Developing Problem-Solving Skills in Thermodynamics Courses

Frederick H. Reardon
California State University, Sacramento

Abstract

In teaching thermodynamics, it is essential to teach a systematic problem-solving methodology because of the nonlinear structure of the subject. The methodology is based on the structure of thermodynamics and so helps to clarify and organize the scientific concepts involved. The methodology has seven steps: (1) Restate the problem; (2) Define the system under consideration and the kind of process involved. Define the system and the kind of process involved; (3) Express the Principles (Laws) of Thermodynamics in a form suitable to the system and process; (4) Determine what Properties are involved and how to find values for them; (5) Describe the Process in terms of the changes in system properties Describe the Process in terms of the changes in system properties; (6) Substitute the known property values and process relations into the Principles equations; and (7) Calculate the desired answers and check their reasonableness. Most students respond favorably to this problem-solving approach. Although this methodology has been developed specifically for thermodynamics, a similar approach can be helpful in other subject areas.

Introduction

Problem-solving is an important skill in all areas of engineering and technology. However, in teaching thermodynamics, it is essential to teach a systematic problem-solving methodology in order that the the scientific concepts can be mastered. Thermodynamics is not a linear subject. In fact, it seems to me that it has a triangular structure, consisting of Principles, Processes, and Properties (Figure 1). In each of these three areas, there are numerous equations. Until they understand the structure of the subject, students tend to be overwhelmed by the number of equations, constants, and parameters. They want an example for every possible kind of problem, so that they can know how to get the answers to homework and exam problems. Rather than doing that, which is really impossible, I teach them a structured problem-solving methodology. The methodology is based on the structure of thermodynamics and so helps to clarify and organize the scientific concepts involved.

The Methodology

The methodology, which has been developed on the basis of three decades of helping students to solve thermodynamics problems, has seven steps:

(1) Restate the problem or question so that you really know what is to be found. This is relatively easy in the classroom, but may be more difficult in an industrial setting.

(2) Define the system under consideration and the kind of process involved. This involves specifying the system boundaries and their properties, what kind of material is in the system, and whether the process involves steady flow or a change from one state of the system to another. I suggest that they draw a sketch that shows the system boundaries and any mass or energy flows across the boundary.

(3) Express the Principles (Laws) of Thermodynamics in a form suitable to the system and process. Rather than dealing with the most general forms of the equations of conservation of mass and energy, and the increase of entropy equation, I show my students that it is easier to deal with separate equations for (a) closed system change of state process, (b) change of state process with mass transfer (open system), and (c) steady flow process of an open system. At the undergraduate level, we do not take up problems involving transient (time-dependent) processes.

(4) Determine what Properties are involved and how to find values for them. The properties needed are those involved in the principles equations, rather than all properties for which equations or tables are available. What I ask the students to do at this point is write down the property equations or state what tables are to be used.

(5) Describe the Process in terms of the changes in system properties. This involves sorting the given information into initial (or input) property values, final (or output) property values, and energy transfers. Also, any special equations (e.g., for a polytropic process) that apply to the process are to be written down. I encourage the students to make a table in which the system properties can be entered, the given values at first, and then each of the values calculated during the solution of the problem,

(6) Substitute the known property values and process relations into the Principles equations. This procedure (which tests their ability to do algebra) is helpful in showing how to proceed toward the determining of “what is to be found.”

(7) Calculate the desired answers and check their reasonableness. At first, of course, the students do know what is reasonable, unless they have paid some attention to what has happened in energy processes they have experienced. Later, they have a better idea of what answers are reasonable, but have to be reminded (repeatedly) to look at the numbers they have calculated.

Teaching the Methodology

This methodology is introduced by a detailed discussion of the diagram of Figure 2, using a PowerPoint presentation. It is demonstrated by examples whenever a new topic is introduced. Initially, students are guided, in class work and then in homework problems, by questions related to each step. Figure 3 shows a typical homework problem, with the solution, which is discussed in class (after all students have turned in the homework) with emphasis on the methodology rather than on number crunching. Figure 4 shows a typical examination, in which the steps of the problem-solving methodology are specifically required.

