Development and Integration of an Equation-Solving Program for Engineering Thermodynamics Courses

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ABSTRACT

Thermodynamics problems can be separated into conceptual and mathematical parts. The conceptual part consists of the problem formulation and analysis. The mathematical part seeks to obtain an answer to a problem by solving the equations identified in the analysis. The mathematical part can be complex and time-consuming and often directs the students' focus away from the concepts. An equation solving program called Engineering Equation Solver (EES) was developed to reduce the time and effort required by students to solve the mathematical part of thermodynamics problems. EES differs from existing equation solving programs in that it is designed for use by students and it includes an extensive library of built-in functions for thermodynamic and transport properties of fluids. Thermodynamic and transport property data needed for solving engineering problems (eg, steam tables, refrigerant properties, psychrometric and combustion gas data) are built into the program. By eliminating table lookups and algebra, EES allows students to concentrate on engineering fundamentals, as well as to do more complex design problems. © 1993 John Wiley & Sons, Inc.

INTRODUCTION

Undergraduate students in mechanical engineering at the University of Wisconsin-Madison are required to take two courses in thermodynamics. The first course introduces the concepts of equilibrium properties, mass and energy balances, and the second law of thermodynamics. This material is typically presented in the first half of popular undergraduate textbooks. The second course introduces additional concepts for psychrometrics, combustion, and chemical equilibrium, and applies these concepts to the analysis and design of common thermal systems such as power and refrigeration cycles, typically following the presentation in the second half of the textbooks. The thermal science curriculum at many other engineering colleges is similar to that at Wisconsin.

Thermodynamics has been taught for many years with relatively few changes. Many new textbooks have appeared, but they have changed little from the textbooks used 10 or more years ago. Mechanical engineering thermodynamics is applications-oriented, so that it is essential to work problems. Textbooks usually provide a large number of problems. However, the type and complexity of the problems in textbooks have also changed little in the last decade. In spite of the tremendous increase in computing capability available to engineering students today, homework problems are still designed to be

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done using a hand calculator, interpolating from property data tables as required. Assigned problems lack design content since the inclusion of design considerations necessitates an excessive amount of computation if done by hand. Although heat transfer and fluid dynamics are often important considerations in the applications being studied, a consideration of these effects is usually excluded, partly because of the computational complexity they introduce and also because courses introducing these phenomena are often taken at a later point in the curriculum.

A contention of this article is that changes in the order and content of the mechanical engineering thermoscience courses are needed in order to introduce thermal systems design concepts and to take advantage of available computing capability. A general equation-solving program called Engineering Equation Solver (EES) with built-in thermodynamic and transport property functions has been developed by the author especially for the thermodynamics and heat transfer courses. This article describes EES and relates the experience of the author in using this program in a modified thermodynamics course which centered on a series of practical thermodynamic system design problems.

JUSTIFICATION FOR DEVELOPMENT OF EES

Mechanical engineering thermodynamics is a problem-oriented course. Concepts are presented which are intended to be used in analyses of practical thermal systems. It is essential to work problems to learn this material. It is interesting to speculate on how the problems provided in thermodynamics textbooks are composed. One consideration must be that students (and the textbook author) should be able to do the problem in a reasonable amount of time by hand. This consideration necessarily compromises the practical merit of the problems and virtually eliminates design problems.

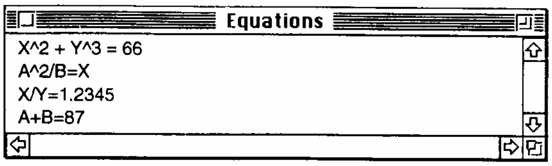
A thermodynamic analysis of a system results in a simultaneous set of algebraic equations representing mass and energy balances, second law considerations, and property relations. The resultant set of equations can require significant computational effort to solve, depending on what information is provided, particularly if it is necessary to interpolate property information from tables. When transport mechanisms, such as heat exchanger relationships or radiation, are also included in the analysis, the equations become more complicated by the introduction of non-linearities, eg, log-mean temperature differences or fourth power temperature dependence. Problems of this type are not usually found in popular undergraduate thermodynamics textbooks, perhaps because of their computational complexity.

Many thermodynamics problems require property data. Property data tables are ordinarily provided in the appendices of the textbook. Learning how to use property tables is an important skill which is taught early in the first thermodynamics course. However, the significant effort involved in repeatedly looking up (and often interpolating) data in the property values is of little educational value once the student is familiar with the use of the tables. Some textbooks provide a computer program that returns the desired property data for given inputs. Although the property data programs eliminate the need for the student to interpolate the tables, they do not further assist in the problem solving since the values obtained from the program must then be used in a separate solution of the governing equations. Because of the need for property data, design studies requiring repeated solutions of the equations describing a thermodynamic system over a range of parameter values cannot be routinely assigned to students for homework. Design studies yield far more information about a system than a single point solution and are an integral part of engineering optimization. However, they require significant computational effort.

