AC 2007-195: TEACHING PSYCHROMETRY TO UNDERGRADUATES

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Teaching Psychrometry to Undergraduates

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Abstract

A mutli-faceted approach (lecture, spreadsheet and laboratory) used to teach introductory psychrometric concepts and processes is reviewed. During introductory lectures, basic thermodynamic principles are employed in the presentation of elementary psychrometric processes; various process lines are shown not only on traditional psychrometric charts, but also on temperature-volume diagrams, with which the students are already familiar. During their first exposure to psychrometry, most students usually find the layout and interpretation of the psychrometric chart particularly difficult to comprehend; in the current approach, an interactive psychrometric chart (written in Excel™ using Visual Basic for Applications) allows students to use sliding bars to visualize in real time how lines of constant relative humidity, specific volume, and wet bulb temperature vary; the effect of varying barometric pressure may also be viewed by using another sliding bar. Students are then required to construct their own psychrometric charts in a parametric fashion, producing lines of constant relative humidity, specific volume, and wet bulb temperature; these charts are produced for the prevailing barometric pressure, rather than for standard atmospheric pressure. The instruction is supplemented with a simple laboratory, wherein wet and dry bulb temperatures are measured inside the classroom and outside, and which are, in turn, used to calculate relative humidity, specific humidity, and other parameters associated with the building air conditioning process. An integral part of this laboratory is that the psychrometric chart previously produced by each student in Excel™ is employed in the analysis—since it was constructed for the barometric pressure which was recorded during the experiment, students may use it in their data reduction, rather than the chart provided in their text (for standard atmospheric pressure). This synergistic approach has been found to enhance student understanding of the basic psychrometric and HVAC processes.

Background/Impetus

Historically, engineering students have a difficult time understanding psychrometry, even though only basic thermodynamic principles are involved (mass and energy conservation, evaporation/condensation, partial pressure, ideal gas). Up to this point in their studies, they have almost always dealt with pressure vs. volume (p-T), temperature vs. volume (T-v), or temperature (or enthalpy) vs. entropy (T-s or h-s) plots of working fluid properties. When confronted with the psychrometric chart and its lines of constant enthalpy, humidity ratio, relative humidity, and volume, they find it somewhat daunting. Students frequently have difficulty understanding psychrometric processes, and would benefit significantly if they were able to relate these to the same process depicted on another diagram—in particular, to the temperature vs. volume diagram. They also usually find it difficult to comprehend the fact that the vapor in the air around them is superheated. In addition, for cadets at the United States Air Force Academy (situated at an elevation of 7200 feet, where the atmospheric pressure is usually on the order of 11.3 psia), the psychrometric charts which are included in most engineering textbooks are not appropriate, since they are almost always provided only for standard atmosphere. The important effects of barometric pressure on psychrometric processes and the psychrometric chart are often ignored when teaching psychrometry.

Basic Method of Course Delivery

The Department of Engineering Mechanics at the United States Air Force Academy recently adopted the thermal fluids approach to replace the more traditional thermodynamics-fluid mechanics-heat transfer sequence[1], and chose a suitable text that supported this transition[2]. A brief (five 53-minute lectures in a 40-lesson, 3-semester hour course) introduction to psychrometry is presented to mechanical engineering majors in the fall semester of their senior year during the third course of the thermal fluids engineering sequence, and includes the following major topics: basic psychrometric principles (partial pressures, humidity ratio (ω), relative humidity (φ), and wet- and dry-bulb temperatures (T_{wb}, T_{db})), basic control volume analysis, and a brief introduction to elementary air conditioning applications (cooling/heating at constant composition, dehumidification / humidification, evaporative cooling, and mixing). Due to the five-lecture limitation, the topic of adiabatic saturation is omitted. While other institutions have found one or two class sessions to be adequate for teaching this subject[3], the current authors deemed it necessary to devote five lectures to this material.