Later, when dealing with more complex problems, the students are asked to describe their solution process in addition to giving the answers. After one or two homework assignments involving such descriptions, most students are able to do it reasonably well and understand how it relates to the problem-solving process.

Evaluation of Students' Problem Solving

The problem-solving methodology has been taught for several years at CSUS. However, specific assessment of the students use of the methodology has not been attempted until recently. The data in this paper are derived from the spring and fall semesters of 2000. In the MET program at CSUS, the fundamentals of thermodynamics are taught in the spring term; applications to more complex systems, including power plants and HVAC, are studied in the fall semester. Students' approach to solving problems in a systematic way was evaluated, using the primary trait analysis approach of Walvoord and Anderson[1], on both homework assignments and examinations.

The second of two mid-term examinations given in the first thermodynamics course is shown in Figure 4. The grading spreadsheet for this exam is given in Figure 5. Overall, this exam showed somewhat better scores in terms of the problem-solving methodology than the first examination (not shown here). On the first problem, defining the system and writing the principles equations were handled reasonably well, with average student scores of 82% and 85% of the maximum, respectively. The class performance on defining the process was nearly as good (78%), probably because the problem dealt with steady flow (also called "steady state flow" or "steady-state, steady-flow"). It can be seen that the students were more successful in setting up the properties table (65%) than in finding the properties (58%) and using them to calculate the answer (46%), probably because they were dealing with steam and had to use tables. On the second problem, they had more trouble with the principles equations, with an average score of 67%, compared to the 85% on the first problem. The second problem was of the type that I call "open-system change-of-state", for which the principles equations are more complex. than for the steady flow type of process. The students were more successful in finding the properties of helium (71%) than they were on the first problem with the properties of water (58%). On both problems, they had difficulty in putting all of the information together and finding answers. The overall class results were discussed when the graded exams were returned; the discussion focused on the weak places in the students' problem-solving techniques. To compensate for the time pressure involved in the examination process, as well as for the fact that it was only the second of four exams, the grades recorded with adjusted to move the class average to 75.

Figure 6 shows the second of three problems on the final examination, along with a summary of the grading results. Note that the students were not specifically directed to follow the problem-solving methodology, but did so reasonably well, given the time pressure. They still had problems with the properties of H_2O and with putting all of the information together to get the required answers.

The first homework of the second semester (Figure 7) was graded in terms of the problem-solving methodology (Figure 8). The homework grading is done on a coarser scale than that used for exams. In general, the results show that the students remembered the problem-solving methodology and were able to use it reasonably well. Of course, homework does not have the time pressure of an exam (and allows for discussion with classmates). Throughout the second semester, the students were asked to describe their solution procedure. Most of them did follow the methodology described here in solving both homework and examination problems.

Conclusions

Although there is not yet very much statistical evidence, this problem-solving methodology appears to be learned and retained by students. Most students respond favorably to this problem-solving approach. They come to understand that the small amount of extra time and effort involved in specifying each step actually can save them time in working out the solution to a problem. Of course, there still exists the typical student desire to have an example of every kind of problem that they will ever confront so that they can just change the numbers and crank out the answers. Fighting this desire is a never-ending process, and it is helpful to be able to point out that with the seven-step problem-solving method, there is no need for a vast collection of examples.

Tthis methodology has been developed specifically for thermodynamics; however, a similar approach can be helpful in other subject areas. In fact, it would be very beneficial if systematic problem-solving methodologies were stressed in all courses. The students could see that the different courses they take are not unrelated, but are part of a professional whole.

