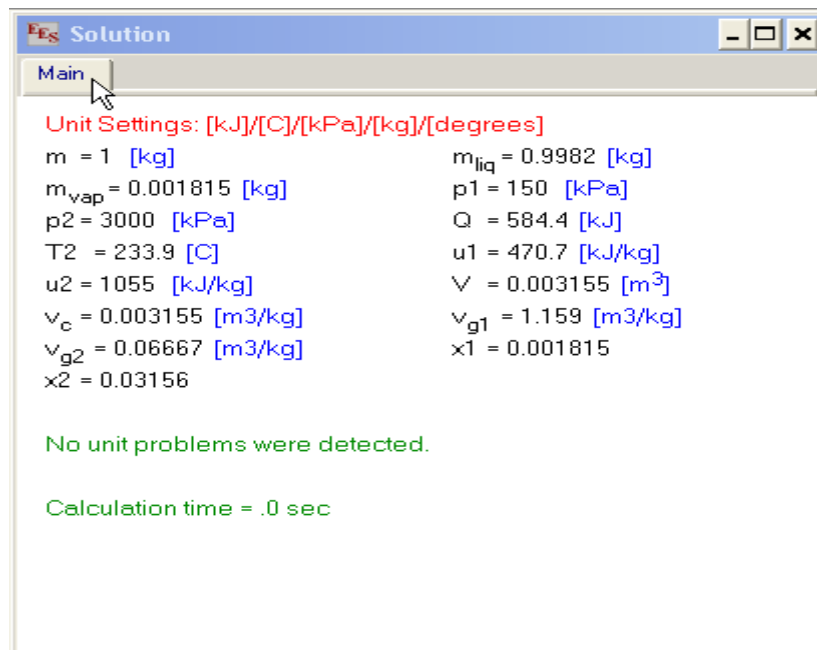


Fig. 3.36b. Solution for Prob.3.6 from EES

Very slight difference in u_2 , x_2 and Q obtained from TEST and EES are due to the approximation made in EES code, viz. $x_1.v_{g1} = x_2.v_{g2}$.

Problem 3.7: A vessel having a capacity of 0.85 m^3 , contains steam at 12 bar and 0.92 dry. Steam is blown off until the pressure drops to 6 bar. The valve is then closed and the vessel is cooled until the pressure is 4 bar. Assuming that the specific enthalpy of steam is constant during the blowing off period, determine:

- quantity of steam blown off
- quality of steam in the vessel after cooling, and
- quantity of steam in the vessel after cooling [VTU, 2004]

Solution:

Since the problem involves finding out the states, TEST is most convenient to use.

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at $P_1 = 12$ bar, $\text{Vol}_1 = 0.85 \text{ m}^3$, $x_1 = 0.92$. Enter these values and press 'Calculate'. All properties at state 1 are presented immediately:



Fig. 3.37a. Properties of H2O with TEST – state 1

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We get mass, $m_1 = 5.65329$ kg, enthalpy $h_1 = 2625.9255$ kJ/kg.

Now, some steam is blown off at constant enthalpy, till the pressure becomes 6 bar. i.e. at state 2, $P_2 = 6$ bar, $h_2 = h_1$, and vessel volume remains same as Vol_1 . Enter these values for state 2. Click on 'Calculate'. We get:

Property	Value	Unit
p_2	6.0	bar
T_2	158.85	deg-C
x_2	0.93727	fraction
y_2	0.99977	fraction
v_2	0.29594	m ³ /kg
u_2	2448.3635	kJ/kg
h_2	=h ₁	kJ/kg
s_2	6.45708	kJ/kg.K
Vel_2	0.0	m/s
z_2	0.0	m
e_2	2448.3635	kJ/kg
j_2	2625.9255	kJ/kg
ϕ_2		kJ/kg
ψ_2		kJ/kg
m_2	2.87224	kg
Vol_2	=Vol ₁	m ³
MM_2	18.0	kg/kmol

Fig. 3.37b. Properties of H2O with TEST – state 2

Now, we note that the mass m_2 in the vessel is $m_2 = 2.87224$ kg.

Now, the vessel is cooled at constant volume Vol_1 until the pressure is 4 bar; this is state 3. So, select state 3 and enter $P_3 = 4$ bar, $Vol_3 = Vol_1$, $m_3 = m_2$; click on 'Calculate'. Properties at state 3 are presented:

Property	Value	Unit
p_3	4.0	bar
T_3	143.61063	deg-C
x_3	0.6385	fraction
y_3	0.99868	fraction
v_3	0.29594	m ³ /kg
u_3	1848.8472	kJ/kg
h_3	1967.1146	kJ/kg
s_3	5.04547	kJ/kg.K
Vel_3	0.0	m/s
z_3	0.0	m
e_3	1848.8472	kJ/kg
j_3	1967.1146	kJ/kg
ϕ_3		kJ/kg
ψ_3		kJ/kg
m_3	=m ₂	kg
Vol_3	=Vol ₁	m ³
MM_3	18.0	kg/kmol

Fig. 3.37c. Properties of H2O with TEST – state 3

Note from the above that steam quality, $x_3 = 0.6385$. Therefore, we have the results:

- Quantity of steam blown off = $(m_1 - m_2) = 2.781$ kg.
- Quality of steam in the vessel after cooling = $x_3 = 0.6385$
- Quantity of steam in the vessel after cooling = $x_3 \cdot m_3 = 1.834$ kg of dry steam

The entire process can be shown on a h-T diagram by selecting the h-T plot in TEST as shown below. In the plot: 1–2 is blowing off at constant enthalpy and 2–3 is cooling at constant volume.

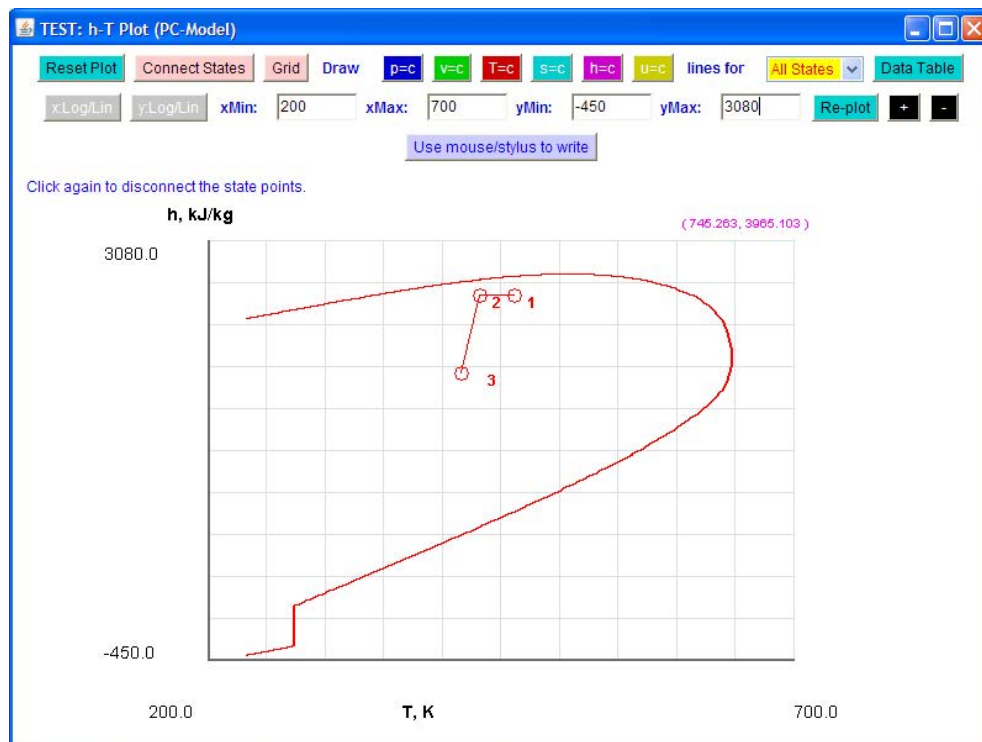


Fig. 3.37d. Properties of H₂O with TEST – (h-T) plot

Problem 3.8: A rigid tank of 2 m³ volume is filled with dry sat. steam at 0.2 MPa. Owing to poor insulation of the tank, the pressure of steam is found to be 0.1 MPa after some time. Determine the final state of the steam and the amount of energy transferred as heat to the surroundings. [VTU, 2001]