Prior to their introduction to psychrometry, most students are familiar with many of the other diagrams associated with property variations: h-s, T-s, T-v, and p-v. Unfortunately, the psychrometry chart can be somewhat intimidating the first time it is encountered by a budding thermodynamics student, and some link with prior
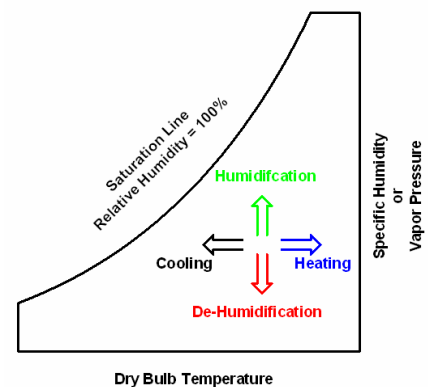

Figure 1: Basic layout of psychrometric chart

knowledge facilitates the introduction of this topic.   Figure 1 illustrates a fairly common first exposure to the psychrometric chart. Unfortunately, most thermodynamics textbooks provide little (if any) correlation between the process line on a psychrometric chart and its counterpart on a T-v diagram; a synopsis of the more common psychrometric processes and the "mappings" between the T-v diagram and the psychrometric chart is shown in Table 1.
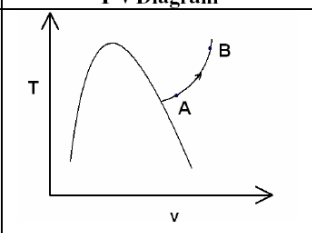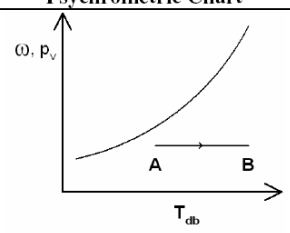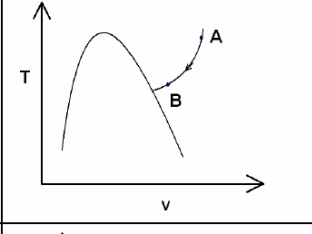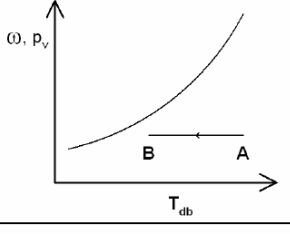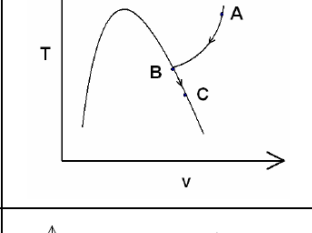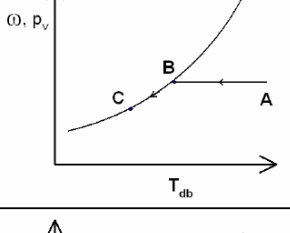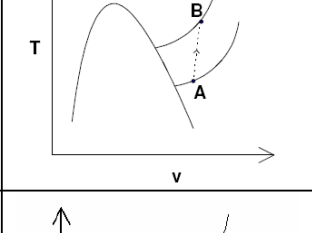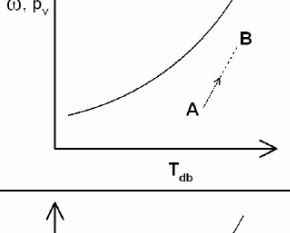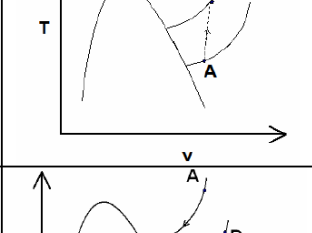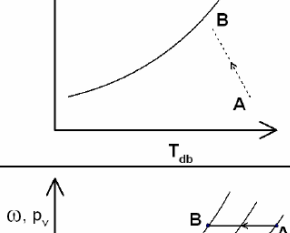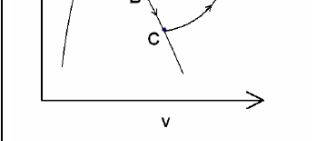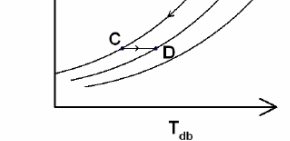
Process	T-v Diagram	Psychrometric Chart
Constant Composition Heating		
Constant Composition Cooling		
Cooling with Condensation		
Humidification (Steam Injection)		
Humidification (Liquid Injection) (also, Evaporative Cooling)		
Dehumidification		