One possibility is to have students write their own specialized computer programs to do design studies for a particular thermodynamic system. Mechanical engineering students are expected to be able to program in FORTRAN or other high-level languages. Public-domain property subroutines exist for steam, R-12, and other substances. These subroutines, along with general plotting routines, could be supplied by the instructor so that the students could integrate them into their computer programs. The experience of the author with this approach in recent years has been unsatisfactory. Students are generally not proficient programmers and their capability to implement numerical methods is limited. The students tend to become focused on programming details, rather than on the fundamental principles. The many computer operating systems and languages now available makes this approach even more difficult. Each computer operating system requires different instructions for compiling and linking external subroutines. The property data subroutines are usually written in FORTRAN and are not easily linked to programs written in other languages such as Basic, Pascal, or C. The alternative of having students write their own programs was actually more satisfactory before microcomputers became popular when students all used the same language and computer system.

The possibility of using existing commercial software for thermodynamic design problems was investigated. Spreadsheet programs provide automated calculations and plotting capability and they have the advantages of being inexpensive, widely available, and familiar to many students. However, it is difficult to apply spreadsheet programs to the task of solving sets of non-linear equations. In addition, the spreadsheet notation, useful for accounting applications, is cryptic when applied to problems in thermodynamics. Commercial equation-solving programs, eg, Mathematica [1], MathCad [2], TK Solver [3], and others, are now widely used. However, the large number of equations (often more than 100) involved in a thermodynamic system analysis requires a numerical solution which is at best painful to obtain with Mathematica or MathCad. In any case, none of the existing equation-solving programs known to the author include the necessary thermodynamic property data. Some programs allow property data to be incorporated with functions or tables provided by the user but the incorporation of all of the thermodynamic data provided in the appendices of thermodynamics textbooks is very difficult. Furthermore, these property functions must be designed to accept any independent variables in a natural format that is easily understandable by students.

The need for a specialized tool to help solve problems in the thermal sciences has motivated the author to develop EES [4]. EES is functionally similar to some existing programs in its numerical equation-solving, optimization, and plotting capabilities, but it differs from them in that it has been designed from the start to operate within the classroom context and to incorporate the property information needed for solving problems in the thermal sciences area. For example, the steam tables are implemented such that any thermodynamic property can be obtained from a built-in function call in terms of any two other independent properties. Similar capability is provided for many refrigerants including R-134a and R-123, ammonia, methane, propane, butane, carbon dioxide, oxygen, and other fluids. Air tables are built-in, as are psychrometric functions and JANAF table data for many common gases. Transport properties are also provided for all of these substances. Provisions have been made for the user to supply additional property data.



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X^2 + Y^3 = 66
A^2/B=X
X/Y=1.2345
A+B=87
```

Figure 1 System of four equations and four unknowns.[a]

[a] The figures represent the Macintosh version of EES. The different versions provide the same information but with slightly different appearance.

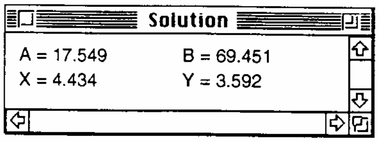
CAPABILITIES AND METHODS USED IN EES

Versions of EES have been developed for Macintosh computers, as well as for the DOS and Windows operating systems on IBM/compatible computers. A demonstration version of EES and several example problems are provided in compacted form for the DOS operating system on the diskette distributed with this issue. The demonstration version is fully functional, although it limits problems to 50 variables and it disables the Save and Print commands. The complete version is capable of solving up to 500 nonlinear algebraic and differential equations, depending on the version and available memory. Instructions for installing the program on your computer are provided in the Appendix of this article.

The basic capability provided by EES is the numerical solution of nonlinear algebraic equations. Consider the four equations shown in Figure 1 with unknowns A, B, X, and Y. These equations can be entered in any order or format into the Equations window. (EES makes no distinction between upper and lower case letters and the ^sign (or **) is used to signify raising to a power.)

Selecting the Solve command will initiate the calculations. EES will first check to see that the number of equations is equal to the number of unknowns, and then will display the Solution window shown in Figure 2.

Engineering Equation Solver uses a variant of Newton's method [5–8] to solve systems of nonlin-



```
A = 17.549        B = 69.451
X = 4.434         Y = 3.592
```

Figure 2 Solution to the four equations shown in Figure 1.

ear algebraic equations. The Jacobian matrix needed in Newton's method is evaluated numerically at each iteration. Sparse matrix techniques [9–11] are employed to improve calculation efficiency and permit large problems to be solved in the limited memory of a microcomputer. The efficiency and convergence properties of the solution method are further improved by the step-size alteration and implementation of the Tarjan [12] blocking algorithm, which breaks the problem into a number of smaller problems that are more easily solved. For example, EES would recognize that the equations entered above are not a coupled set of four equations with four unknowns, but rather two sets of two equations each with two unknowns. The first and third equations can be solved simultaneously to determine X and Y. With X known, the second and fourth equations can be solved. This equation blocking is evident in the Residuals window (Fig. 3), which displays the residual (ie, the difference between the left- and right-hand sides of the equation) and the block for each equation in the order of solution.

Nonlinear equations can have multiple solutions. However, the numerical techniques used in EES will only find one solution. The solution that results may depend upon the guess values. EES allows the guess value and the lower and upper bound of each variable to be specified, defaulting to a guess value of 1.0 with no bounds. In some problems, the default guess values (and possibly the bounds) must be changed to obtain a satisfactory solution.

A major feature of the EES program is its built-in functions for thermodynamic and transport property data. For example, the steam tables are implemented such that any thermodynamic property can be obtained from a built-in function call in terms of any two other properties. The enthalpy of steam at 300°C and 100 kPa can be obtained by[b]:

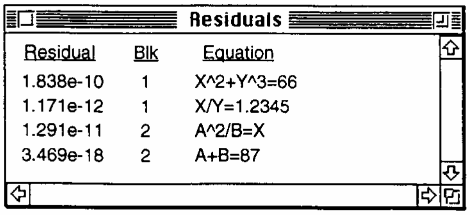
```
h=ENTHALPY(STEAM,T=300,P=100)
```

ENTHALPY is a built-in EES function. The first argument of this function is the name of the substance. The remaining arguments are the independent properties, in any order, preceded by an identifying letter and an equal sign. Valid identifiers are T, P, H, U, S, V, and X corresponding to temperature, pressure, specific enthalpy, specific internal energy, specific entropy, specific volume, and quality. Arguments to the property functions do not necessarily need to be known quantities. For example, the unknown temperature, T1, corresponding to specific enthalpy of steam of 3000 kJ/kg at 200 kPa could be found from:

```
3000=ENTHALPY(STEAM,T=T1,P=200)
```

Alternatively, the temperature could have been found (more efficiently) using

```
T1=TEMPERATURE(STEAM,h=3000,P=200)
```



Residual	Blk	Equation
1.838e-10	1	X^2+Y^3=66
1.171e-12	1	X/Y=1.2345
1.291e-11	2	A^2/B=X
3.469e-18	2	A+B=87

Figure 3 Residuals and blocking order for the system of four equations in Figure 1.

Engineering Equation Solver uses an equation of state approach rather than internal tabular data to calculate the properties of real fluids. Currently, EES uses the Martin-Hou [13] equation of state for the gaseous state of all real fluids except water. Several equations of state are provided for water, the most accurate (and computationally intensive) being the equation of state published by Harr, Gallagher, and Kell [14]. Ice properties rely upon correlations developed by Hyland and Wexler [15]. Thermodynamic property relations are used to determine enthalpy, internal energy, and entropy values based upon the equation of state and additional correlations for liquid density, vapor pressure, and zero-pressure specific heat as a function of temperature. JANAF [16] table data provide the enthalpy of formation and absolute entropy for combustion gases such as CH_4, CO_2, H_2, H_2O, N_2, and NO at a reference state of 298 K, 1 atm. Specific heat correlations for these gases and the ideal gas law are used to calculate the thermodynamic properties at conditions other than the reference state. Viscosity and thermal conductivity of liquids and low-pressure gases are correlated as polynomials in temperature. The effect of pressure on the gas transport properties is estimated using correlations from Reid and Sherwood [17]. All property correlations are programmed such that any independent variable(s) can

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[b] EES operates in SI or English units. The following discussion assumes EES to be configured for SI units with temperature in Celsius, pressure in kPa, and specific properties such as enthalpy expressed per kg.

be supplied. EES will internally solve the property data equations regardless of whether the property correlations are implicit or explicit in the unknown variables.

One of the most useful features of EES is its ability to automate a series of calculations and plot the results. This capability is provided with the Parametric table, which is similar in operation to a spreadsheet. The user selects the variables for the columns of the Parametric table from the list of variables appearing in the entered equations. Independent variables are identified by entering their values in the table cells. Each row in the table constitutes a separate problem. EES will solve for the values of the dependent variables in each row of the table. Plotting capability is provided to display the relationship between any two variables in the table. As a very simple example, a plot of the specific volume of ammonia at 50°C versus pressure can be developed by entering the following equation.

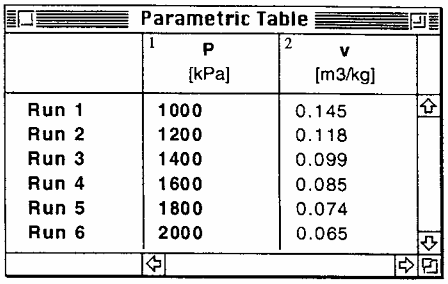
```
v=Volume(AMMONIA,T=50,P=P)
```

The variables P and v are then selected to appear in a Parametric table having six rows with the New Table command. The values of P that are entered into the table become the independent variables and they are shown in bold type. The Solve Table command calculates the dependent variable(s) in each row of the table, which is only v in this case. The completed table appears in Figure 4.

The New Plot command can then be applied to produce a high quality graph of the results, as shown in Figure 5. EES also uses the Parametric table with the Integral function to numerically solve initial-value differential equations.

THERMODYNAMICS COURSE MODIFICATIONS

Engineering Equation Solver provides the property data and does the computations needed to solve a thermodynamics problem. It was surprising at first to find that, with these capabilities, many of the problems provided in textbooks are trivial. These problems were designed to be done by hand in a reasonable time. They can be done within seconds using EES.



	1 P [kPa]	2 v [m3/kg]
Run 1	**1000**	0.145
Run 2	**1200**	0.118
Run 3	**1400**	0.099
Run 4	**1600**	0.085
Run 5	**1800**	0.074
Run 6	**2000**	0.065

Figure 4 Calculated values of ammonia specific volume at 50°C and various pressures.

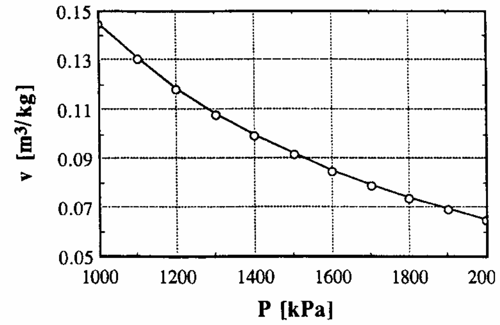


Figure 5 Plot of ammonia specific volume at 50°C versus pressure.

Engineering Equation Solver provides the instructor with both an opportunity and a challenge. The opportunity arises because students can be expected to learn the subject matter more quickly and to solve more complicated problems when the purely computational aspects are identified and eliminated. The challenge is that, to exploit the advantages of using the computer, it becomes necessary for the instructor to devise new lectures and problems since the necessary materials are not currently provided in sufficient quantity in existing textbooks. Interesting practical problems involving heat transfer and fluid dynamics in addition to thermodynamics can be developed to include parameter studies, plots, and optimization. Problems of this complexity can be solved within a reasonable amount of student time using EES.