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at $P_1 = 0.2$ MPa, $\text{Vol}_1 = 2.0$ m³, $x_1 = 1$, since dry saturated. Enter these values and press 'Calculate'. All properties at state 1 are presented immediately:

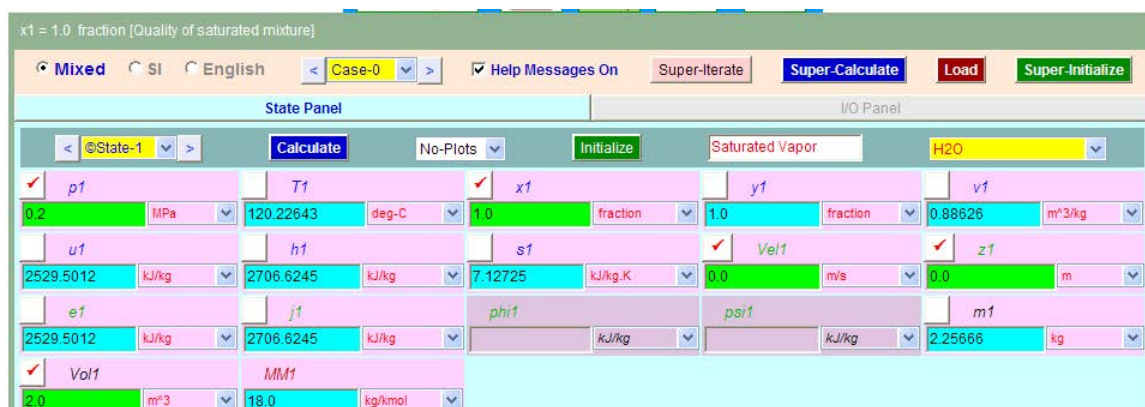


Fig. 3.38a. Properties of H₂O with TEST – state 1

Note that mass of steam, $m_1 = 2.25666$ kg, and internal energy of steam, $u_1 = 2529.5012$ kJ/kg.

Now, select state 2, and enter the known conditions, i.e. $Vol_2 = Vol_1$, $m_2 = m_1$ and $P_2 = 0.1$ MPa. Click on 'Calculate'. We get:

The screenshot shows the TEST software interface for H2O. The State Panel is active, and the 'Calculate' button has been clicked. The properties for state 2 are displayed as follows:

Property	Value	Unit
p_2	0.1	MPa
T_2	99.61999	deg-C
x_2	0.52288	fraction
y_2	0.99944	fraction
v_2	0.88626	m^3/kg
u_2	1509.4971	kJ/kg
h_2	1598.1234	kJ/kg
s_2	4.46951	kJ/kg.K
Vel_2	0.0	m/s
z_2	0.0	m
e_2	1509.4971	kJ/kg
j_2	1598.1234	kJ/kg
ϕ_2	0.0	
ψ_2	0.0	
m_2	$=m_1$	kg
Vol_2	$=Vol_1$	m^3
MM_2	18.0	kg/kmol

Fig. 3.38b. Properties of H2O with TEST – state 2

We read: $u_2 = 1509.4971$ kJ/kg. and quality, $x_2 = 0.52288$. Energy transferred to surroundings = $m.(u_2 - u_1) = -2.25666$ kg x 1020 kJ/kg = -2301.79 kJ. (-ve sign indicates that heat is rejected.)

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Finally, the process can be shown on (T-v) plot as shown below:

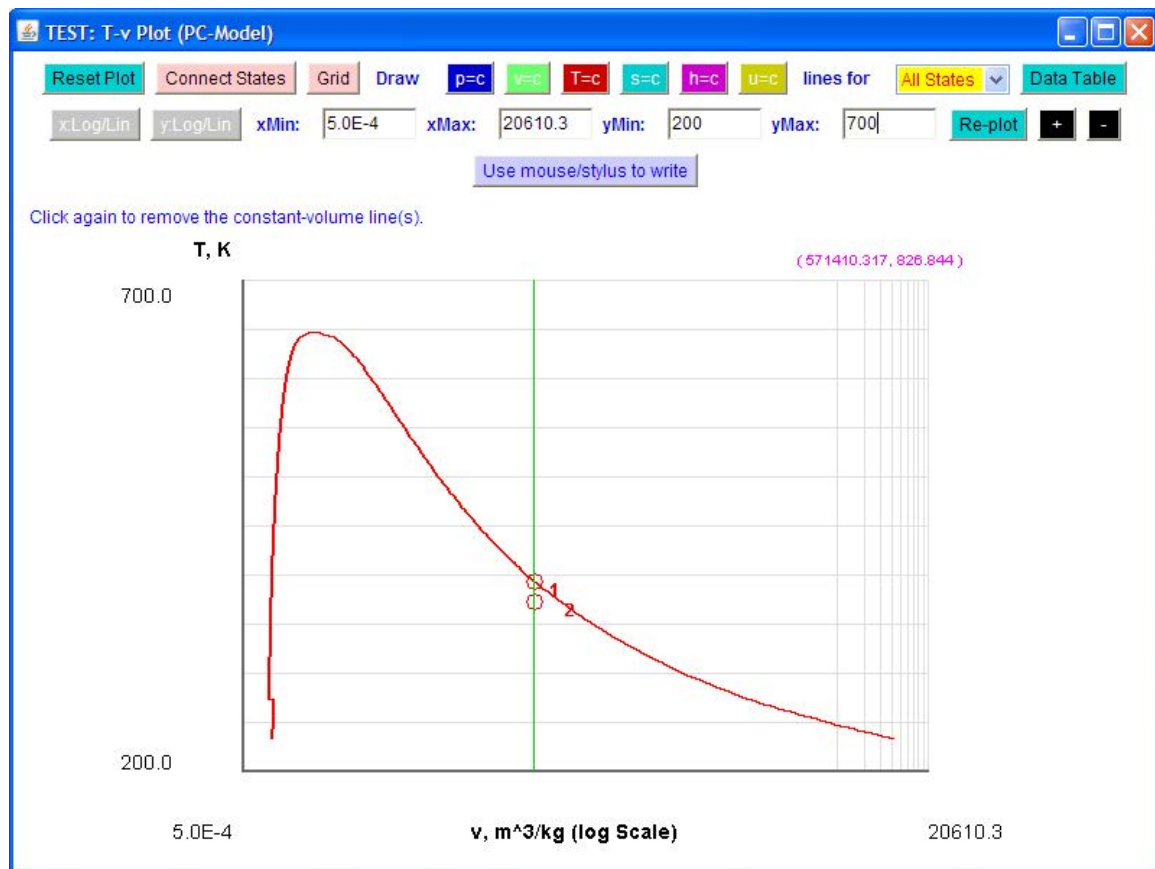


Fig. 3.38c. Properties of H₂O with TEST – (T-v) plot

Problem 3.9: Two boilers, one with a super-heater and the other without superheater, are delivering equal quantities of steam into a common main. The pressure in the boiler and main is 20 bar. The temperature of steam from the boiler with super-heater is 350 deg.C and temperature of steam in the main is 250 deg.C. Determine the quality of steam supplied by the other boiler. Take $c_{p,s} = 2.25 \text{ kJ/kg.C}$[VTU, 2001]

Solution: First, let us solve this problem with EES.

