INTERACTIVE GRAPHIC DEPICTION OF WORKING FLUID THERMAL PROPERTIES USING SPREADSHEETS

Michael Maixner, U.S. Air Force Academy

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Abstract

An interactive method for using spreadsheets to calculate and graphically display the properties of various thermodynamic working fluids is presented; the detailed calculation of individual property values is accomplished via Thermal Fluids Toolbox, a freeware program provided by Spreadsheet World, Inc. Interface with the cells containing calls to Thermal Fluids Toolbox is provided with Visual Basic for Applications sliding toolbars which allow a smooth variation of property values. Properly used by students, these worksheets have the potential to reinforce and enhance understanding of the fundamental interrelationships among various properties; students are free to change various parameters such as pressure, temperature, and quality, and immediately view the effect of these changes on the associated Mollier and T-s diagrams. Students may quickly visualize the effect of these changes, rather than being mired in the minutiae of table lookups, interpolation, transcription, and manual plotting. An additional benefit of the rapid and very accurate plotting of thermodynamic properties is a better understanding of approximations frequently employed in the compressed liquid region, wherein the effect of pressure may be neglected (i.e., properties may be evaluated principally as functions of temperature); the relationship between saturation pressure and saturation temperature is also immediately discernable, as well as property variations in the compressed liquid and superheated vapor regions. In addition to the dynamic visualization of the Mollier and T-s diagrams, students may be tasked to use the worksheet to construct their own Mollier and T-s diagrams for prescribed property values using a “copy and paste” technique. A detailed description of the spreadsheet construction for Mollier and T-s diagrams for water is provided, along with suggested tutorial questions for students and recommendations for additional applications. Feedback comments are provided from seniors who used the Mollier and T-s diagrams, and from juniors who used a similar application which provided a tutorial on p-v and T-v diagrams. Several screen shots of the worksheets are provided. The spreadsheet files are available from the author via email.

Introduction

To the budding thermodynamics student, nothing can be quite as daunting as the initial exposure to the property tables for gases and (even more so) two-phase fluids. Many undergraduates, even at the end of their careers as mechanical engineering degree candidates, are uncertain of the relationships between the properties of various thermodynamic working fluids: pressure (p), temperature (T), specific volume (v), specific entropy (s), quality (x), and specific enthalpy (h) are the most commonly referenced properties. While gases are generally not the problem, two-phase fluids are usually more difficult to understand--the interrelationships between graphic and tabular presentations of the data are also often not fully appreciated. One possible solution is to have students plot tabular data manually; this becomes exceptionally tedious, especially if several different plots are required (p-v, T-v, T-s, h-s, etc.). By actually constructing the graph of interest, and investigating how lines of constant property plot and change (isobars, isotherms, isentropes, etc.), it is hoped that students will better understand and retain the nature of these diagrams. What is needed, however, is some method of relieving the students of the tedium associated with the construction of these diagrams, yet not totally divorcing them from the fundamental nature of these plots. Many students are “visual learners” and would benefit greatly from a dynamic, graphical depiction of how properties vary.
The “kernel” used in this technique is the Thermal Fluids Toolbox (TFT) published as freeware by Spreadsheet World, Inc. on their website (www.spreadsheetworld.com). The “Toolbox Overview” provided within TFT describes this Excel™ “add-in:”

*The Thermal Fluids Toolbox provides the capability to determine the thermodynamic state of 40 common working fluids in four different sets of units. The methods and equations utilized in this module are based on the computational equations published in “Thermodynamic Properties in SI” by William C. Reynolds, Stanford University, 1979. The toolbox functions may be accessed directly from either the Excel™ worksheet or Visual Basic for Applications (after making a reference to the toolbox). A graphic interface is also available which provides instant access to the toolbox functions and provides the ability to insert these functions onto a worksheet for subsequent analysis.*

Use of TFT at the University of California at Northridge and at the United States Air Force Academy have been reported previously. Having employed TFT in various homeworks and on student projects, a logical extension was to use it to perform the tedious calculations quickly in a graph of thermodynamic properties that allows the student to quickly visualize how property plots change—used in an introductory thermodynamics course, the students are not required to enter the TFT function calls themselves—TFT is transparent to the students in this application. (Here, TFT is employed solely for the evaluation of thermal properties in individual cells; the spreadsheet layout, slide-bar interface, and tutorials were designed by the current author).

Anyone over a certain age can remember the use of interpolation in tables to obtain trigonometric, logarithmic, and other mathematical function values. While this is a very straightforward method, and tabular data for thermodynamic properties are presented in a fashion which facilitates interpolation, many students are either unable or unwilling to master this technique. It is not the intent of this paper to let students incorrectly assume that they will not be held responsible for understanding how to use tables and property graphs—they should still gain facility with interpolation and should be tested on this during their coursework.

