Use of Computer Tools in Teaching Mechanical Engineering Thermodynamics

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Introduction

Mechanical Engineering thermodynamics is a problem-solving discipline. To learn the required material, it is necessary for the student to work problems. This paper describes two computer programs in use at Wisconsin which have been developed to help students learn to solve thermodynamics problems. The objectives and approach of each program are presented along with our experiences in using them in classes.

CP/Thermo: Computerized Problems for Thermodynamics

CP/Thermo is a tutorial program intended to help students learn to solve thermodynamics problems on their own, outside of class. The program is designed for use on APPLE Macintosh or IBM PC/XT/AT/PS2 (or compatible) microcomputers. *CP/Thermo* is specifically intended for students in their first and second Mechanical Engineering thermodynamics courses. The program includes 170 thermodynamics problems covering nearly all subjects encountered in a two-semester mechanical engineering thermodynamics course sequence, including power/refrigeration cycles, psychrometrics, combustion, and chemical equilibrium. *CP/Thermo* has a highly interactive structure which has been designed to allow students to solve a problem in an unrestrictive manner. The major feature of the program is the availability of very specific help, appropriate to the solution path chosen by the student, if it is requested.

To learn thermodynamics, one must work problems. In most thermodynamics courses, students are assigned problems to work outside of class. For some students, *CP/Thermo* offers the following advantages over the conventional approach of doing homework. First, in the event that the student is stuck and cannot solve the problem, he or she can obtain a hint or a specific suggestion with the HELP command. The help is provided at several levels. At first, a clue is given, followed by increasingly detailed suggestions as more help is requested. The alternative with the conventional approach is to ask the instructor or more likely, to discontinue working on the problem. Second, the computer eliminates some of the work associated with solving problems, such as looking up some properties in tables and solving algebraic equations. Freed from these tasks, the student is more able to concentrate his or her attention on the concepts. *CP/Thermo* may also offer advantages to the course instructor by reducing the student's dependence on the instructor outside of class and by providing a base of well-formulated, solved problems.

A problem, typical of what could be assigned in a first semester thermodynamics course, will be briefly presented to demonstrate *CP/Thermo*. The following overview is specific to the Macintosh version, but operation is similar on the IBM/compatible version. At the start of the program, the student selects a problem by clicking the mouse button on the problem name from the scrollable list shown in Figure 1.

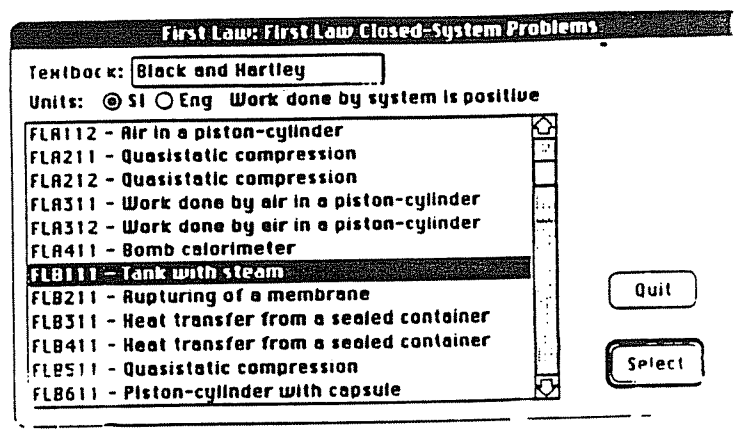


Figure 1: Problem selection menu

The student can change the textbook specification by clicking the mouse button in the textbook rectangle near the top of the window. A pop-up menu will display the textbook choices. The textbook choice affects the reference states used for the air tables and the psychrometric chart, as well as the sign convention used for work done by the system. All problems operate in both SI and English units as determined by clicking the SI or English button.

After selecting the problem, *CP/Thermo* will display windows showing the problem statement, a figure, and a status screen which summarizes known information, as shown in Figure 2. This problem, which involves the first law of thermodynamics, would ordinary be assigned in a first semester course. There is also a nomenclature, equation summary, and score window. Any of these windows can be brought to the front, moved, resized, or hidden.