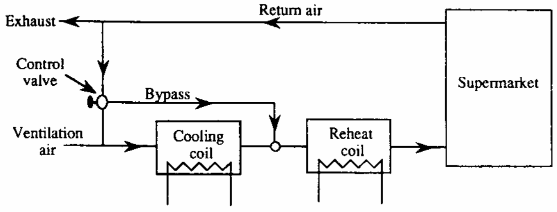
The thermodynamics courses at Wisconsin were revised with these thoughts during the 1991–1992 and 1992–1993 academic years. Independent of the computer software, it was judged that somewhat more than half of the textbook could be covered in the first course. The first course was modified to include analyses of power and refrigeration cycles, so as to cover approximately 75% of the textbook. EES was not used during the first course. Emphasis was placed upon concepts and use of property tables. Homework problems were done in the conventional manner using a hand calculator. CP/Thermo [18], a thermodynamics instructional program, was used in some problem assignments.

Major changes occurred in the second course. The remaining 25% of the textbook was covered in approximately the first half of the semester, leaving the remaining half for new material and design studies. The new material (ie, subjects which were not presented in this class in previous years) were heat exchanger relationships, finite-time thermodynamic considerations in power cycles, chemical equilibrium using LaGrange undetermined multipliers, performance and environmental effects of alternative refrigerants, and absorption and desiccant cooling cycles. Rather than short homework problems due the following session, much more extensive problems (approximately one per week) were assigned in the second half of the course. These problems often integrated a number of concepts such as heat exchanger relations and refrigeration cycles, or combustion, chemical equilibrium, and power cycles. A short report summarizing the methods used and the conclusions was required with each problem. Examples of two of these problems follow and are included with the demonstration version of the program.

PSYCHROMETRICS PROBLEM

The following psychrometrics problem focuses on the energy requirements for air conditioning a supermarket. The problem uses psychrometric principles in a parametric system analysis to arrive at an optimum design. This problem was the first problem assigned in the course which required a computer solution.

Supermarkets have unusual cooling needs during the summer. Because the freezer cases are normally left uncovered for shopper convenience, frost accumulates on the frozen food products, making them unsightly and reducing the efficiency of the frozen food cases. This problem can be reduced by lowering the humidity in the store. A cooling system designed for this purpose is shown in the figure. 4000 cfm of air at 62°F, 55% relative humidity are supplied at state 5 to maintain comfort conditions in the supermarket. Air returns from the supermarket at 74°F, 54% relative humidity at state 6. 15% of the return air is exhausted and replaced with outdoor ventilation air at 82°F, 48% relative humidity (state 1). Some of the recirculated air is mixed with the ventilation air (state 2) and passed through the cooling coil from which it emerges at saturated conditions (state 3). The rest of the recirculated air bypasses the cooling coil, mixes with the cooling coil outlet air and then enters the reheat coil at state 4. Calculate and plot: a) the heat transfer in the cooling coil; b) the air temperature at state 3; and c) the heat transfer in the reheat coil: as a function of the fraction of the recirculation air which bypasses the cooling coil. What can be concluded from these plots?

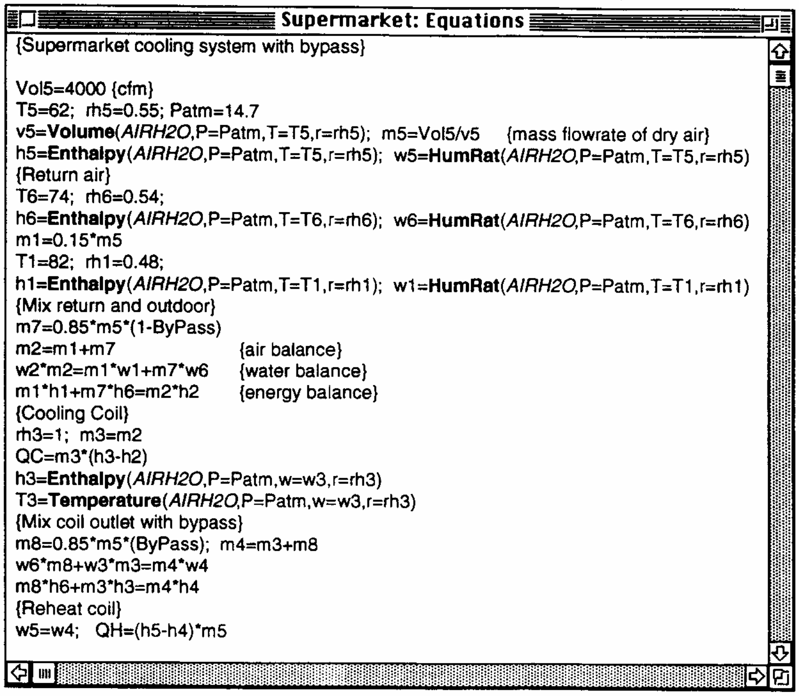


Psychrometric problem figure

The equations entered into EES to solve this problem are shown in Figure 6. Comments appear within curly braces, function names are in bold, substance names are in italics, and semicolons are used to separate multiple equations on the same line. The calculated values of the required cooling coil outlet temperature (T3), and the cooling (QC) and heating (QH) energy rates appear in Figure 7. Figure 8 shows plots of these variables versus bypass fraction (ByPass). The purpose of this problem, in addition to applying psychrometric principles, was to have the students recognize an optimum bypass ratio and practical difficulties. The required coil temperature decreases as the bypass fraction increases. There is a bypass fraction at about 0.6 that minimizes the cooling coil and reheat energy requirements for the conditions of this problem. However, bypass fractions greater than about 0.5 require coil air outlet temperatures that would likely result in formation of ice on the cooling coil. The required amount of water cannot be removed from the supply air with a bypass fraction above about 0.75. A logical extension of this problem would be to also consider the reduction in the performance of the refrigeration cycle which provides energy removal in the cooling coil with increasing bypass fraction.

VAPOR COMPRESSION CYCLE PROBLEM

Most thermodynamic textbooks present a discussion of the effect of source and sink temperature on the coefficient of performance of a refrigeration cycle, but they do not ordinarily discuss the effect of outdoor temperature on the heating or refrigeration capacity. This effect is addressed in the following problem assigned to the undergraduate class. Although the problem involves heat transfer as well as thermodynamics, the necessary heat transfer