**Methodology**

In their first exposure to thermophysical properties, students are usually introduced to the p-v and T-v diagrams; the columns covered in the property tables presented in thermodynamics texts at this point specifically exclude those associated with entropy, since this property is not normally covered until later in the curriculum. Water is normally the first working fluid covered, so that the concepts of saturation, phases, saturated mixtures, superheat, and subcooling / pressurized liquid are all required vocabulary elements to be mastered; air is frequently the next working fluid introduced. Although the p-v and T-v diagrams are the most common plots used when students are introduced to working fluids in a thermal-fluids curriculum, the Mollier and T-s diagrams will be presented in the current paper, since these are more usually more widely used.

While it would be instructive for students to fill in the entire spreadsheet with the TFT function calls, that was not the intent of these worksheets; that might be appropriate for later stages of the
thermal-fluids curriculum. Accordingly, students were provided spreadsheets with the TFT function calls already entered into the appropriate cells—this allowed the instructors to concentrate more on the pedagogical aspects of instruction.

What was desired was the ability to change one cell in the spreadsheet to cause the various plots (T-s, h-s, etc.) to be modified interactively; this allows the students to see how isobars, isotherms, and the like change. The cells which may be changed by the user are highlighted in gold, and each is named (“pressure,” “temperature,” “quality,” etc.); calls to the TFT functions reference these names, which, in essence, make them absolute cell references. As a further refinement, Active-X scroll bars are included and programmed in Visual Basic for Applications (VBA) to change the values of these cells more smoothly; this allows students to focus on the graph instead of typing in changes to each property (gold) cell value, thereby enhancing the pedagogical worth of the spreadsheet.

For the Mollier (h-s) diagram, the calls to TFT specify that the enthalpy is to be the output property. The cells which are plotted in the Mollier diagram are shown in Figures 1 and 2, and are framed in blue. Column A contains the values of entropy, one of two independent variables. Enthalpies (the dependent variable) are depicted in the remaining columns:

- **Column B**: the second independent property here is quality. To the right of the critical point, a value of x = 1.0 is used (saturated vapor); to the left of the critical point, a value of x = 0 is employed (saturated liquid). Note that the cells associated with the critical point are highlighted in blue. When plotted versus the entropy values, this column produces the so-called “vapor dome.”

- **Column C**: quality is the second independent property here, as specified in the gold “quality” cell. To the right of the critical point, x is used as the second argument to TFT calls; to the left of the critical point, (1-x) is used as the second TFT argument. Consequently, for a gold cell value of 0.95, enthalpy values are calculated for x = 0.95 (for entropies to the right of the critical point) and for x = 0.05 (for entropies to the left of the critical point). When plotted, this column produces lines of constant quality or, alternatively, moisture content.

- **Column D**: the second independent property employed in this range is pressure, as specified in the gold “pressure” cell. When plotted, this column results in an isobar.

- **Column E**: similar to Column D, except that the value in the “temperature” cell is used. An isotherm is produced when this column is plotted.

As mentioned above, TFT fails to converge in the vicinity of the critical point, and returns, instead of a value for the desired property, an error code which is negative. In fact, the spreadsheet cells contain a logical “IF” function which checks the value provided by the TFT functional call. If the value is positive, that value is displayed in the cell; if negative, “#N/A” appears in the cell (Excel™ recognizes this as essentially an “empty” cell); the appropriate “radio button” in TOOLS/OPTIONS/CHART menu is selected so that “empty” cells are not plotted. Otherwise, negative error values returned by the TFT functions would result in curve discontinuities. This convergence issue may also exist at extreme property values, so it is important to employ the above logic statement at all functional evaluations which are liable to be plotted.
A similar range may be constructed which outputs temperature, rather than enthalpy, as the desired property—this is used to construct the T-s diagram. This range is framed in green, and appears adjacent to the T-s diagram (see Figures 1 and 3). Isobars and lines of constant quality are linked to the scroll bars and gold property cells; changing these property values changes both the Mollier and T-s diagrams simultaneously, so that students are able to view how both plots change.

As students continue their work, they are required to answer questions contained on a separate “Questions” worksheet. Possible questions to ask or points to make may include the following:

- Comment on the qualitative similarity of isobars between gases and superheat region of 2-phase fluids.
- How, for an isobar on the Mollier diagram, the isotherm that corresponds to the associated saturation temperature lines up with the isobar “under the dome,” and diverges in the superheated region. Comment on the same relationship on the T-s diagram.
- Discuss the requirement to have two independent, intensive properties in order to fix any fluid state.
- Compare property values obtained with values obtained from tables and charts, using manual interpolation for selected points.
- Compare location of the critical point on T-s and Mollier diagrams.
- Comment on the location and extent of the compressed liquid region on the Mollier diagram, and compare to the same region on the T-s diagram.
- Proximity of isobars and the saturated liquid line in compressed liquid region. Comment on why approximations such as \( h(T,p) \approx h(T) \) work in this region. This is a point that is frequently depicted graphically in a greatly exaggerated fashion in textbooks, so that an appreciation of the propriety of such approximations is not readily evident.