Table 1: Relation ("mappings") between T-v diagram and psychrometric chart for several HVAC processes.

Spreadsheet Psychrometric Chart

Biasca[4] presented an on-line tutorial which is an excellent introduction to the structure of a psychrometric chart. There does not appear to be a way in that tutorial, however, to fabricate a psychrometric chart associated with a particular atmospheric pressure, something that is important for laboratory work which might be done at elevations other than sea level (such as the 7200-foot elevation such as the United States Air Force Academy). Additionally, reliance on a web-based instruction method entailed some uncertainty—what to do if the site were discontinued? What was desired was a tutorial which could be "stand-alone," was written in universally-available software, and which included the important effect of atmospheric pressure.

Previous work[5,6] by the first author at automated property lookup involved use of the Thermal Fluids Toolbox produced by Spreadsheet World, Inc. when calculating properties for water vapor. Unfortunately, this Excel™ "add-in" is not employed in the current application because it could not provide property values for a wide variety of temperatures. Instead, curve fits were incorporated as "user-defined" functions in Excel™ for

- Vapor pressure as a function of temperature
- Enthalpies (saturated liquid and saturated vapor) as functions of temperature

These curve fits result in correlation coefficient (R) values of .998 or better over the range of interest. Additionally, as is common practice in the construction of psychrometric charts, a constant value of specific heat at constant pressure is used in the calculation of the enthalpy of air.

The psychrometric spreadsheet contains several worksheets:
- Instruction sheet: includes basic usage and layout of the "Calculation Sheet" and the questions to be answered in the tutorial
- Atmospheric pressure psychrometric chart:
  - An embedded graphic chart from the course text[2]
  - Included for comparison to standard atmospheric conditions
- Calculation sheet (an overall view is provided in Figure 2):
  - Upper part: provides real-time depiction as properties are changed.
    - Each of the following properties has its own gold-highlighted cell (appropriately named) and an associated scroll bar (programmed in Visual Basic for Applications) to allow rapid and smooth changes:
      - Relative humidity (φ)
      - Barometric (atmospheric) pressure (p)
      - Wet bulb (adiabatic saturation) temperature (T_{wb})
      - Mixture specific volume ($v_{mixture}$).
    - Cell ranges either
      - Calculate specific humidity (ω) values for
        - Relative humidity (pink)
        - Wet bulb temperature (green)

- o Mixture specific volume (blue)
      OR
- Contain equations which calculate these values for specific humidity (ω) taken directly from or derived from equations in an elementary thermodynamics text[2] are shown in Table 2. In these equations:
  - o $\overline{R}$ is the universal gas constant
  - o Subscript "A" refers to air
  - o The subscripts "f" and "g" refer to the saturated liquid and saturated vapor states for water, respectively, for use with enthalpies, h.
  - o $v_{mixture}$ is the specific volume for the mixture, per unit mass of air.
  - o T_{wb} and T_{db} are, respectively, the wet and dry bulb temperatures.
  - o M_A is the molecular weight of air.
- ▪ The psychrometric plot shows how various lines change as sliding bars are moved.
  - This reflects changes in cells which calculate humidity ratio
  - The cells are color coded to correlate to the color of the associated line on the psychrometric chart
  - For each of these lines, the independent property is dry bulb temperature (T_{db}), and the dependent property is humidity ratio, ω.
- o Lower part: provides an initially blank range where the cadets construct their own psychrometric chart, based on the prevailing atmospheric pressure. Figure 3 provides a view of the lower portion of the worksheet after completion. When completed, this portion of the worksheet is used in conjunction with the laboratory; the pre-lab was graded by the instructor prior to cadets using it in their laboratory report.
  - ▪ To construct this portion, students change the gold cells in the upper part, either by directly entering values in the cell for each property value, or by using the sliding bars to change the gold cell values. The values in each gold cell are modified to match those which appear at the heading of each blank column in the lower part of the worksheet.
  - ▪ The cells in the upper part which contain the calculated values for ω are then copied, and their *values only* pasted in the corresponding portion of the lower part of the worksheet (to avoid pasting formulas). The associated line is automatically plotted on the new psychrometric chart in the lower part of the worksheet.
  - ▪ This process is continued until all blank cells in the lower portion of the worksheet are filled. Hand annotation is required for lines associated with constant wet bulb temperature, mixture specific volume, and relative humidity.