```
{Supermarket cooling system with bypass}

Vol5=4000 {cfm}
T5=62; rh5=0.55; Patm=14.7
v5=Volume(AIRH2O,P=Patm,T=T5,r=rh5); m5=Vol5/v5    {mass flowrate of dry air}
h5=Enthalpy(AIRH2O,P=Patm,T=T5,r=rh5); w5=HumRat(AIRH2O,P=Patm,T=T5,r=rh5)
{Return air}
T6=74; rh6=0.54;
h6=Enthalpy(AIRH2O,P=Patm,T=T6,r=rh6); w6=HumRat(AIRH2O,P=Patm,T=T6,r=rh6)
m1=0.15*m5
T1=82; rh1=0.48;
h1=Enthalpy(AIRH2O,P=Patm,T=T1,r=rh1); w1=HumRat(AIRH2O,P=Patm,T=T1,r=rh1)
{Mix return and outdoor}
m7=0.85*m5*(1-ByPass)
m2=m1+m7              {air balance}
w2*m2=m1*w1+m7*w6     {water balance}
m1*h1+m7*h6=m2*h2     {energy balance}
{Cooling Coil}
rh3=1; m3=m2
QC=m3*(h3-h2)
h3=Enthalpy(AIRH2O,P=Patm,w=w3,r=rh3)
T3=Temperature(AIRH2O,P=Patm,w=w3,r=rh3)
{Mix coil outlet with bypass}
m8=0.85*m5*(ByPass); m4=m3+m8
w6*m8+w3*m3=m4*w4
m8*h6+m3*h3=m4*h4
{Reheat coil}
w5=w4; QH=(h5-h4)*m5
```

Figure 6 Equations entered into the EES program to solve the psychrometrics problem.

concepts can be simplified and presented to students who have not yet taken a formal heat transfer course.

A major problem with vapor compression heat pumps is that the capacity, as well as the COP, decreases as the outdoor temperature decreases. The purpose of this problem is to investigate causes of this effect. Consider the vapor compression heat pump shown in the figure which uses R-12. The compressor is a reciprocating constant-displacement device which produces a volumetric flow of 0.0043 m^3/sec. The isentropic efficiency of the compressor is 0.60. The condenser heat transfer rate (which is used to heat the building) is (approximately) described by

$$\dot{Q}_H = \beta(T_C - T_H)$$

where

β is the condenser effectiveness times the mass flow rate times the specific heat of air supplied to the condenser. In this case, $\beta = 1.75$ kW/°K.
T_C is the saturation temperature in the condenser.
T_H is the temperature of air supplied from the building = 20°C.

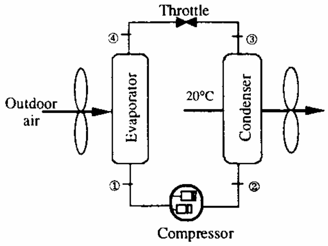
Similarly, the evaporator heat transfer rate is

$$\dot{Q}_L = \alpha(T_{amb} - T_E)$$

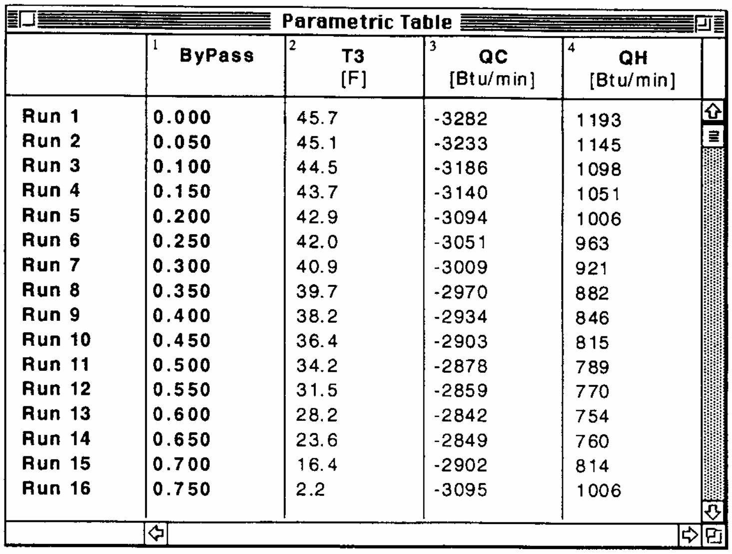
where

α is the evaporator effectiveness times the mass flow rate times specific heat of air supplied to the evaporator which is equal to 0.75 kW/°K.
T_E is the saturation temperature in the evaporator.
T_{amb} is the temperature of air supplied from outdoors to the evaporator.

Construct a plot of the heating capacity ($\dot{Q}_H$) and COP versus T_{amb}. Provide an explanation for the trends shown in the plot.