Bibliography

1. Walvoord, B. E., and Anderson, V. J., *Effective Grading: A Tool for Learning and Assessment*, San Francisco, CA: Jossey-Bass Publishers (1998)

FREDERICK H. REARDON

Fred Reardon is Professor of Mechanical Engineering and Coordinator of the Mechanical Engineering Technology Program at California State University, Sacramento. He received his B.S. and M.S. degrees in Mechanical Engineering from the University of Pennsylvania and his Ph.D. in Aeronautical Engineering from Princeton University (1961). He joined the faculty of CSUS in 1966 and has served as department chair and associate dean.

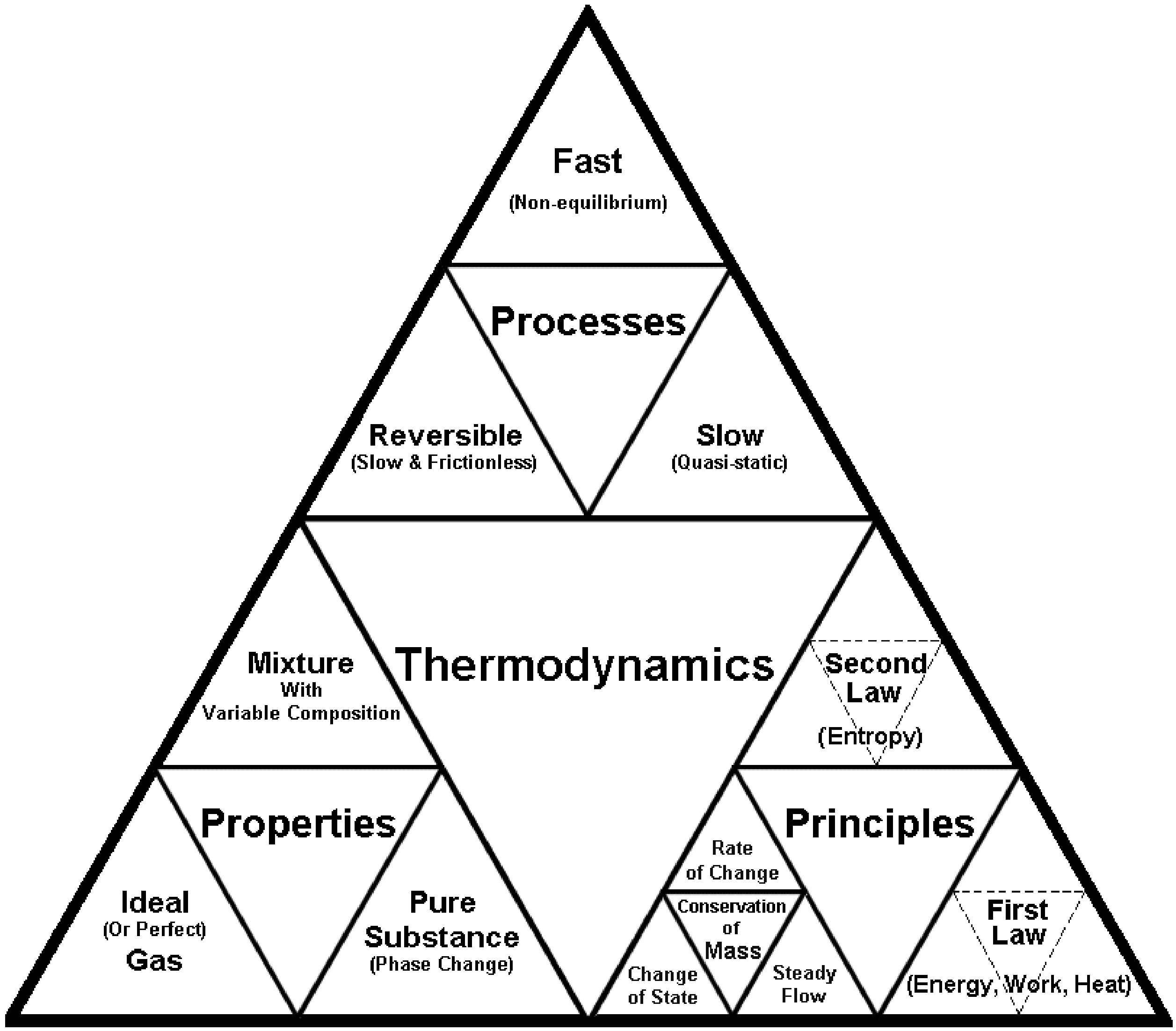


Figure 1. Thermodynamics Triangle

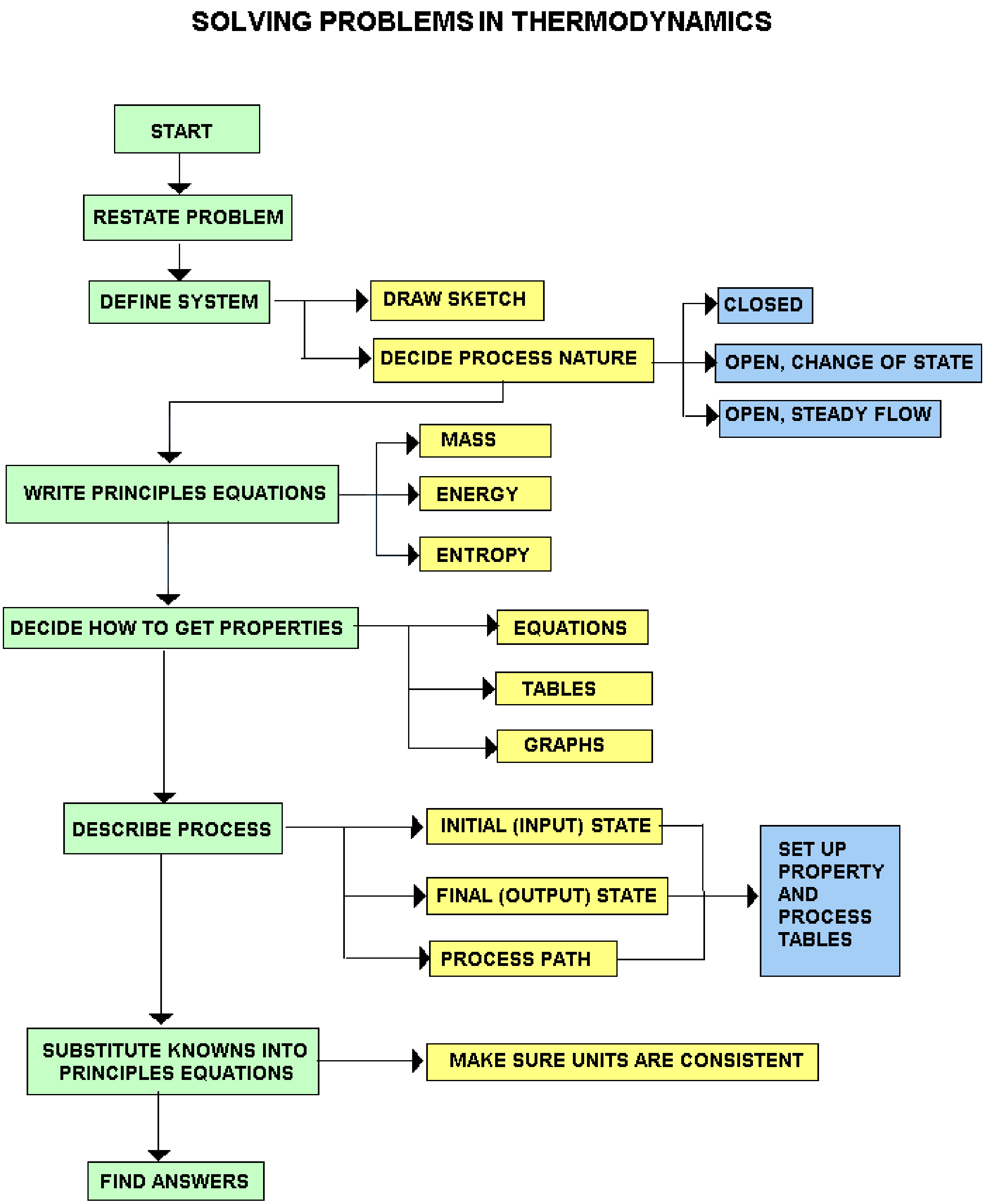
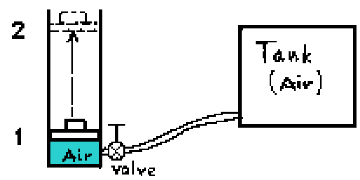