For φ = constant; For T_db = constant; For v = constant tables:

p= 10 psia
φ= 0.397
T_wb= 68 °F
v= 19.8 ft³/lbm air

$p_v(T_{wb})$= 0.33901 psia
ω'= 0.02183 lbm vapor/lbm air
c_p= 0.24 B/lbm·°R
$h_f(T_{wb})$= 16.32 B/lbm
$h_g(T_{wb})$= 1090.95 B/lbm
$h_f(T_{db})$= 35.75 B/lbm

T_{db} (°F)	For φ = constant			For T_{db} = constant				For v = constant
	$p_s(T)$	p_v	ω	p_s	$h_a(T)$	$h_v(T)$	ω	ω
10	0.03	0.01	0.001	9.99	2.40	1065.66	0.036	0.087
20	0.05	0.02	0.001	9.98	4.80	1070.02	0.033	0.072
30	0.08	0.03	0.002	9.97	7.20	1074.38	0.031	0.058
40	0.12	0.05	0.003	9.95	9.60	1078.74	0.029	0.044
50	0.18	0.07	0.004	9.93	12.00	1083.11	0.026	0.031
60	0.26	0.10	0.006	9.90	14.40	1087.47	0.024	0.019
70	0.36	0.14	0.009	9.86	16.80	1091.83	0.021	0.007
80	0.51	0.20	0.013	9.80	19.20	1096.19	0.019	-0.005
90	0.70	0.28	0.018	9.72	21.60	1100.55	0.017	-0.016
100	0.95	0.38	0.024	9.62	24.00	1104.91	0.014	-0.027
110	1.28	0.51	0.033	9.49	26.40	1109.27	0.012	-0.038
120	1.70	0.67	0.045	9.33	28.80	1113.63	0.010	-0.048
130	2.22	0.88	0.060	9.12	31.20	1117.99	0.008	-0.057

Values of ω for

T_{db} (°F)	φ =					T_{wb} (°F) =					v (ft³/lbm air) =			
	0.2	0.4	0.6	0.8	1.0	20	30	40	50	60	16	17	18	19
10														
20														
30														
40														
50														
60														
70														
80														
90														
100														
110														
120														
130														

Figure 2: Overall view of "Calculations" worksheet.

A 15-minute classroom familiarization session is conducted, wherein basic movement of the lines in the upper plot is shown, and the values of one or two columns of data are copied and pasted into the lower part of the worksheet. It is emphasized that the "paste values" option was employed for proper construction of the lower plot! When completed, the lower plot represents the psychrometric chart for the chosen barometric pressure; thus, the students have constructed their own psychrometric charts. Although the "Calculations" worksheet is protected to prevent inadvertent deletion of equations in the various cells, the cadets are provided the password.

Copies of the spreadsheet are available from the first author at Michael.Maixner@usafa.af.mil.