Let 1, 2, 3 denote boiler without super-heater, boiler with super-heater and the main.

In Equation window of EES, enter the following code. Read the explanatory comments against each equation:

```

EES Equations Window
"Prob. 3.9"
"data:"
m1=1.0"kg...mass of steam from boiler without superheater...assumed"
m2=m1"kg...mass of steam from boiler with superheater.."
m3=m1+m2"kg...total mass of steam in the main"
p1=2000"kPa...pr. in the boilers and main"
T2=350"C...temp. of steam from boiler B2, i.e. boiler with superheater"
T_m=250"C...temp. of steam in the main"
cps=2.25"kJ/kg.C...sp. heat of superheated steam"
"_____ "
h_g2=enthalpy(Steam_IAPWS,P=p1,x=1)"enth. of sat. steam from boiler B2"
T_s2=T_sat(Steam_IAPWS,P=p1)"C...sat. temp. at B2"
h2=h_g2+cps*(T2-T_s2)"kJ/kg..enth. of steam from B2"
"Note: We could have found out h2 by directly plugging in the values of P2 = p1, and T2 = 350C;
but, since value of cps was given, above eqn for h2 is used."
h_f1=enthalpy(Steam_IAPWS,P=p1,x=0)"kJ/kg..sat. liq. enthalpy from boiler B1"
h_g1=enthalpy(Steam_IAPWS,P=p1,x=1)"kJ/kg..sat. vap. enthalpy from boiler B1"
h1=h_f1+x1*(h_g1-h_f1)"kJ/kg...enth. of steam from boiler B1, with dryness x1, to be found"
"Energy balance:"
h_g3=h_g2"...since the pressures are same"
h3=h_g3+cps*(T_m-T_s2)"kJ/kg...Ts2=sat. temp. in the main "
"Therefore:"
m1*h1+m2*h2=m3*h3"...energy balance...gives x1"

```

Fig. 3.39a. Properties of H₂O with EES

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...I finally learned to speak it in just six lessons"

Jane, Chinese architect

ENGLISH OUT THERE

Click to hear me talking before and after my unique course download



Now, press F2 to get solution:

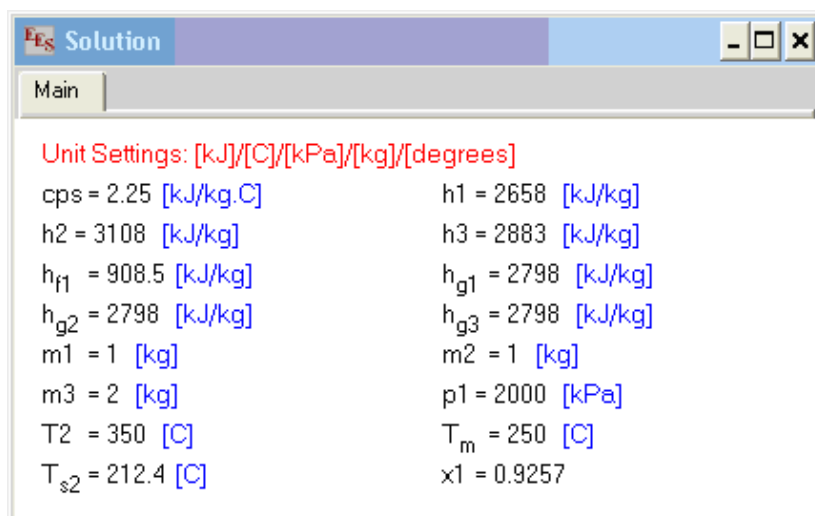


Fig. 3.39b. Solution with EES

It may be observed from the solution that quality of steam supplied by boiler-1 is 0.9257.

Now, let us verify this solution with TEST:

Open TEST, Click Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at P1 = 20 bar, m1 = 1 kg, x1 = to be determined. Temperature T1 is also not known. However, from energy balance, we have:

$$m1 \cdot h1 + m2 \cdot h2 = m3 \cdot h3$$

$$\text{i.e. } h1 = \frac{(m3 \cdot h3 - m2 \cdot h2)}{m1}$$

Enter these values for P1, m1 and h1, and press 'Calculate'. We see that all properties can not be calculated at this stage:



Fig. 3.40a. Solution with TEST-state 1

However, we proceed to states 2 and 3 and ‘Supercalculate’ and TEST will refer back to state 1 and calculate properties at state 1 at that stage.

For state 2, we have: $P_2 = 20$ bar, $T_2 = 350$ C, $m_2 = m_1$. Enter these values and click on ‘Calculate’. We get:

Fig. 3.40b. Solution with TEST-state 2

Next, for state 3 (i.e. Steam main), $P_3 = P_1$, $T_3 = 250$ C, $m_3 = (m_1 + m_2)$. Enter these values and press ‘Calculate’. We get:

Fig. 3.40c. Solution with TEST-state 3

Now, click 'Supercalculate': Go to state 1 and following screen appears for state1:

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

Mixed SI English Case-0 Help Messages On Super-Iterate Super-Calculate Load Super-Initialize

State Panel I/O Panel

State-1 Calculate No-Plots Initialize Saturated Mixture H2O

p_1	T_1	x_1	y_1	v_1
2000 bar	212.42111 deg.C	0.93043 fraction	0.99912 fraction	0.09276 m³/kg
u_1	h_1	s_1	Vel_1	z_1
2482.4153 kJ/kg	2482.4153 kJ/kg	6.06998 kJ/kg.K	0.0 m/s	0.0 m
e_1	j_1	ϕ_1	ψ_1	m_1
2482.4153 kJ/kg	2667.9282 kJ/kg			1.0 kg
Vol_1	MM_1			
0.09276 m³	18.0 kg/kmol			

Fig. 3.40d. Solution with TEST-state 1

It may be seen that quality of steam supplied by the boiler with no super-heater is: $x_1 = 0.93043$.

'Supercalculate' also generates TEST code which can be copied to a MS Word file and used to regenerate the results at a later date if required, and also a property table. The property table from the TEST report is reproduced below:

-----Property spreadsheet starts: The following property table can be copied onto a spreadsheet (such as Excel) for further analysis or plots.-----

# State	p(kPa)	T(K)	x	v(m³/kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg)
# 01	2000.0	485.6	0.9	0.0928	2482.42	2667.93	6.07
# 02	2000.0	623.2		0.1386	2859.8	3136.94	6.956
# 03	2000.0	523.2		0.1114	2679.56	2902.43	6.545

Fig. 3.40e. Solution with TEST- property table

Problem 3.10: Temperature of feed water entering a boiler is 50 deg.C and the pressure of steam in the boiler is 13 bar. How much heat will be required to produce one kg of steam if the steam produced is:

- 0.97 dry
- Dry saturated
- Superheated with 40 deg.C of superheat

Take c_p for superheated steam as 2.1 kJ/kg.C and c_p of water as 4.187 kJ/kg.C ...[VTU, 2000]

Solution: First, let us solve this problem with Mathcad. In Mathcad, there are no built-in properties for steam. So, we will get the steam properties from 'SteamTab companion' and use them in Mathcad for further calculations. Mathcad worksheet is shown below:

Let h_1 = enthalpy of feed water at 50 C and 13 bar,

h_2 = enthalpy of 0.97 dry steam

h_3 = enthalpy of dry sat. steam

h_4 = enthalpy of superheated steam with 40 deg. C superheat



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Get h1: Entering the values of P and T in SteamTab companion and click 'Calculate'. We get:

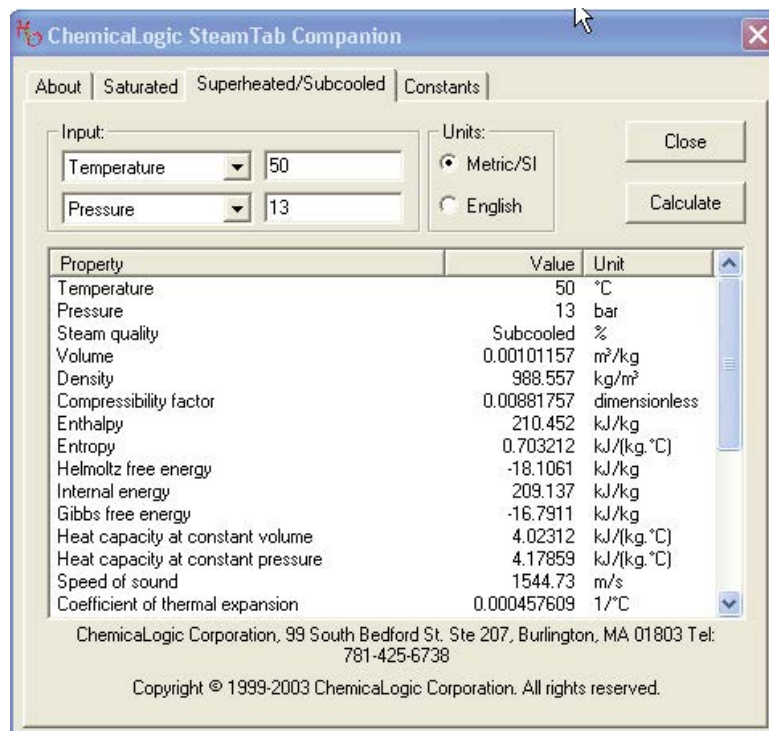


Fig. 3.41a. Solution with Mathcad & SteamTab companion

i.e. $h_1 = 210.452 \text{ kJ/kg}$

Next, to get h2: In SteamTab companion, click on 'Saturated' tab; choose Pressure as 13 bar, select 'Two phase' and enter 0.97 (for dryness fraction value), and click 'Calculate'. We get:

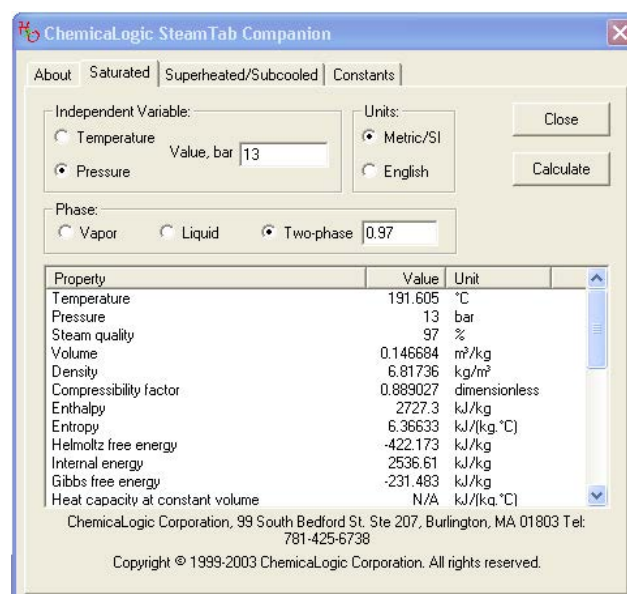


Fig. 3.41b. Solution with Mathcad & SteamTab companion

i.e. $h_2 := 2727.3 \text{ kJ/kg}$

Next, to get h_3 : This is equal to enthalpy of dry sat. steam at 13 bar. So, in the above screen, choose 'Vapor' and click 'Calculate' as shown below:

ChemicalLogic SteamTab Companion

About Saturated Superheated/Subcooled Constants

Independent Variable:
☐ Temperature
☒ Pressure Value, bar: 13

Units:
☒ Metric/SI
☐ English

Phase:
☒ Vapor ☐ Liquid ☐ Two-phase 0.97

Close Calculate

Property	Value	Unit
Temperature	191.605	°C
Pressure	13	bar
Steam quality	100	%
Volume	0.151186	m³/kg
Density	6.61438	kg/m³
Compressibility factor	0.916308	dimensionless
Enthalpy	2786.46	kJ/kg
Entropy	6.49362	kJ/(kg·°C)
Helmoltz free energy	-428.024	kJ/kg
Internal energy	2589.92	kJ/kg
Gibbs free energy	-231.483	kJ/kg
Heat capacity at constant volume	2.00678	kJ/(kg·°C)

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i.e. $h_3 := 2786.46 \quad \text{kJ/kg}$

Next, to get h_4 : This is equal to enthalpy of dry sat. steam at 13 bar plus $c_p \Delta T$. So, we calculate h_4 as follows:

$h_4 := h_3 + 2.1 \cdot 40$ i.e. $h_4 = 2.87 \cdot 10^3 \quad \text{kJ/kg}$

Now, we get the results:

$Q_1 := h_2 - h_1$...Amount of heat reqd to get steam 0.97 dry

i.e. $Q_1 = 2.517 \cdot 10^3 \quad \text{kJ/kg}$

$Q_2 := h_3 - h_1$...Amount of heat reqd to get dry steam

i.e. $Q_2 = 2.576 \cdot 10^3 \quad \text{kJ/kg}$

$Q_3 := h_4 - h_1$...Amount of heat reqd to get superheated steam with 40 deg. superheat

i.e. $Q_3 = 2.66 \cdot 10^3 \quad \text{kJ/kg}$

Alternatively:

Let us demonstrate this calculation in **MS Excel spreadsheet**.

Free Steam properties Add-in is available for Excel (i.e. Water97_v13.xla – Excel Add-In for Properties of Water and Steam in SI-Units, authored by Bernhard Spang, Hamburg, Germany, Ref: <http://www.cheresources.com/staff.shtml>).

The file Water97_v13.xla is put in the Add-In directory in Excel and is then available as a set of built-in functions.

Open Excel and first calculate h_1 . To calculate h_1 , we have to choose the relevant function from Add-in directory. Go to Excel > Insert > function and select 'User defined' category. Steam functions are presented. Select EnthalpyW and click OK. Enter values of T (in Kelvin) and P (in bar) as shown. Immediately, the result appears. You get:

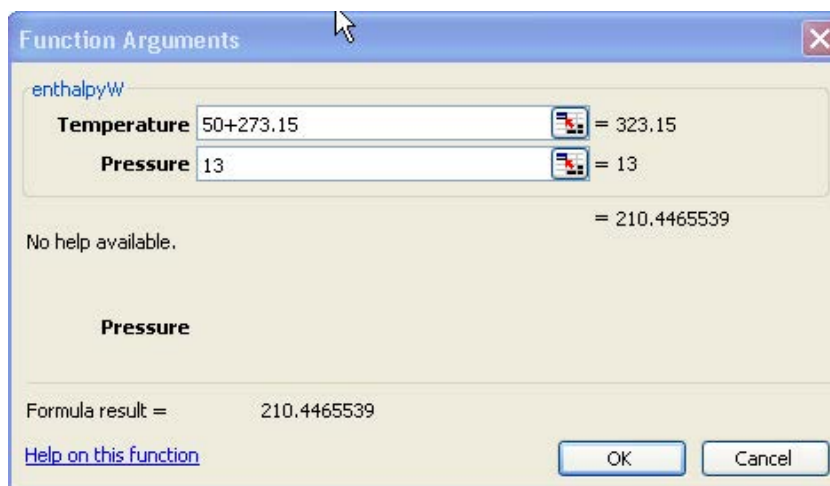


Fig. 3.41d. Solution with Excel

Now, click OK and the value is transferred to the cell in the worksheet:

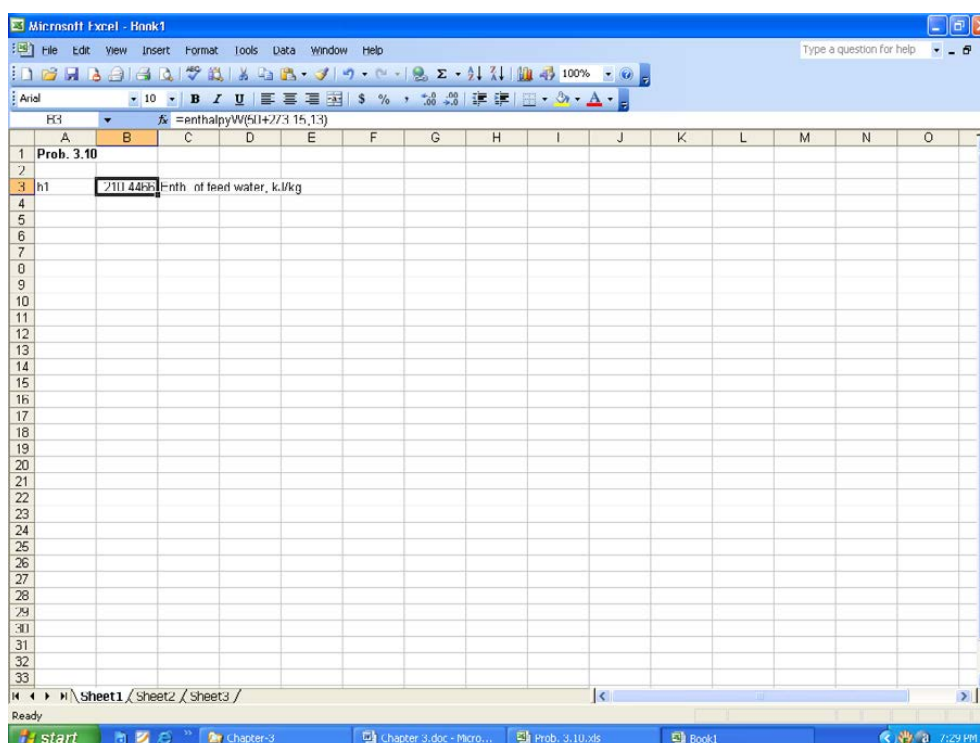


Fig. 3.41e. Solution with Excel

In a similar manner, calculate other values:

Microsoft Excel - Prob. 3.10.xls

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2		Prob. 3.10										
3												
4		h1	210.4466	Enth. of feed water, kJ/kg								
5												
6		hf2	814.7637	Enth. of sat. water at 13 bar, kJ/kg								
7												
8		hg2	2786.493	Enth. of sat. vap at 13 bar, kJ/kg								
9												
10		h2	2727.341	Enth. of wet steam with x = 0.97, kJ/kg								
11												
12		h3	2786.493	Enth. of dry sat. vap, kJ/kg								
13												
14		h4	2870.493	Enth. of super heated steam, 40 C degree of superheat, kJ/kg								
15												
16		Q1	2516.895	kJ/kg....amt of heat reqd to get 0.97 dry steam								
17												
18		Q2	2576.047	kJ/kg....amt of heat reqd to get dry steam								
19												
20		Q3	2660.047	kJ/kg....amt of heat reqd to get superheated steam								
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												
31												
32												
33												

Fig. 3.41f. Solution with Excel

Note that values for Q1, Q2, Q3 obtained by Mathcad and Excel agree.

3.6 Determination of 'quality' (or dryness fraction) of wet steam:

3.6.1 Throttling calorimeter:

Here, wet steam from the steam mains (state 1) is throttled in a throttling valve in such a way that the final state 2 is in the super-heated region. Throttling is a constant enthalpy process. In state 1, P and T are interdependent; so, P₁ is measured. In state 2, both P₂ and T₂ are measured. See fig. 3.44a and 3.44b. Then, h₂ can easily be calculated (or found out from steam tables). Since h₁ = h₂, we can write:

$$h_1 = h_{f1} + x_1 \cdot h_{fg1}$$

$$\text{i.e. } h_1 = h_{f1} + x_1 \cdot (h_{g1} - h_{f1}) \quad \dots(3.9)$$

$$\text{and, } x_1 = \frac{h_1 - h_{f1}}{h_{g1} - h_{f1}} \quad \dots(3.10)$$

Knowing P₁, sat. liq. enthalpy h_{f1} and sat. vap. enthalpy h_{g1} are easily determined and thus the quality of steam in the mains, x₁ is determined.



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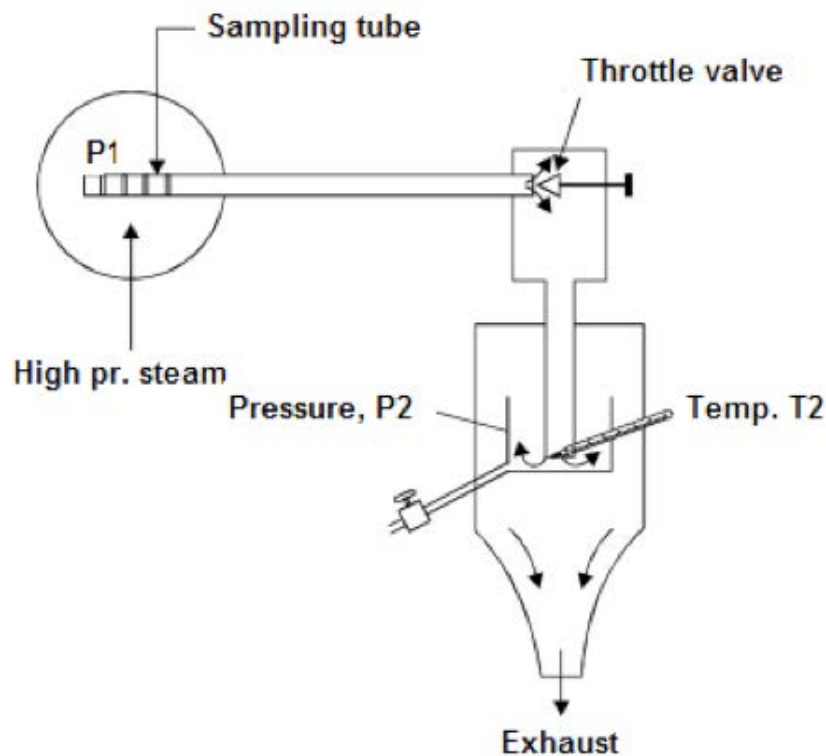