Figure 2. Problem Solving Methodology Diagram

4. Air is contained in a vertical cylinder at a pressure of 20 psia. The pressure is imposed by a weight on a frictionless piston, so that the pressure remains constant. The initial volume of the air in the cylinder is 0.05 ft^3 and the initial conditions of the air are u = 89.14 Btu/lbm, v = 9.64 ft^3/lbm. Air is added from a large tank in which the enthalpy is 129.6 Btu/lbm until the volume of the air in the cylinder has increased to 0.5 ft^3. During the process the pressure P, specific internal energy u, and specific volume v remain constant at their initial values. In this process,

a. How much air is added (lbm)?
b. How much work is done (Btu)?
c. How much heat is transferred (Btu)?

(4)



System = air in cylinder

1 = initial state
2 = final state
T = tank properties

Principles equations:

$$m_2 - m_1 = m_{in} - m_{out}$$

$$m_2 u_2 - m_1 u_1 = {}_1Q_2 - {}_1W_2 + \int_1^2 h_{in}\,dm_{in} - \int_1^2 h_{out}\,dm_{out}$$

Process info:

$P_1 = P_2 = 20$ psia (lb/in²) $\quad m_{out} = 0$

$V_1 = 0.05\ ft^3 \quad V_2 = 0.50\ ft^3$

$u_1 = 89.14$ Btu/lbm $= u_2 \quad h_T = 129.6$ Btu/lbm

$v_1 = 9.64\ ft^3/lbm = v_2$

Auxiliary equations:

$$v = \frac{V}{m} \quad \text{or} \quad m = \frac{V}{v}$$

$${}_1W_2 = \int_1^2 P\,dV = P_1(V_2 - V_1)$$

Solution:

$$m_1 = \frac{V_1}{v} = \frac{0.05\ ft^3}{9.64\ ft^3/lbm} = 0.00519\ lbm$$

$$m_2 = \frac{V_2}{v} = \frac{0.5}{9.64} = 0.0519\ lbm$$

$$\therefore m_{in} = 0.0467\ lbm$$

$$\int_1^2 h_{in}\,dm_{in} = h_T \cdot m_{in} = 129.6\ \frac{Btu}{lbm} \cdot 0.0467\ lbm = 6.052\ Btu$$

$${}_1W_2 = 20\ \frac{lb}{in^2}\,(0.50 - .05)\ ft^3 * 144\ \frac{in^2}{ft^2} * \frac{1}{778.169}\ \frac{Btu}{ft\,lb} = 1.665\ Btu$$

$$m_2 u_2 - m_1 u_1 = (m_2 - m_1)u_1 = m_{in} * u_1 = 0.0467 * 89.14 = 4.163\ Btu$$

Putting into energy equation:

$$4.163 = {}_1Q_2 - 1.665 + 6.052$$

$$\therefore {}_1Q_2 = -0.224\ Btu \quad \text{(heat from air in cylinder to surroundings)}$$

Figure 3. Homework Problem with Solution

EXAM #2
(OPEN BOOK, OPEN NOTES)

1. Steam enters a device called a “desuperheater” at 500 kg/hour, at 500 kPa, 200 C. It leaves as saturated vapor at 400 kPa. To accomplish this “desuperheating,” compressed liquid water at 1 Mpa, 40 C is sprayed into the steam. The device is well insulated and has no moving parts. The velocities are very small.