The equations in Figure 9 have one degree of freedom, ie, there is one more variable than equation. The degrees of freedom becomes zero by parametrically varying the outdoor air temperature, Tamb in a Parametric table. Calculated results are shown in Figure 10. A plot of the COP and heating capacity (QH) versus the outdoor temperature



Parametric Table

	1 ByPass	2 T3 [F]	3 QC [Btu/min]	4 QH [Btu/min]
Run 1	0.000	45.7	-3282	1193
Run 2	0.050	45.1	-3233	1145
Run 3	0.100	44.5	-3186	1098
Run 4	0.150	43.7	-3140	1051
Run 5	0.200	42.9	-3094	1006
Run 6	0.250	42.0	-3051	963
Run 7	0.300	40.9	-3009	921
Run 8	0.350	39.7	-2970	882
Run 9	0.400	38.2	-2934	846
Run 10	0.450	36.4	-2903	815
Run 11	0.500	34.2	-2878	789
Run 12	0.550	31.5	-2859	770
Run 13	0.600	28.2	-2842	754
Run 14	0.650	23.6	-2849	760
Run 15	0.700	16.4	-2902	814
Run 16	0.750	2.2	-3095	1006

Figure 7 Calculated results as a function of bypass factor.

(Tamb) appears in Figure 11. One explanation for the reduction in heating capacity, which is apparent from the data in Figure 10, is that the refrigerant mass flow rate decreases as the outdoor temperature decreases. The mass flow rate decreases because the volumetric flow rate is constant and the density of the refrigerant at the compressor inlet decreases with decreasing outdoor temperature due to its decreasing saturation pressure.

A number of additional studies could be done at this point. For example, R-12 is known to be a major factor in the depletion of stratospheric ozone. What reduction in performance arises if R-134a is substituted for refrigerant R-12? How are the above results changed if the heat exchanger parameters are varied? How is the capacity related to compressor displacement? Would a more detailed heat transfer analysis affect the trends obtained with this simple analysis? Answers to these and other questions could be obtained literally in a few seconds. An extension to this problem which could be assigned to students who have taken a heat transfer course is to have the students determine the heat transfer effectiveness factors from the heat exchanger geometry and flow conditions.

WHAT DID STUDENTS THINK OF THE CHANGES?

Another change that was made in the modified course was a reduction from 3- to 2-hour exams.

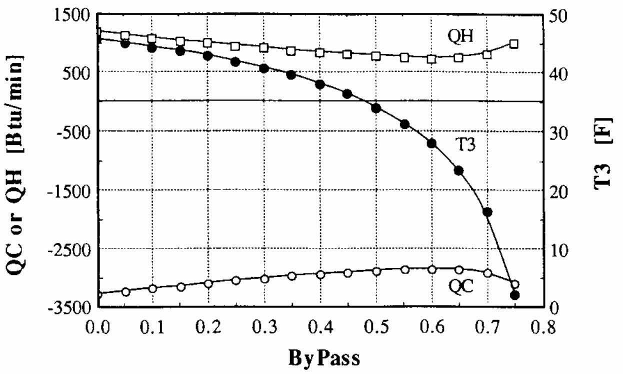
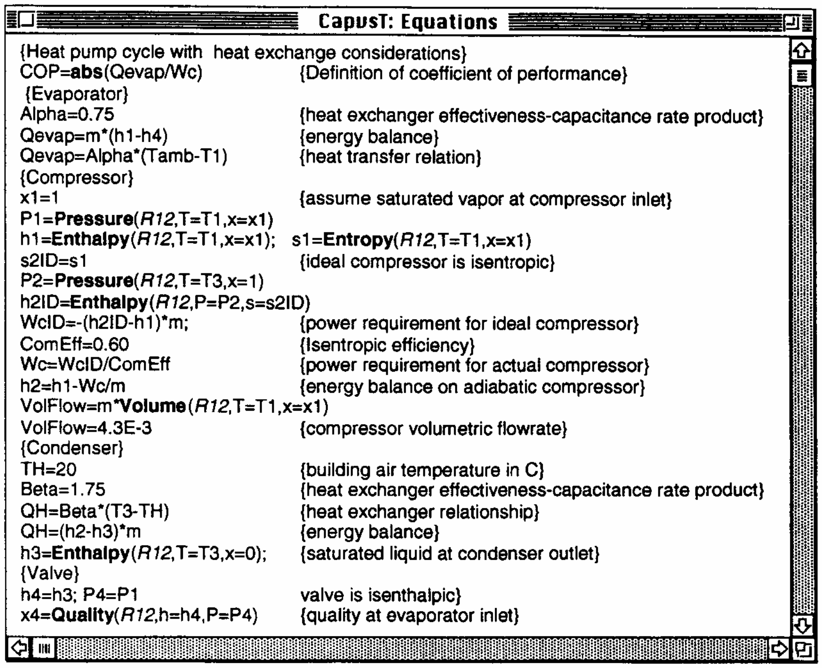


Figure 8 Solution to the psychrometrics problem showing plots of the coiling coil temperature (T3) and the cooling (QC) and reheat (QH) energy rates as a function of the fraction of the return air which bypasses the cooling coil.

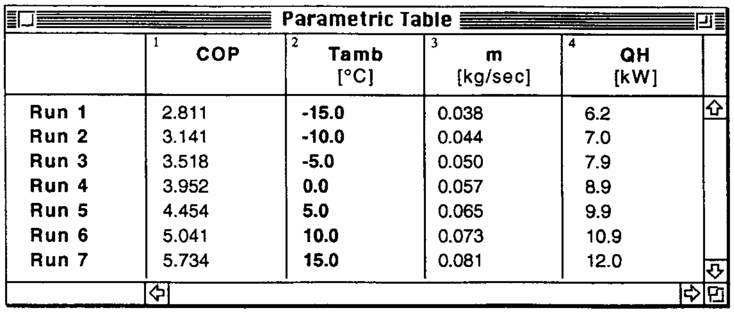