Fig. 3.42a. Throttling calorimeter

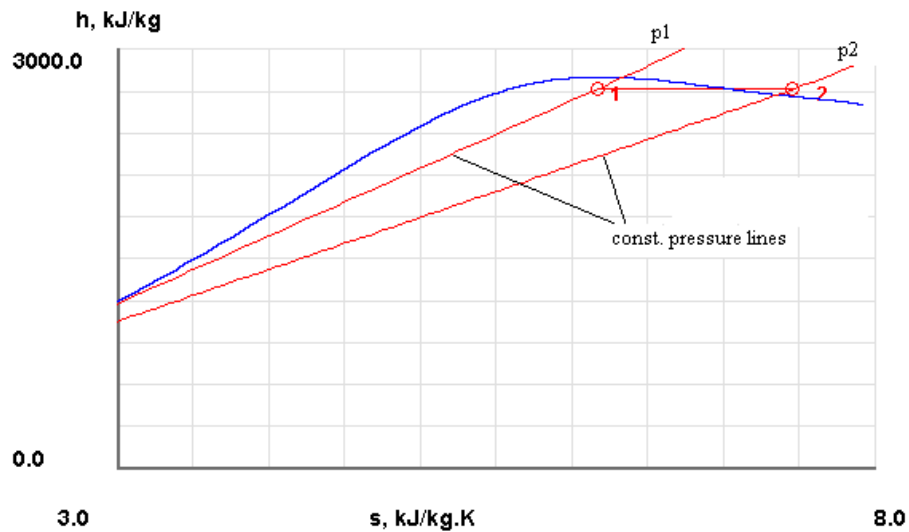


Fig. 3.42b. (h-s) diagram for Throttling calorimeter (from TEST)

Problem 3.11: In a throttling calorimeter, pressure in the steam mains is 20 bar and the pressure and temperature after throttling are 1 bar and 125 C. What is the quality of steam in the mains?

Solution: This problem is worked out easily using TEST.

Go to TEST > Map > Uniform system > Phase Change model. (See Figs. 3.18a and 3.18b.). State 1 is at $P_1 = 20$ bar, $x_1 =$ to be determined. Temperature T_1 is also not known. However, we know $h_1 = h_2$, where h_2 will be determined later. So, enter the value of P_1 and for h_1 enter $h_1 = h_2$. Click 'Calculate'. We see that all properties can not be calculated at this stage. We get:

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

Mixed SI English Case-0 Help Messages On Super-Iterate Super-Calculate Load Super-Initialize

State Panel I/O Panel

< @State-1 > Calculate No-Plots Initialize Unknown Phase H2O

p_1 20.0 bar	T_1 deg-C	x_1 fraction	y_1 fraction	v_1 m ³ /kg
u_1 kJ/kg	h_1 =h2 kJ/kg	s_1 kJ/kg.K	Vel_1 0.0 m/s	z_1 0.0 m
e_1 kJ/kg	j_1 kJ/kg	ϕ_1 kJ/kg	ψ_1 kJ/kg	m_1 kg
Vol_1 m ³	MM_1 kg/kmol			

Fig. 3.43a. Throttling calorimeter – properties at state 1 (from TEST)

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Next, we proceed to state 2. Enter values of P_2 and T_2 . Click 'Calculate'. Properties at state2 are immediately calculated.

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

Mixed SI English Case-0 Help Messages On Super-Iterate Super-Calculate Load Super-Initialize

State Panel I/O Panel

State-2 Calculate No-Plots Initialize Superheated Vapor H2O

p_2	T_2	x_2	y_2	v_2
1.0 bar	125.0 deg-C	0.96129 fraction	0.99952 fraction	0.0958 m ³ /kg
u_2	h_2	s_2	Vel_2	z_2
2544.6836 kJ/kg	2726.2905 kJ/kg	7.48723 kJ/kg.K	0.0 m/s	0.0 m
e_2	j_2	ϕ_2	ψ_2	m_2
2544.6836 kJ/kg	2726.2905 kJ/kg	0.0 kJ/kg	0.0 kJ/kg	0.0 kg
Vol_2	MM_2			
0.0 m ³	18.0 kg/kmol			

Fig. 3.43b. Throttling calorimeter – properties at state 2 (from TEST)

Now, click on 'Supercalculate' and TEST refers back to state 1 with $h_1 = h_2$, and calculates all properties. Now, if we go back to state 1, we see:

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

Mixed SI English Case-0 Help Messages On Super-Iterate Super-Calculate Load Super-Initialize

State Panel I/O Panel

State-1 Calculate No-Plots Initialize Saturated Mixture H2O

p_1	T_1	x_1	y_1	v_1
20.0 bar	212.42111 deg-C	0.96129 fraction	0.99952 fraction	0.0958 m ³ /kg
u_1	h_1	s_1	Vel_1	z_1
2534.7007 kJ/kg	2726.2905 kJ/kg	6.19017 kJ/kg.K	0.0 m/s	0.0 m
e_1	j_1	ϕ_1	ψ_1	m_1
2534.7007 kJ/kg	2726.2905 kJ/kg	0.0 kJ/kg	0.0 kJ/kg	0.0 kg
Vol_1	MM_1			
0.0 m ³	18.0 kg/kmol			

Fig. 3.43c. Throttling calorimeter properties at state 1 (from TEST)

Observe that $h_1 = h_2 = 2726.29$ and x_1 , the quality of steam in the steam mains, is 0.961.

(h-s) plot for this throttling calorimeter is shown below:

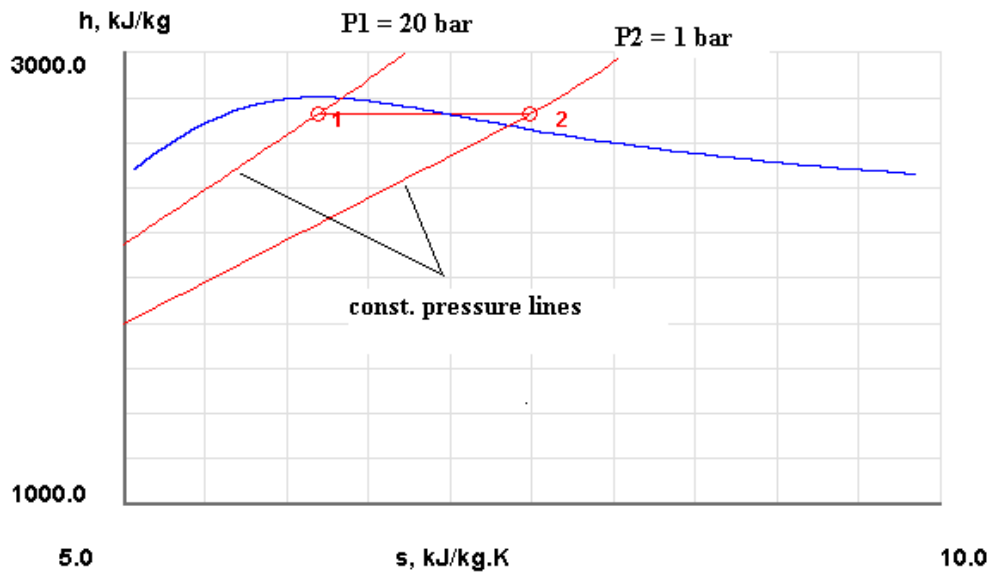


Fig. 3.43d. Throttling calorimeter – (h-s) plot from TEST

Note: While using throttling calorimeter, it is important that the exit state 2 is in the super-heated region. Also, at least 5 deg. Superheat must be provided in state 2. Then, if the exit P_2 is 1 bar (with $T_{sat} = 99.61$ C), T_2 should be, say, 105 C. Now, if the inlet pressure from mains, P_1 is 20 bar, we see by a similar calculation in TEST that max. dryness fraction that can be measured with the throttling calorimeter is 0.94.

3.6.2 Separating and Throttling calorimeter:

If the steam in the mains is very wet, i.e. by throttling the state 2 does not reach superheated region, we use a Separating and Throttling calorimeter, where excess water is separated in the separating section and the wet steam is then throttled in a throttle valve (TV) in the throttling section. See fig. below. Pressures P_1 , P_2 , P_3 and temperature T_3 are measured. Also, the moisture separated out in the separating calorimeter, m_s , is measured; steam after throttling is condensed and this amount, m_c , is also measured.