For lines of constant	Equations used to calculate ω
φ	$\omega = 0.622 \dfrac{p_v}{p - p_v}$, where $p_v = p_g\,\varphi$ is the partial pressure of the water vapor and p_g is the saturation pressure of the water vapor at the dry bulb temperature
T_{wb}	$\omega = \dfrac{h_A(T_{wb}) - h_A(T) + \omega'\left[h_g(T_{wb}) - h_f(T_{wb})\right]}{h_g(T) - h_f(T_{wb})}$ where $\omega' = 0.622\,\dfrac{p_g(T_{wb})}{p - p_g(T_{wb})}$
$v_{mixture}$	$\omega = 0.622\left[\dfrac{M_A\,v_{mixture}}{\overline{R}\,T_{db}} - 1\right]$

Table 2: Equations used in calculation of specific humidity when various properties are specified.

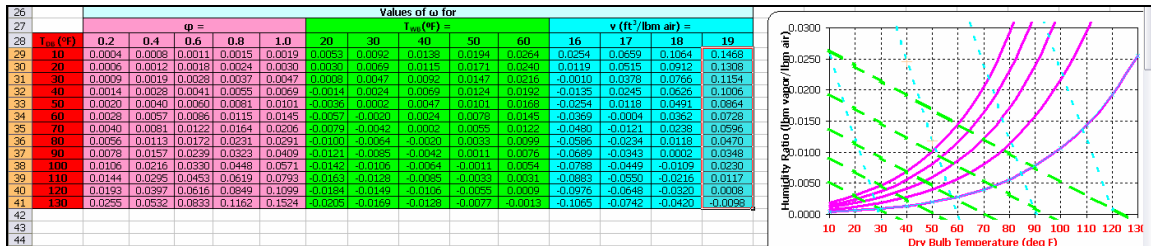|		φ =				T_{wb}(°F) =					v (ft³/lbm air) =			
T_{db} (°F)	0.2	0.4	0.6	0.8	1.0	20	30	40	50	60	16	17	18	19
10	0.0004	0.0008	0.0011	0.0015	0.0019	0.0053	0.0092	0.0138	0.0194	0.0264	0.0254	0.0659	0.1064	0.1468
20	0.0006	0.0012	0.0018	0.0024	0.0030	0.0030	0.0069	0.0115	0.0171	0.0240	0.0119	0.0515	0.0912	0.1308
30	0.0009	0.0019	0.0028	0.0037	0.0047	0.0008	0.0047	0.0092	0.0147	0.0216	-0.0010	0.0378	0.0766	0.1154
40	0.0014	0.0028	0.0041	0.0055	0.0069	-0.0014	0.0024	0.0069	0.0124	0.0192	-0.0135	0.0245	0.0625	0.1006
50	0.0020	0.0040	0.0060	0.0081	0.0101	-0.0036	0.0002	0.0047	0.0101	0.0168	-0.0254	0.0118	0.0491	0.0864
60	0.0028	0.0057	0.0086	0.0115	0.0145	-0.0057	-0.0020	0.0024	0.0078	0.0145	-0.0369	-0.0004	0.0362	0.0728
70	0.0040	0.0081	0.0122	0.0164	0.0206	-0.0079	-0.0042	0.0002	0.0055	0.0122	-0.0480	-0.0121	0.0238	0.0596
80	0.0056	0.0113	0.0172	0.0231	0.0291	-0.0100	-0.0064	-0.0020	0.0033	0.0099	-0.0586	-0.0234	0.0118	0.0470
90	0.0078	0.0157	0.0239	0.0323	0.0409	-0.0121	-0.0085	-0.0042	0.0011	0.0076	-0.0689	-0.0343	0.0002	0.0348
100	0.0106	0.0216	0.0330	0.0448	0.0571	-0.0142	-0.0106	-0.0064	-0.0011	0.0054	-0.0788	-0.0449	-0.0109	0.0230
110	0.0144	0.0295	0.0453	0.0619	0.0793	-0.0163	-0.0128	-0.0085	-0.0033	0.0031	-0.0883	-0.0550	-0.0216	0.0117
120	0.0193	0.0397	0.0616	0.0849	0.1099	-0.0184	-0.0149	-0.0106	-0.0055	0.0009	-0.0976	-0.0648	-0.0320	0.0008
130	0.0255	0.0532	0.0833	0.1162	0.1524	-0.0205	-0.0169	-0.0128	-0.0077	-0.0013	-0.1065	-0.0742	-0.0420	-0.0098

Figure 3: Detailed view of lower portion of "Calculations" worksheet following completion.