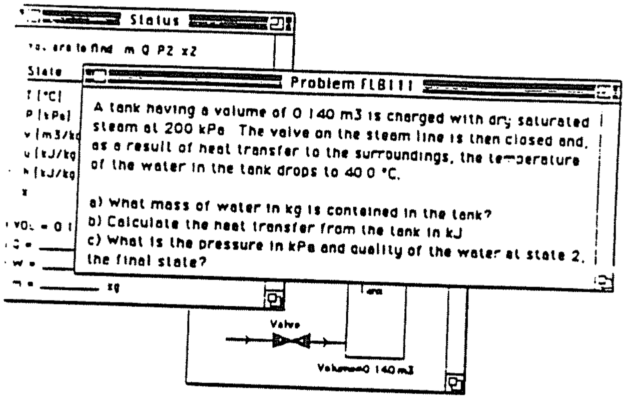


Figure 2: Problem statement, status and figure windows at the start of a problem

CP/Thermo is controlled from seven pull-down menus at the top of the screen.

File	**Options**	**System**	**Operation**	**Properties**	**Window**	**Help**

The **FILE** menu allows printing and a means to quit the program or begin another problem.

The **OPTIONS** menu provides settings for the sound effects, new user reminders, and a stacking command to organize the positions of the windows on the screen.

The **SYSTEM** menu contains a list of system choices appropriate to the problem at hand. In a simple gas turbine problem, for example, the choices would be the compressor, turbine, combustor, and entire cycle.

The **OPERATION** menu lists the operations (e.g. mass balance, energy balance, etc.) appropriate to the selected system. This menu changes as different systems are selected.

The **PROPERTIES** menu contains an entry for each state in the problem. Selecting a state opens a window in which known properties values for the state are listed and the values of unknown properties can be entered. The program checks all entered values to ensure that they are correct. The function of this menu is analogous to that of steam tables (or other appropriate property relations) which must be called upon to solve the problem.

The **WINDOW** mean lists all of the windows for the problem. Selecting a window from this menu brings the window to the front and makes it visible if it were previously hidden.

The **HELP** menu has two entries which provide (1) help with the problem and (2) help using the program. The Help processor is quite complex and it is the major feature of *CP/Thermo*. Both types of help are context-sensitive. If help using the program is requested, the information provided is specific to the frontmost window. This is true also for the help provided in solving the problem. In addition, the Help processor monitors the student's progress and attempts to provide useful information specific to the manner the student has chosen to solve the problem. Help is provided in steps. The first request provides a hint; progressively more information is provided with additional help requests. Using the **HELP** menu, the student will always be able to complete the problem, since with enough help requests, the program will walk the student, step-by-step, through the problem in an organized manner.

The student proceeds with the problem solution by choosing a system and an operation. Selecting an operation from the menu opens a window for the operation, placing it in front. Depending on the operation selected, one of three situations will occur.

a) The appropriate equation for the operation will be displayed with check marks above the symbols in the equation which have known values. Clicking on a symbol which has a check mark above it (e.g., VOL in Figure 3) causes its value to be displayed. Clicking on any other symbol (e.g., m) will open an edit box so that its value can be entered as shown in Figure 3. An algebraic expression with numbers and/or symbols of known quantities can be entered in the box.

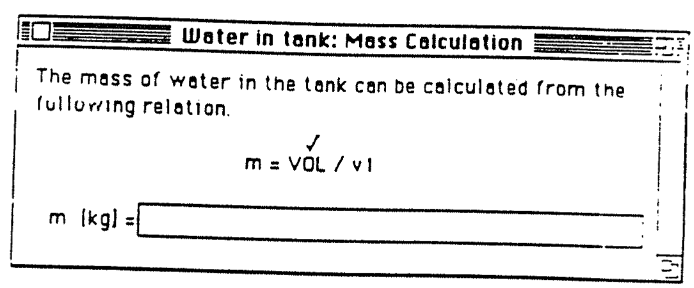


Figure 3: Mass calculation screen waiting to accept the value of m

b) An edit box will be presented for the student to enter the appropriate equation symbolically. A "calculator" will appear with buttons showing all of the allowable symbols, as shown in Figure 4. Some of these symbols do not belong in the equation. The calculator is provided for convenience and to minimize typing. Of course, the keyboard and standard editing features can be used as well.