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(h-s) plot for this case of separating and throttling calorimeter is shown below:

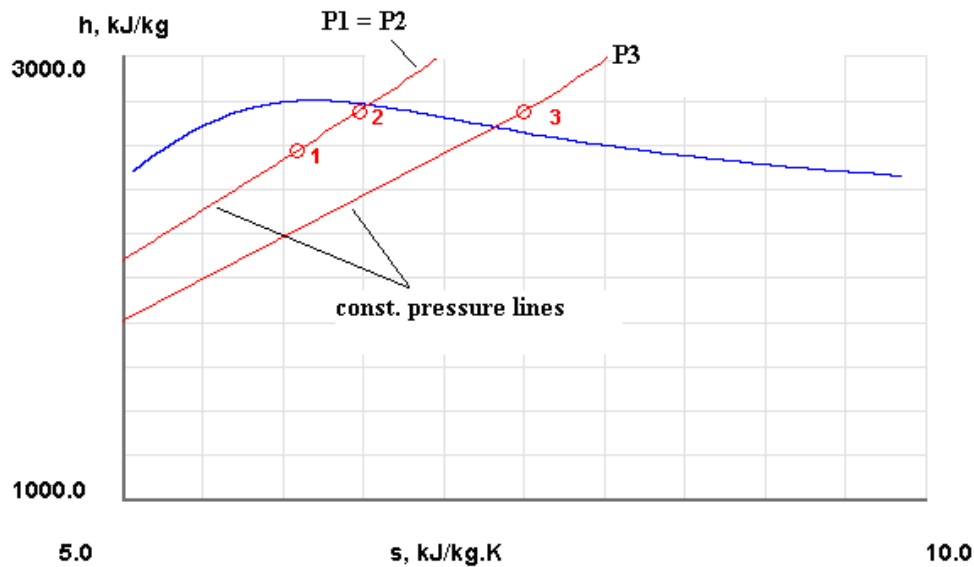


Fig. 3.44b. Separating and Throttling calorimeter-(h-s) plot from TEST

Then, since P_3 , T_3 are measured, h_3 can be calculated. Also, $h_2 = h_3$ for throttling. Further,

$$h_2 = h_f + x_2 (h_{g2} - h_f)$$

i.e. $x_2 = \frac{h_2 - h_f}{h_{g2} - h_f}$... (3.11)

Therefore, x_2 can be calculated. Then, $x_2 m_c$ = amount of dry steam at state 2. This must also be the amount of dry steam at state 1. Therefore, quality of steam at state 1 is calculated as:

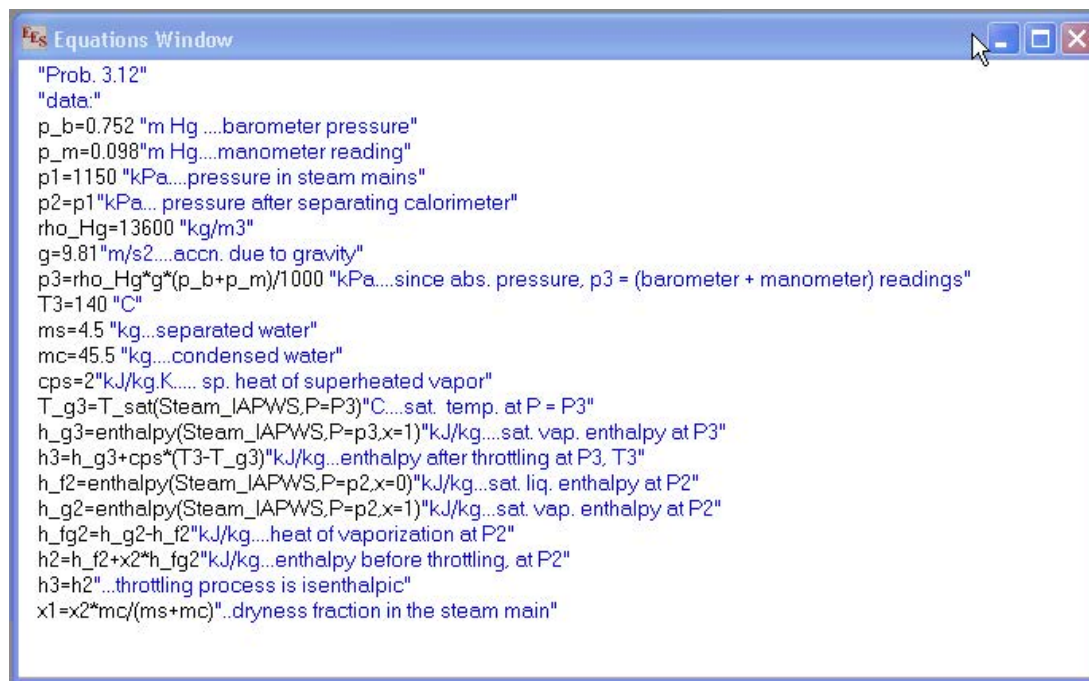
$$x_1 = \frac{x_2 m_c}{m_s + m_c} \quad \dots (3.12)$$

Problem 3.12: In a test conducted to determine the dryness fraction of steam using combined separating and throttling calorimeter, following observations were recorded:

Water collected in separating calorimeter = 4.5 kg; steam condensed after throttling = 45.5 kg; Initial pressure of steam = 11.5 bar; temp. of steam after throttling = 140 C; manometer reading = 98 mm Hg; barometer reading = 752 mm Hg. Estimate the dryness fraction of steam as it enters the throttling calorimeter. Also, determine the dryness fraction of steam entering the separating calorimeter. Take c_p for superheated steam as 2.0 kJ/kg.K....[VTU, 2005]

Solution:

We shall solve this problem in EES. In the Eqns. Window of EES, enter the code as shown below. Read the explanatory comments given in each line.

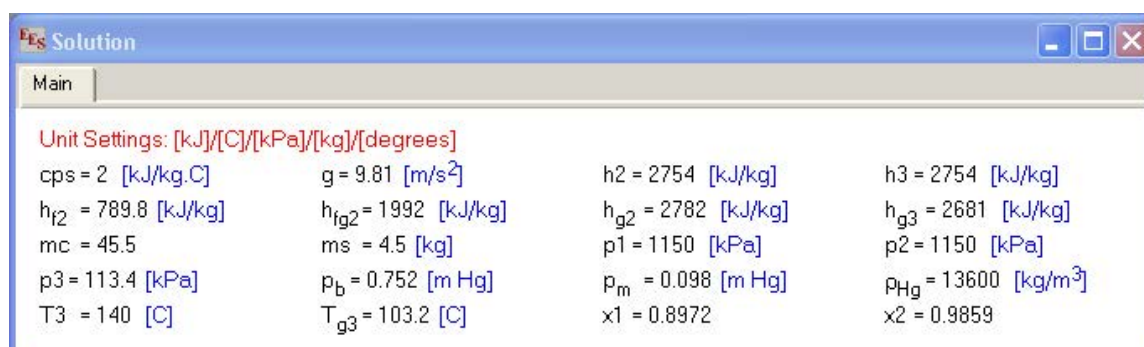


```

"Prob. 3.12"
"data:"
p_b=0.752 "m Hg ....barometer pressure"
p_m=0.098 "m Hg....manometer reading"
p1=1150 "kPa....pressure in steam mains"
p2=p1 "kPa... pressure after separating calorimeter"
rho_Hg=13600 "kg/m3"
g=9.81 "m/s2....accn. due to gravity"
p3=rho_Hg*(p_b+p_m)/1000 "kPa....since abs. pressure, p3 = (barometer + manometer) readings"
T3=140 "C"
ms=4.5 "kg...separated water"
mc=45.5 "kg....condensed water"
cps=2 "kJ/kg.K..... sp. heat of superheated vapor"
T_g3=T_sat(Steam_IAPWS,P=p3)"C....sat. temp. at P = P3"
h_g3=enthalpy(Steam_IAPWS,P=p3,x=1)"kJ/kg....sat. vap. enthalpy at P3"
h3=h_g3+cps*(T3-T_g3)"kJ/kg...enthalpy after throttling at P3, T3"
h_f2=enthalpy(Steam_IAPWS,P=p2,x=0)"kJ/kg...sat. liq. enthalpy at P2"
h_g2=enthalpy(Steam_IAPWS,P=p2,x=1)"kJ/kg...sat. vap. enthalpy at P2"
h_fg2=h_g2-h_f2"kJ/kg....heat of vaporization at P2"
h2=h_f2+x2*h_fg2"kJ/kg...enthalpy before throttling, at P2"
h3=h2"...throttling process is isenthalpic"
x1=x2*mc/(ms+mc)"...dryness fraction in the steam main"
  