    a. Define the system, including the boundary characteristics and the substance inside, and draw a sketch, showing the mass and energy flows.
    b. Write the principles equations in the appropriate form.
    c. Write the appropriate equations defining the properties or state which tables will be used.
    d. Write any equations describing the process.
    e. Make a table for the necessary properties, filling in all needed property values.
    f. Determine the mass flow rate of liquid water needed: _______ kg/hour

2. A rigid, 2-cubic-foot tank containing helium is immersed in a water bath so that the temperature of the helium is maintained at 150 F. Initially, the pressure of the helium in the tank is 75 psia.

    A valve on the tank is opened, allowing helium to escape from the tank. When the pressure reaches 60 psia, the valve is closed.

    a. Define the system, including the boundary characteristics and the substance inside, and draw a sketch, showing the mass and energy flows.
    b. Write the principles equations in the appropriate form.
    c. Write the appropriate equations defining the properties or state which tables will be used.
    d. Write any equations describing the process.
    e. Make a table for the necessary properties, filling in all needed property values.
    f. Determine how much helium escapes from the tank: _________ lbm
    g. Determine how much heat is transferred from the water bath to the helium in the tank: __________ Btu

Figure 4. Typical Examination

MET 140 Spring 2000 Exam 2																
	1a	1b	1c	1d	1e	1f	Total 1	2a	2b	2c	2d	2e	2f	2g	Total 2	Total Exam
	5	10	5	5	20	5	50	5	8	6	6	15	5	5	50	100
Student	Define system	Principles	Properties	Process	Properties Table	Calculate mdot		Define system	Principles	Properties	Process	Properties Table	Calculate mout	Calculate Heat In		
1	5	10	5	5	20	5	50	3	8	4	2	11	5	5	38	88
2	3	10	5	5	15	5	43	2	6	4	2	10	0	5	29	72
3	4	8	5	5	15	0	37	5	8	4	4	11	5	3	40	77
4	4	5	0	5	16	5	35	5	5	2	4	11	0	3	30	65
5	4	7	3	2	15	0	31	2	6	3	4	7	0	0	22	53
6	3	10	0	5	17	2	37	3	0	6	0	5	0	0	14	51
7	5	10	0	5	15	4	39	5	8	6	6	15	5	5	50	89
8	5	5	5	5	15	0	35	5	6	4	4	11	5	0	35	70
9	5	7	5	3	10	2	32	4	6	3	0	11	0	2	26	58
10	4	10	5	5	10	3	37	4	8	4	4	11	5	5	41	78
11	4	10	0	5	10	0	29	5	5	6	5	15	5	5	46	75
12	5	10	5	5	18	5	48	4	5	4	4	13	5	0	35	83
13	5	10	0	0	10	0	25	5	3	6	0	15	0	0	29	54
14	4	10	0	5	15	0	34	3	5	3	0	11	5	0	27	61
15	5	8	5	5	10	0	33	5	8	6	6	13	5	5	48	81
16	3	10	0	0	10	5	28	3	5	4	0	11	0	0	23	51
17	5	10	5	2	10	3	35	5	3	2	2	7	0	0	19	54
18	5	10	2	5	10	5	37	5	5	6	4	7	5	0	32	69
19	0	2	5	2	5	0	14	3	2	4	0	7	0	0	16	30
Average	4.1	8.5	2.9	3.9	12.9	2.3	34.7	4.0	5.4	4.3	2.7	10.6	2.6	2.0	31.6	66
Ave/Max,%	82	85	58	78	65	46	69	80	67	71	45	71	53	40	63	66

Figure 5. Grading Spreadsheet, Exam of Figure 4

2. It is proposed to raise the temperature of liquid water in a well-insulated tank from 10 C to 80 C by adding steam to it. (The steam will condense as it mixes with the water so that at the end of the process all of the water in the tank will be liquid.) The steam is to be supplied at a pressure of 1000 kPa and a temperature of 500 C.