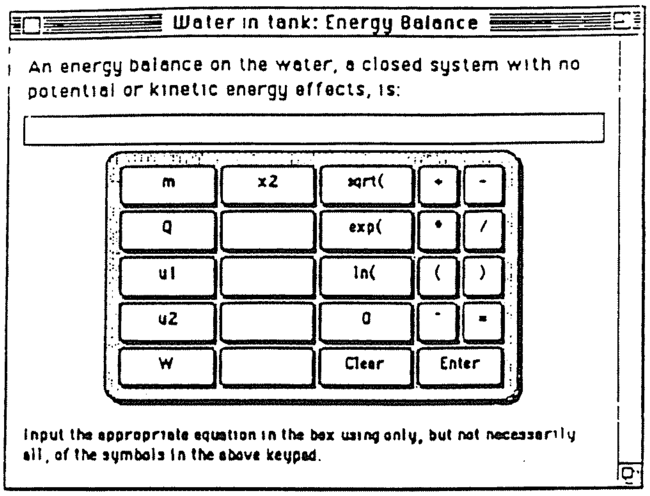


Figure 4: Energy balance screen waiting to accept symbolic equation

c) An edit box will appear for the student to enter the numerical value for a specified quantity in the correct units, as shown in Figure 5 for the specific volume at state 2. An algebraic expression can be entered. *CP/Thermo* will evaluate the expression using the same rules as used in FORTRAN. The expression can contain numerical constants or any of the symbols shown in the Status window, provided that their values are known.

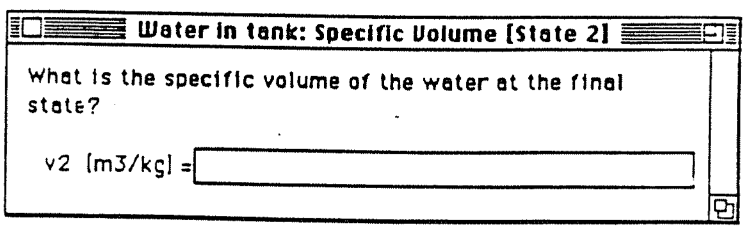


Figure 5: Specific volume screen waiting to accept numerical value of v2

Use of the program proceeds with the student entering the values of quantities, state properties and necessary equations in a manner similar to that used when the problem is being solved by hand in the conventional manner. The status and equation summary windows are continuously updated as the solution progresses. At an intermediate point in a problem, the status screen appears as shown in Figure 6, with blanks indicating as yet unknown values. The student may enter values or algebraic expressions directly into blank spaces on the status window, if desired. At the conclusion of the problem, a problem summary is provided showing the problem statement, figure, nomenclature, all appropriate equations and the completed status table. A score and elapsed time and students name are also provided on the printed output.

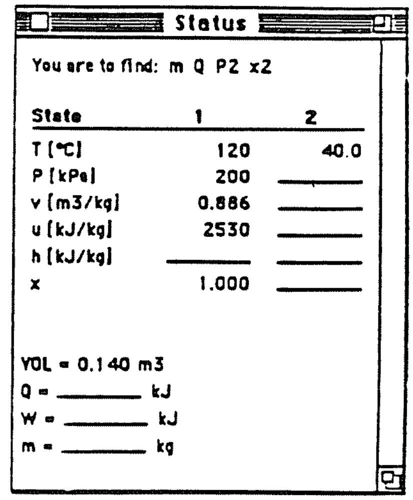


Figure 6: Status screen for problem FLB111 at an intermediate point

CP/Thermo began as an independent study project with six mechanical engineering seniors in Spring, 1984. The project first focused on identifying the areas which give thermodynamics students trouble. The results of this analysis were not as clear-cut as we initially hoped. We learned that students encounter a variety of problem types in two semesters of mechanical engineering thermodynamics and each problem type requires somewhat different skills. In some cases, the students have difficulty knowing what assumptions can be applied for a given process; in other cases, e.g., psychrometrics, students have trouble with definitions and fundamental relations. Together with the six students, we designed a general format for an instructional thermodynamics program that would accommodate the variety of problems encountered in the course. The six students were then each assigned to write a section of the program in BASIC for the Apple II computer. Although none of the original code written by the students remains in the current version of *CP/Thermo*, the ideas generated during the independent study project determined the program design.