```

Fig. 3.45a. Separating and Throttling calorimeter-EES code

Now, press F2 to get the solution:



Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]			
cps = 2 [kJ/kg.C]	g = 9.81 [m/s ²]	h2 = 2754 [kJ/kg]	h3 = 2754 [kJ/kg]
h_f2 = 789.8 [kJ/kg]	h_fg2 = 1992 [kJ/kg]	h_g2 = 2782 [kJ/kg]	h_g3 = 2681 [kJ/kg]
mc = 45.5	ms = 4.5 [kg]	p1 = 1150 [kPa]	p2 = 1150 [kPa]
p3 = 113.4 [kPa]	p_b = 0.752 [m Hg]	p_m = 0.098 [m Hg]	ρ _{Hg} = 13600 [kg/m ³]
T3 = 140 [C]	T_g3 = 103.2 [C]	x1 = 0.8972	x2 = 0.9859

Fig. 3.45b. Separating and Throttling calorimeter-Solution from EES

It may be observed that dryness fraction of steam entering the throttling calorimeter = $x_2 = 0.9859$ and dryness fraction of steam entering the separating calorimeter (i.e. in the steam mains) = $x_1 = 0.8972$. (h-s) plot for this case is shown below:

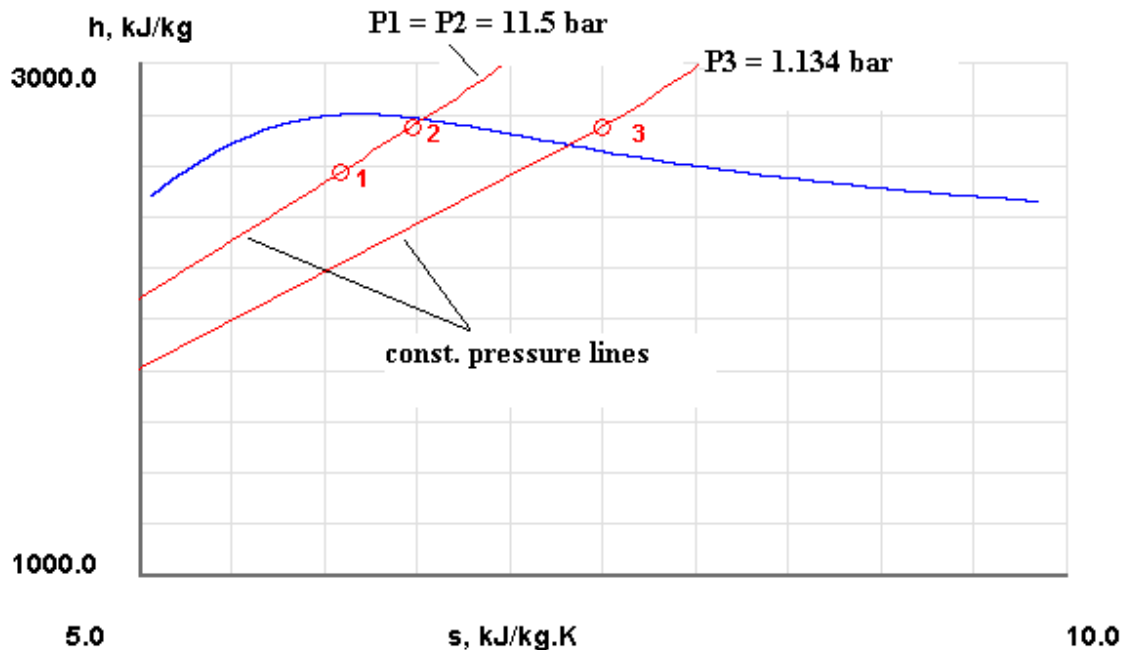


Fig. 3.45c. Separating and Throttling calorimeter-(h-s) plot from TEST

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3.7 Conclusion:

In this chapter, we studied about pure fluids. Various property diagrams were explained, with particular reference to water. Use of software to plot property diagrams for different substances was demonstrated. Methods of finding out property values and generating property tables were also shown using different software. Determination of dryness fraction (or quality) of steam with 'throttling calorimeter' as well as 'separating and throttling calorimeter' was explained.

3.8 References:

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15. www.spreadsheetworld.com ((for free Excel Add-In: XLThermalFluids which gives values of P, v, T, s, u, h and x for 37 common fluids)

3.9 Exercise Problems:

1. A 200-m³ rigid tank is filled with saturated liquid-vapor mixture of water at 125°C. If 25% of the mass is liquid and the 75% of the mass is vapor, find out the total mass in the tank.
2. Water is boiled at 300 kPa pressure in a pressure cooker. The cooker initially contains 2.5 kg of water. Once boiling started, it is observed that half of the water in the cooker evaporated in 20 minutes. If the heat loss from the cooker is negligible, find the average rate of energy transfer to the cooker.
3. A 0.25-m³ rigid tank contains 8.5 kg of water (in any phase or phases) at 500 kPa. Find the temperature in the tank.
4. A rigid tank contains 0.7 kg of steam at 9 MPa and 300°C. What is the volume of the tank?

5. Fill up the following Table:

Fluid	P(kPa)	T(deg.C)	v(m ³ /kg)	x	Phase
R-22	100	-25			
H ₂ O		120	0.5		
H ₂ O	100		1.8		
NH ₃	100	20			
R-134a		50		0.8	
R-134a			0.005	0.5	
R-12	350		0.036		
N ₂	100	-75			
R-22		50	0.05		
NH ₃	550		0.31		

- A rigid vessel has a volume of 0.01 m³ and contains 4 kg of water at 40 deg. C. Calculate the quality and masses of liquid and vapor.
- A pressure cooker contains 1.5 kg of sat. steam at 5 bar pressure. Find the quantity of heat which must be rejected so that the quality of steam becomes 0.6 dry. Determine the pressure and temperature at new state.
- The dryness fraction of steam at a pressure of 22 bar is measured with a throttling calorimeter. After throttling, pressure in the calorimeter is 13 bar and the temperature is 115 C. Find the dryness fraction of steam entering the calorimeter.
- What is the dryness fraction that can theoretically be determined in a throttling calorimeter if the steam to be tested is at a pressure of 15 bar and the pressure after throttling is 1.1 bar, with 5 degree C superheat?
- Following data are obtained with a separating and throttling calorimeter:
Pressure in the mains: 15 bar; condition after throttling: 1 bar, 115 degree C; Moisture collected in the separator in 5 min: 155 cm³ at 70 degree C; steam condensed after throttling, in 5 min: 3.2 kg. Find the quality of steam in the mains.

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