Laboratory Experience

As part of the psychrometry instruction block in the thermal-fluids curriculum, the lectures are supplemented with an in-class laboratory which includes psychrometric measurements conducted with a hygrometer and a sling psychrometer (see Figure 4 and Figure 5). During this laboratory, measurements are made to determine relative humidity and humidity ratio, both indoors and out; the objective is to demonstrate humidity measurements and to use them to determine the nature of the air conditioning process employed in the building's heating, ventilation, and air conditioning (HVAC) system.

The laboratory is conducted in class and outside, with the data read as a class; the measurements take no more than 15 minutes to perform. After reading the barometric pressure, the hygrometer provides dry bulb temperature and relative humidity, and the sling psychrometer is used to record wet and dry bulb temperatures; the "slide rule" on the sling psychrometer provides an immediate value for the relative humidity during the lab—cadets are reminded that this scale is constructed for standard atmospheric

conditions. Cost of a complete set of the lab equipment is minimal, totaling less than $100.

Cadets are divided into pairs for data reduction, comparison, and write-up. A major emphasis in the thermal fluids systems engineering curriculum at the United States Air Force Academy is on interpreting the data, while de-emphasizing the more common detailed write-up requirement. Accordingly, the maximum length of the write-up is set at 1-1/3 pages, with answers required to a specific set of questions. Anomalies and disagreements among the various measuring devices are, however, still to be an important source for comment in the report.

Figure 4: Digital hygrometer.

Figure 5: Sling psychrometer.

Cadets are required to provide the data indicated in Figure 6.

Procedure:
As a class, fill in the data on the attached spreadsheet for both the classroom and outside conditions.

Deliverables:
Follow the format provided on the TFSE web site. Comment briefly on the following questions in your report, numbering your answers to agree with the following paragraphs:
1. Fill in the items highlighted in blue on the spreadsheet, and provide a copy. On a separate sheet, describe how each item was calculated.
2. Comment on the difference between the variation of the different calculated items as obtained from the four different means of measurement/calculation.
3. Using your data from the sling psychrometer, answer the following:
    a. On the printout of your spreadsheet psychrometric chart ("Build Your Own Psychrometric Chart" homework from the previous lesson)
        i. Plot and clearly label the outside and inside states
        ii. Draw the process line connecting the two state points.
    b. What type of process did the air undergo as it passed through the air handlers in the HVAC system?
    c. If water was added or removed, calculate how much.
    d. Sketch the process on a T-v diagram.
    e. What is an acceptable range for relative humidity in a dwelling? Cite your source.

			Hygrometer	Sling Psychrometer	BYOPC	Fig T-4E
$P_{barometric}$=		mmHg	Data			
	=	psia	Calculations			
					Psychrometric Charts	
Classroom	T_{DB} (°F)					
	T_{WB} (°F)	N/A				
	φ					
	ω					
Outside	T_{DB} (°F)					
	T_{WB} (°F)	N/A				
	φ					
	ω					

Figure 6: Psychrometry "mini-lab" procedure, deliverables, and data sheet.