CP/Thermo has been used in our undergraduate thermodynamics courses since the Fall semester of 1985. At the end of each semester, we solicited anonymous comments from the students. A number of refinements in the program interface have been made in the past few years, based on the students' comments. In addition, we experimented with different ways of using *CP/Thermo* in our classes. We have found that:

a) *CP/Thermo* should be integrated into the course along with conventional homework. It is generally unsatisfactory to assign only two or three *CP/Thermo* problems during a semester. The effort required to become comfortable with the program operation doesn't pay off if the program is used for only a few problems.

b) The best strategy is to allow *CP/Thermo* problems to be done either on the computer or by hand. Some student preferred to do homework problems on the computer; others cannot think in front of a video screen. In some cases, it is inconvenient for a student to find an open computer terminal at the time he or she wishes to do the homework.

c) *CP/Thermo* cannot be used without some faculty encouragement. Some students who used the program extensively indicated that they would not have even tried using the program if it were entirely optional. This result is not a negative reflection on the program in that most students would not do any type of homework if it were not required. We have found that it is useful to force students to use *CP/Thermo* to do 2 or 3 problems. At that point, they can decide whether or not to continue using the program.

d) No significance should be attached to the score. The major purpose of the score is to make the student think twice about asking for help; in the majority of cases, this strategy seems to work. The elapsed time may actually provide a better indication of the student's effort than the score.

In our classes, we assign about 50% of the homework from the *CP/Thermo* problem library. Each class period has an associated homework set with problems selected from *CP/Thermo* , the text or both. We distribute the problem statements of the *CP/Thermo* problems we have assigned with the syllabus. We accept either the *CP/Thermo* output or a handwritten solution for the problem assignment.

A version of *CP/Thermo* has been developed to accompany the second edition of Black and Hartley's THERMODYNAMICS published by Harper-Collins. The problems currently in *CP/Thermo* have been added to the textbook, with an identifying icon in the margin indicating that these problems can be done using the software. Schools which adopt this textbook will be licensed to use *CP/Thermo* at no charge.

Although we have several years of experience in using *CP/Thermo* we have no definitive measure of the extent to which the program helps students learn to solve thermodynamics problems. Students learn the material in a variety of ways. They come to lectures, they read the textbook, and they talk to their friends, all of which confounds any effects that program may have on their learning. Our judgement, based on students' comments at the end of each semester since Fall semester 1985, is that the program is useful to many student and not useful to some. The fact that more than 50% voluntarily elect to do their assignments with *CP/Thermo* is encouraging.

A major limitation of *CP/Thermo* is that it relies upon previously prepared problem information. The student cannot alter the problem nor can he or she use the program to determine the effect of changes in parameter values. This capability is provided in the program which is described in the next section.

EES: Engineering Equation Solver

Much of the time and effort required to solve thermodynamics problems results from looking up property information and doing the required algebra. Once the student is familiar with the use of property tables, further use of the tables does not contribute to the student's grasp of the subject; nor does the algebra. The time an effort required for these auxiliary tasks actually detracts from learning of the subject matter by directing attention away from the new or important concepts. An additional problem is that students cannot be expected to do parametric studies because of the effort required to do the necessary calculations. However, the results of parametric studies provide much more information and insight concerning the operation of a thermodynamic system than does a single point calculation.

The computational effort involved in solving thermodynamics problems can be greatly reduced by using one of the many equation-solving programs that have been developed for use on microcomputers within the last few years. With the capabilities provided by such programs, students can be assigned more interesting and practical problems (which tend to be more complicated computationally) and become involved in design studies. Of specific interest to problems in thermodynamics is the ability to solve sets of non-linear algebraic equation, incorporating thermophysical property data. EES was developed specifically for this purpose.