The above charts, ranges, and scroll bars are contained on a sheet entitled “Calculations.” Separate worksheets entitled “Your Mollier” (see Figure 4) and “Your T-s” may be included, so that students will have to produce their own plots for property values specified by the instructor. Blank ranges, with only the entropy values filled in, are provided, along with blank charts. As students modify property values on the “Calculations” worksheet, appropriate ranges are copied and only the values (rather than the cell contents—TFT function calls) are pasted into the blank ranges—plots are automatically produced as these range values are pasted. Another worksheet named “Instructions for Calculations Worksheet” describes how to use the scroll bars and how to copy and paste values from this worksheet to their own plots. Full-page plots are required for turn-in, along with answers to questions posed on the “Questions” worksheet.

All questions and instructions are contained within the same spreadsheet on different worksheets, making it a “stand alone” document. Additionally, all cells are protected, with the exception of the (initially) blank cells on the worksheets entitled “Your Mollier” and “Your T-s”.

Other Possible Graphic Applications

The above description of the spreadsheet structure for Mollier and T-s diagrams was provided to show what is perhaps the most detailed application of the TFT to graphic depiction of working fluid properties. It is perhaps most likely, however, that this would be preceded in a course...
syllabus by similar worksheets produced for p-v and T-v diagrams for two-phase fluids (Figure 5) and/or gases. Again, there are 40 different working fluids in TFT from which to choose.

The only difference when using the TFT for the calculation of gas properties is that reference conditions need to be specified in order that calculated property values match tabulated values. If reference conditions are not specified in the function call, property changes (such as for enthalpy, \(\Delta h\), or for internal energy, \(\Delta u\)) are still properly calculated, since each property is calculated relative to its own datum.

It is interesting to note that the only VBA programming that is employed in any of these spreadsheets is associated with the Active-X scroll controls; even these could be replaced with scroll bars from the controls toolbox, although the refreshing and updating of the plots would not occur nearly as smoothly. For students who are further along in the curriculum or who display ability in programming, VBA could most certainly incorporate more sophisticated VBA routines to streamline their worksheets. TFT, as distributed, includes VBA versions of all the standard TFT spreadsheet functions that may be called from within VBA routines.

**Student Feedback**

The worksheets described herein were used in two different courses in the thermal fluids systems engineering curriculum at the United States Air Force Academy during the 2005 fall term. Junior cadets in the first of a 3-course thermal fluids sequence were provided worksheets which allowed them to explore and plot water property variations on p-v and T-v diagrams; they were provided a brief introduction in the classroom, and then tasked with completing the tutorial outside of class as a “pre-lab” exercise to a water vaporization lab which was performed in class. Their response was overwhelmingly positive. Although there were minor problems with the installation of the Thermal Fluids Toolbox, most students felt the tutorial was excellent, and that it clearly demonstrated the effects of temperature, pressure and quality on fluid properties. The questions posed in the worksheet were thought provoking and provided great preparatory information. A suggestion from another instructor in the course recommended that students perform a few calculations by hand (perhaps even one which required double interpolation!) to compare with the results obtained with Thermal Fluids Toolbox and the worksheet.

Senior cadets entering their third course were emailed a similar worksheet in which they investigated the variation of water properties on Mollier and T-s diagrams, since they had already been exposed to the property of entropy; it was provided prior to the beginning of classes for accomplishment as a review, and due at the beginning of the first lesson. Even without a formal introduction in class, well over 80% were able to work through the tutorial without problem. Almost all were enthusiastic regarding the worksheet, and thought that it would have been an aid when first covering the topic of thermodynamic properties during their first course a year before.

**Conclusion**

TFT has allowed the incorporation of “add-in” functions to Excel™ spreadsheets to automatically calculate thermodynamic properties as reference cells are changed. Accordingly,
students are now able to focus graphically on the way in which various properties change, rather than looking up property values and interpolating within tables or on charts. It is still important, however, to ensure that students retain that “lookup and interpolate” ability.

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Disclaimer

The views expressed are those of the author and do not reflect the official policy or position of the U.S. Air Force, Department of Defense or the U.S. Government.

References


Figure 2: “Calculations” worksheet—detailed view of enthalpy table and Mollier diagram.

Figure 3: “Calculations” worksheet—detailed view of temperature table and T-s diagram.
Figure 4: Blank “Your Mollier” worksheet, ready for user input of values from “Calculations” worksheet.
Figure 5: p-v and T-v diagrams.