Specific requirements for this "mini-lab" include:
- Measurement of atmospheric pressure, wet- and dry-bulb temperatures
- Analytic calculation of
    o Outdoor and indoor
        ▪ Relative humidity
        ▪ Humidity ratio
        ▪ Enthalpies of moist air mixture
    o Amount of moisture added/removed from the air during the HVAC process

- Plotting of the HVAC process on a psychrometric chart constructed for the prevailing atmospheric pressure.
- Verification of the above analytical calculations with the same values obtained from the "custom-made" psychrometric chart based on actual barometric pressure.
- Commenting on differences between analytical calculations, values obtained from hygrometer and sling psychrometers, and values obtained from tailor-made psychrometric charts. Cadets are advised that standard atmospheric conditions are assumed in the fabrication of the psychrometric chart which is provided in their texts, and also on the relative humidity "slide rule" which is stamped on the side of the sling psychrometer.

Prior to the laboratory session, a "pre-lab" is assigned as a homework assignment, wherein cadets are required to construct a psychrometric chart for the prevailing atmospheric pressure. This entails running a tutorial contained on an Excel™ spreadsheet (details provided above), and, using this spreadsheet, cadets are required to construct a psychrometric chart for the actual atmospheric pressure.

Feedback from Cadets

Response from the cadets, both in class and in response to a critique sheet distributed specifically for soliciting input to make the lab better, was overwhelmingly positive to all aspects of the pre-lab (BYOPC—"Build Your Own Psychrometric Chart") and the mini-lab itself. Most thought the Excel™ exercise was very worthwhile, and provided a foundation on which psychrometric principles could be built. Many cadets commented specifically that, had the psychrometric chart been provided without actually having fabricated their own, their understanding of the chart and its applicability to HVAC processes would have been significantly undermined. In particular, the dynamic depiction of how lines of constant φ, T_{wb}, and $v_{mixture}$ changed in the upper portion of the worksheet was invaluable. The lab further reinforced all concepts.

A psychrometry question posed on the final exam required (among other things), that the cadets plot an HVAC process line on a psychrometric chart; although not explicitly required as part of the solution, most cadets also sketched the process line on a T-v diagram to aid in their solution. Unfortunately, no assessment data were maintained on student comprehension of psychrometric concepts prior to the implementation of the pedagogical approach described in this paper.

Summary and Conclusions

The psychrometry block in the third thermal fluids systems engineering course at the United States Air Force Academy was modified to include several items to enhance student understanding of this material. Specifically, the various HVAC processes are described on both a T-v plot and on a psychrometric chart. Additionally, a "stand-alone" Excel™ spreadsheet was designed and implemented as a pre-lab exercise, during which the cadets construct their own psychrometric charts which are appropriate for the

prevailing barometric pressure (as opposed to standard atmospheric pressure); they are also required to complete a tutorial which causes them to use the dynamic features of a psychrometric plot which depicts how various lines changed (constant ϕ, T_{wb}, and $v_{mixture}$). Cadets are then required to use the results of this pre-lab to read various psychrometric properties associated with the actual lab, and to plot the process on the psychrometric chart produced during the pre-lab. Student and instructor satisfaction with the results were most gratifying.

In the future, Biasca's tutorial[4] will also be added to the course syllabus to further enhance student understanding of the various psychrometric processes. Additionally, if possible, an enthalpy axis will be added to the psychrometric chart produced in the Excel™ spreadsheet.

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.

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Nomenclature

h	Specific enthalpy
HVAC	Heating, ventilation, and air conditioning
M	Molecular weight
p	Barometric pressure (absolute)
p_v	Partial pressure of water vapor (absolute)
psia	Pounds (force) per square inch (absolute)
R	Statistical correlation coefficient
$\overline{R}$	Universal gas constant
s	Specific entropy
T	Temperature (absolute temperature used in ideal gas law)
v	Specific volume of water
$v_{mixture}$	Specific volume of water vapor/air mixture

Greek

φ	Relative humidity = ratio of partial pressure of vapor to saturation pressure at the mixture temperature
ω	Humidity ratio = ratio of mass of vapor present to mass of air present in mixture

Subscripts

A	Air
db	Dry bulb condition
f	Saturated liquid condition
g	Saturated vapor condition
Mixture	Mixture of water vapor and air
v	Vapor
wb	Wet bulb condition