EES is similar to other equation solving programs in its ability to solve non-linear equations, but it differs in that it incorporates a large bank of thermophysical property information which is useful 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 most chloro-flouro-carbon refrigerants (including R-123 and R-134a), ammonia and nitrogen. Air tables are built-in, as are psychrometric functions and JANAF table data for many common gases. Transport property functions are also provided for all of these substances. Additional data can be added by the user as functions written directly in EES, in tabular form, or as code written high-level language such as Pascal or C.

It is necessary to consider a specific example to describe EES. The following vapor compression design problem has been prepared as a homework problem for the undergraduate thermodynamics applications 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 a 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

$$Q_H = \alpha(T_C - T_H)$$

where

α is the product of the condenser effectiveness and the mass flow rate and specific heat of air supplied to the condenser. In this case, α = 0.75 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

$$Q_H = \beta\,(T_{amb} - T_E)$$

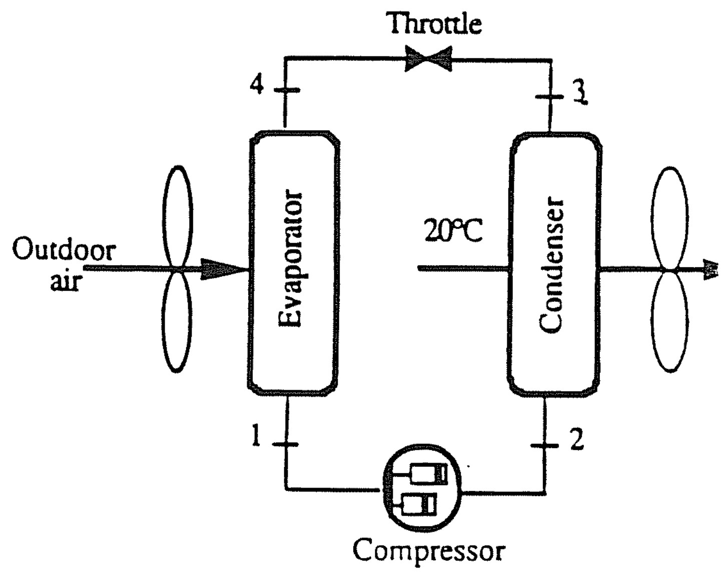
where

β is the product of the evaporator effectiveness and the mass flow rate and specific heat of air supplied to the evaporator which is 1.75 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 and COP versus the outdoor temperature. Provide an explanation for the trends shown in the plot.



A problem of this type does not appear in undergraduate thermodynamics textbooks and it would not ordinarily be assigned in an undergraduate course. Why not? The effect of outdoor temperature on the heat pump heating capacity is surely of importance. Although the problem involves concepts of heat transfer as well as thermodynamics, the necessary heat transfer concepts can be simplified (as done in the problem statement) and presented to students who have not yet taken a formal heat transfer course. The major reason a problem of this type would not be assigned is that the computational effort required by the student would be overwhelming.

Using EES, this problem can be solved with the same (or even less) time and effort required of traditional homework problems appearing in the textbook which are worked by hand. The student enters the appropriate equations, in any desired format and order, as with a word processor. A set of equations which solve this problem appear in Figure 7. The program formats the equations, checks syntax and ensures that the number of unknowns and equations are equal. Figure 7 appears more complicated than it really is since the text within braces are optional comments. Property table data are provided by the program, eliminating a significant part of the student's effort. The property data functions, e.g., **Enthalpy**, are displayed in boldface and fluid names, e.g., *R-12*, are displayed in italics.