   The initial volume of the water is 500 liters. (The water does not completely fill the tank. There is a small space above the liquid occupied by air at one atmosphere pressure.)

   The liquid water in the tank is compressed liquid throughout the process; its properties can be taken to be the properties of saturated liquid at the temperature of the liquid water.

   To simplify the solution, neglect the small amount of work done against the air in the tank. Also, neglect the small amount of air that is forced out of the tank as the liquid level rises.

   Find:

   a. The mass of steam that must be added to achieve this temperature rise.

   b. The amount of entropy that will be generated (produced) during this process (kJ/K).

	MET 140 Final Exam Spring 2000							
	Problem2							
	System Def	Principles	Process	Init. Prop.	Final Prop.	In. Steam	Calc m & Sgen	Total
Max score	2	12	3	4	2	2	8	33
Average	2	9.3	2.3	2.3	1.1	1.2	2.1	20
Ave/Max,%	98	78	75	58	53	58	26	60

Figure 6. Question 2 on Final Exam

1. In a certain reciprocating air compressor, at the beginning of the compression process, the cylinder contains 0.06 lbm of air at 14.6 psia, 70 F. During the compression process, with the intake and exhaust valves closed, the air undergoes a polytropic process, with n=1.2. The volume of the cylinder is reduced by a factor of 12.

   The surroundings are at a temperature of 70 F.

   a. How much work is done on the air? ____________Btu

   b. How much heat is absorbed by the air? ___________Btu

   c. How much entropy is generated in the process? ___________Btu/R

2. Steam (H2O) flows into a duct at a pressure of 500 kPa and a temperature of 240 C. Compressed liquid water at 1.0 MPa, 30 C is sprayed into the steam in the duct. The steam leaves the duct as saturated vapor at a pressure of 400 kPa. The device is well insulated and has no moving parts.

   The mass flow rate of steam into the duct is 500 kg/hour

   a. What is the rate at which liquid water is sprayed into the duct? ________kg/hour

   b. What is the rate at which entropy is generated in this process? ______kJ/K-hour

Figure 7. Second Semester Homework #1

	Problem 1						Problem2						
	Define system, process	Write Principles Eq	Write Process Eq.	Property Eq. or Data	Answers to Questions	Total	Define system, process	Write Governing Eq	Write Process Eq.	Property Eq. or Data	Answers to Questions	Total	Grand Total
Max score	1	1	1	1	1	5	1	1	1	1	1	5	10
Student													
1	1	0.5	1	0.5	0.5	3.5	1	1	1	0.5	1	4.5	8
2	1	1	1	1	0.5	4.5	1	1	1	1	1	5	9.5
3	1	1	1	1	0	4	1	0.5	1	0.5	0	3	7
4	1	1	1	1	1	5	1	1	1	0.5	1	4.5	9.5
5	1	1	1	1	1	5	1	1	1	1	1	5	10
6	1	0.5	1	1	1	4.5	1	1	1	0.5	1	4.5	9
7	1	1	1	1	1	5	1	1	1	0.5	1	4.5	9.5
8	1	1	1	1	1	5	1	1	1	0.5	1	4.5	9.5
9	1	1	1	1	1	5	1	1	1	0.5	1	4.5	9.5
10	1	1	1	1	1	5	1	1	1	0.5	1	4.5	9.5
11	1	1	1	1	1	5	1	1	1	1	1	5	10
12	1	1	1	1	0.5	4.5	1	1	1	1	1	5	9.5
13	1	1	1	1	1	5	1	0.5	1	1	1	4.5	9.5
14	1	0.5	0.5	0.5	0	2.5	1	1	0.5	0.5	0	3	5.5
Average	1	0.89	0.96	0.93	0.75	4.54	1	0.93	0.96	0.68	0.86	4.43	8.96
Ave/Max,%	100	89	96	93	75	91	100	93	96	68	86	89	90

Figure 8. Grading Chart for Second Semester Homework #1