```
{Heat pump cycle with  heat exchange considerations}
COP=abs(Qevap/Wc)               {Definition of coefficient of performance}
 {Evaporator}
Alpha=0.75                      {heat exchanger effectiveness-capacitance rate product}
Qevap=m*(h1-h4)                 {energy balance}
Qevap=Alpha*(Tamb-T1)           {heat transfer relation}
{Compressor}
x1=1                            {assume saturated vapor at compressor inlet}
P1=Pressure(R12,T=T1,x=x1)
h1=Enthalpy(R12,T=T1,x=x1);  s1=Entropy(R12,T=T1,x=x1)
s2ID=s1                         {ideal compressor is isentropic}
P2=Pressure(R12,T=T3,x=1)
h2ID=Enthalpy(R12,P=P2,s=s2ID)
WcID=-(h2ID-h1)*m;              {power requirement for ideal compressor}
ComEff=0.60                     {Isentropic efficiency}
Wc=WcID/ComEff                  {power requirement for actual compressor}
h2=h1-Wc/m                      {energy balance on adiabatic compressor}
VolFlow=m*Volume(R12,T=T1,x=x1)
VolFlow=4.3E-3                  {compressor volumetric flowrate}
{Condenser}
TH=20                           {building air temperature in C}
Beta=1.75                       {heat exchanger effectiveness-capacitance rate product}
QH=Beta*(T3-TH)                 {heat exchanger relationship}
QH=(h2-h3)*m                    {energy balance}
h3=Enthalpy(R12,T=T3,x=0);      {saturated liquid at condenser outlet}
{Valve}
h4=h3; P4=P1                    valve is isenthalpic}
x4=Quality(R12,h=h4,P=P4)       {quality at evaporator inlet}
```

Figure 9 Equations entered into the EES program to solve the heat pump problem.

The grade for the seven homework problems was weighted equivalent to an hour exam. For this reason, students were conscientious about these problems. Anonymous comments were solicited from students at the end of the semester. It is clear from these comments that the students thought highly of EES and the revised curriculum. Many students indicated that they are using EES in their other courses. However, a number of concerns were apparent. The major concern was the nature of what was expected of them for the final exam. They had used EES exclusively for 8 weeks but they were aware that they would not be able to use EES on the final exam. This concern was addressed by devising a final exam that placed emphasis on the solution methods rather than on numerical answers.

Some students indicated that they that had spent a great deal of time trying to get EES to converge. There are several reasons why students experienced difficulties of this type. Approximately half of the assigned problems required the students to provide reasonable starting guesses for intermediate variables, either because the equations were highly nonlinear or to avoid calling property function routines with independent variables which were out of the range of the correlations. In some problems, the correct equations became unsolvable as a design value was varied. The psychrometrics problem, for example, can only be solved for bypass factors up to approximately 0.8. Larger bypass factors do not allow a mass balance to be satisfied. Some students started this problem with a bypass factor of 0.95 and



	1 COP	2 Tamb [°C]	3 m [kg/sec]	4 QH [kW]
Run 1	2.811	**-15.0**	0.038	6.2
Run 2	3.141	**-10.0**	0.044	7.0
Run 3	3.518	**-5.0**	0.050	7.9
Run 4	3.952	**0.0**	0.057	8.9
Run 5	4.454	**5.0**	0.065	9.9
Run 6	5.041	**10.0**	0.073	10.9
Run 7	5.734	**15.0**	0.081	12.0

Figure 10 Parametric table showing calculated results for selected values of Tamb.

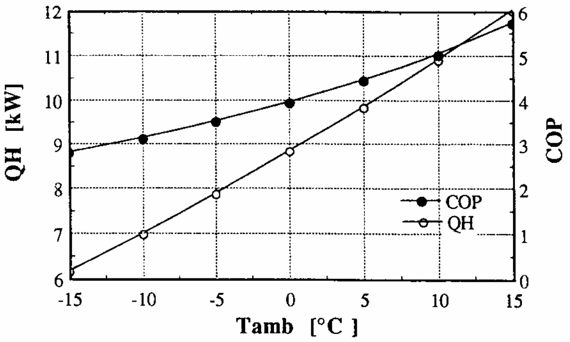


Figure 11 Plot of COP and heating capacity as a function of outdoor temperature.

were never able to find a solution since a real solution is not possible under these circumstances. In the majority of cases in which the students could not obtain a solution, however, they had entered incorrect equations, either because their analysis was incorrect or because they had a small problem, such as a sign error. It is understandable that some students assumed the software was not operating properly before they recognized their error. In fact, only minor problems in EES were encountered during these classes. A common suggestion was that that EES should provide more help identifying problems, rather than simply indicate which equation could not be solved. However, the general nature of EES makes it difficult to incorporate specific diagnostic capability. The experiences in the first offering of the modified course indicated that additional class time should be devoted to a discussion of the numerical methods used in EES and convergence techniques. The second offering, in which this discussion was added, reduced student problems.

It is difficult to quantify the effect of changes in a course of this type. However, one point is clear. Considerably more subject matter was presented to the students within the same number of credit hours and far more difficult problems were assigned than in previous offerings of this course at Wisconsin. Almost all of the students were able to do the assigned problems.

CONCLUSIONS

The content of undergraduate thermodynamics courses was established long before microcomputers existed. Problem assignments appearing in popular textbooks have been developed with an understanding that students will work them by hand. Interesting practical problems which are difficult to solve or which involve parametric studies are usually not assigned because the mathematical complexity would require an unreasonable time investment by the students and the faculty. These considerations have led the author to develop an equation-solving program specifically for problems in the thermosciences. The program allows students to concentrate on the fundamental engineering principles without being distracted by the mathematics and property data required to solve the necessary equations. As a consequence, students can do more comprehensive design problems and cover more material without necessarily devoting more study time to the course.

APPENDIX

The disk distributed with this issue of *Computer Applications in Engineering Education* contains a demonstration version of EES for the DOS operating system in compressed form. EES will operate on any standard IBM-compatible computer having 640 kBytes of memory and DOS 3.0 or later. To uncompress the program and store it and supplementary files in subdirectory \EES hard disk drive C: enter