Equation Worksheet

```
{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}
QL=m*(h1-h4)                                          {energy balance}
QL=Alpha*(Tamb-T1)                        {heat exchanger relationship}

{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 flow rate}

{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 7: EES Equation Worksheet Window

EES has a parametric table option, with plotting capability, so that the equations in the worksheet can be solved repeatedly for a range of parameter values. In this case, the parameter which is to be varied is the outdoor air temperature, T_{amb}. The parametric table for this problem is shown in Figure 8. There is one degree of freedom (i.e., one more variable than equation) in Figure 7. Setting the value of T_{amb} in the parametric table (as indicated by the bold-faced notation in Figure 8) removes this degree of freedom and permits the equations to be solved. The values in the remaining cells are calculated and displayed by EES. A plot of the COP and heating capacity (Q_H) versus the outdoor temperature (T_{amb}) appears in Figure 9.

Parametric Table

	COP	Tamb [°C]	QH [kW]	m [kg/sec]
Run 1	2.811	-15	-6.2	0.038
Run 2	3.141	-10	-7.0	0.044
Run 3	3.518	-5	-7.9	0.050
Run 4	3.952	0	-8.9	0.057
Run 5	4.454	5	-9.9	0.065
Run 6	5.041	10	-10.9	0.073
Run 7	5.734	15	-12.0	0.081
Avg	4.093	0	-9.0	0.058
Sum	28.650	0	-62.8	0.407

Figure 8: EES Parametric Table showing tabular solution

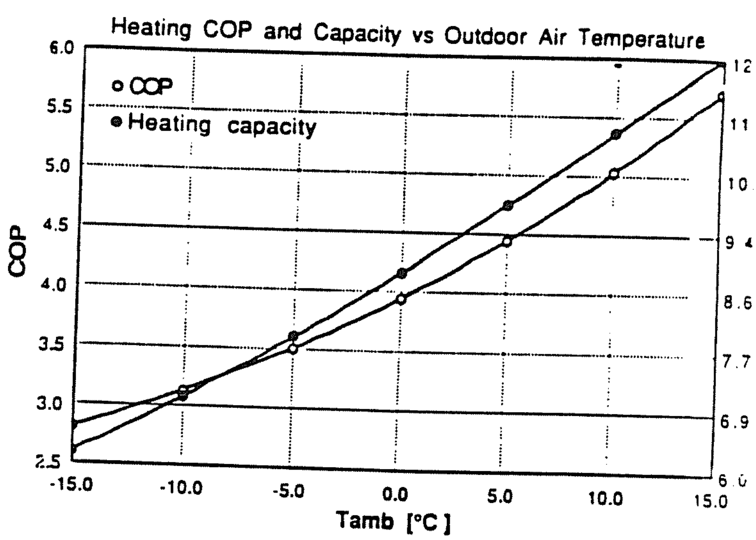


Figure 9: EES plot of COP and heating capacity as a function of outdoor temperature

A number of additional studies could be done at this point. For example, refrigerant-12 is known to be a major factor in the depletion of stratospheric ozone. What reduction in performance arises if refrigerant-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 the simple analysis? Answers to these and other questions could be obtained, literally, in a few seconds.

Conclusions

Although *CP/Thermo* and EES are both designed to help students learn thermodynamics, they use very different approaches. The strengths of *CP/Thermo* are that it conforms closely to the type of thermodynamics problems currently assigned in undergraduate courses; it provides very specific tutorial help for such problems individualized to the needs of the student. The major disadvantage is that the problems are fixed; students cannot change the problems and they cannot use the program to answer *"what if"* type questions.

EES, on the other hand, is a computational tool, rather than a tutorial program. EES eliminates the algebra and property table look-ups associated with thermodynamics problems, but it does not provide specific help relating to how the problem should be solved. At this point, we have had little experience to report on using EES in the undergraduate thermodynamics courses. We have observed that students need little encouragement to use EES and that they tend to use it for assignments in their other courses, even those that do not require thermophysical property data.

With this program and others of this type, it is possible to assign students design studies and problems that are more involved than those appearing in current textbooks. Problems involving concepts of heat transfer and fluid mechanics as well as thermodynamics can be considered whereas they would not previously be assigned because of the computational complexity. The capabilities of the program have caused us to reconsider the sequence of courses offered in our thermal sciences curriculum. It may be advantageous to modify the existing curriculum so that fluid mechanics and heat transfer are prerequisite to the second thermodynamics course. Students would then be in a much better position to appreciate the integration of the thermal sciences in the design of thermal equipment presented in the final thermodynamics applications course. More generally, a reevaluation of the sequence and content of all engineering courses is warranted by the existence of increasingly powerful computer tools.