```
UNZIP
```

Instructions for installing EES on other drives and additional information are provided in the README file on the EES disk. To view these instructions, enter

```
README
```

An EXAMPLES subdirectory will be created within the EES directory. The two problems presented in this paper, SUPERMKT.EES and CAPVST.EES, are in the EXAMPLES subdirectory, along with other example files.

ACKNOWLEDGMENT

The sparse matrix equation-solving algorithms in EES were developed by F. L. Alvarado of the Electrical Engineering Dept. at University of Wisconsin-Madison.

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BIOGRAPHY

Dr. S. A. Klein is a professor of Mechanical Engineering at University of Wisconsin-Madison. His engineering degrees (BS, University of Illinois-Chicago; MS, PhD, University of Wisconsin-Madison) were obtained in Chemical Engineering. Professor Klein is a member of the Solar Energy Laboratory at Wisconsin. He is the developer of the F-Chart method for sizing solar heating systems, and the TRNSYS simulation program, which is widely used in simulations of solar processes. Currently, Professor Klein is involved in research on solar energy system performance, absorption power cycles, finite-time thermodynamics applications, adsorption processes for air conditioning and air quality control, and alternative refrigerants and systems for refrigeration and air conditioning applications. Professor Klein is also involved in the development of engineering computer tools for both instruction and research. In addition to the EES program described in this paper, he is the primary author of the thermodynamics instructional program, CP/Thermo, and the finite element program, FEHT.