MOIST AIR PROPERTY EVALUATIONS IN A SPREADSHEET TO ENHANCE STUDENT LEARNING OF PSYCHROMETRICS

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Abstract

Excel is a useful tool for teaching students the fundamental concepts of psychrometrics and their application in solution of problems requiring repeated evaluation of psychrometric parameters or recurring use of psychrometric charts. A series of spreadsheet exercises have been developed to evaluate parameters such as relative humidity, humidity ratio, dew point temperature, and the enthalpy of air-water vapor mixture. Goal Seek and Solver functions of Excel are introduced to aid the solution process for problems requiring iterative processes. This paper provides several worked examples to demonstrate the effectiveness of Excel in teaching and learning the fundamentals of psychrometric principles and it application in solution of problems requiring the recurring evaluation of psychrometric parameters, which otherwise might be described as tedious. Feedback from students has been positive and shows the use of spreadsheets reinforce the understanding of the fundamental concepts.

1. Introduction

All mechanical engineering degree programs in the United States require either a single course consisting of 3-4 semester credit hours (SCH) or a two-course sequence in thermodynamics, each consisting 3 SCH. The fundamental concepts, including the evaluation of properties using tables or formulas are covered in the early stages of a single required course or in the first course for those programs requiring a two-semester course sequence. At the latter stages of the course coverage, students are introduced to thermodynamics cycles, including the air-standard power and refrigeration cycles. The coverage also includes an introduction to chemical reactions, mixture of ideal gases which including pschrometric analysis of moist air. The moist air properties are usually obtained using steam tables in combination with the properties of air.

In undergraduate courses in applied thermodynamics or heating, ventilation and air conditioning, mechanical engineering students are introduced to psychrometric principles. Thermal analysis of systems involving dry air and water vapor mixture requires a good understanding of psychrometric concepts and definitions of such parameters as humidity ratio, relative humidity, dew point temperature, and mixture enthalpy. Formulas defining the psychrometric parameters are employed in conjunction with property values obtained from the steam tables and ideal gas tables (or equations) in design and analysis of air conditioning systems, cooling tower, and other processes involving the control of water vapor content in the air. Alternatively, psychrometric charts are employed to reduce the time and ease the effort necessary for such analysis. However, human error in reading values off the charts reduces the accuracy of the analysis. In addition, solving open-ended problems usually involves many steps which may require repeated use of psychrometric charts at each step, making the solution process tedious and time consuming.

Many modern thermodynamic textbooks provide a software packages to aid students with property evaluation [1-3]. Some software packages such as Interactive Thermodynamics (IT) or Engineering Equation Solver (EES) have programming capabilities [4, 5]. These programs are general purpose, non-linear equation solvers with built-in property functions. They are capable of exploring and graphing the effects of change in variables on the solution to a given problem. These software packages are also very useful to students in solving complex thermodynamic problems requiring parametric studies or trial and error iteration processes. The most significant advantage of these software programs is that no prior knowledge of programming language is necessary in their applications. Both IT and EES are very useful problem solving tools, especially in an applied thermodynamics course.

When IT or EES are not provided as a package with a textbook, to avoid additional expenses to students, Excel spreadsheet which is available on almost all desktop or laptop computers, can be employed as a computational tool for solving problems involving ideal gases. The “Solver” or “Goal Seek” tools of Excel can be employed for solving problems requiring iterative processes. The use of these tools has been demonstrated in recent studies for solving heat transfer and thermodynamic problems [6-11].

This paper focuses on the application of Microsoft Excel in solving problems involving moist air. It provide several examples demonstrating the use of “Solver” and “Goal Seek” tools of Excel in solving problems requiring iterative processes.

2. Definitions and Basic Equations Psychrometrics

The following paragraphs provide the basic definitions and equations used in psychrometric analysis.

At low pressures a mixture of air and water vapor mixture behaves as an ideal gas. Therefore, ideal gas equations can be used for thermodynamic analysis of moist air close to atmospheric pressures.

The equation of state for ideal gases can be expressed in the following forms:

$$PV = n\overline{R}T \tag{1}$$

where, $\overline{R}$ is the universal gas constant and

$$PV = mRT \tag{2}$$

where, $R = \overline{R}/M$ and M is the molecular weight of the substance.

$$Pv = RT \tag{3}$$

For the moist air, the total pressure is expressed as

$$P = P_a + P_v \quad (4)$$

where, P_a and P_v are the partial pressures of air and water vapor, respectively.

Using Eq. (2), P_a and P_v can be expressed as:

$$P_a V = m_a \frac{\overline{R}}{M_a} T \quad (5)$$

$$P_v V = m_v \frac{\overline{R}}{M_v} T \quad (6)$$

For moist air, relative humidity, ϕ, is defined as

$$\phi \equiv \left.\frac{P_v}{P_g}\right)_T \quad (7)$$

where, P_v is the partial pressure of water vapor in moist air at a temperature of T, and P_g denotes the saturation pressure of water vapor evaluated at the same temperature.

Humidity ratio or absolute humidity is defined as

$$\omega \equiv \frac{m_v}{m_a} \quad (8)$$

Substituting m_a and m_v derived from Eqs. (5) and (6), Eq. (8) can be expressed as

$$\omega = \frac{M_v P_v V/\overline{R}T}{M_a P_a V/\overline{R}T} = \frac{M_v P_v}{M_a P_a} = 0.622 \frac{P_v}{P_a} \quad (9)$$

Applying Eqs. (4) and (6), Eq. (9) can also be expressed as

$$\omega = 0.622 \frac{P_v}{P - P_v} = 0.622 \frac{\varphi P_g}{P - \varphi - _g} \quad (10)$$

The mass of mixture can be expressed as

$$m = m_a + m_v = m_a (1 + \omega) \quad (11)$$

The enthalpy of the air water vapor can be expressed as

$$H = H_a + H_v = m_a h_a + m_v h_v = m_a (\mathrm{h_a} + \omega\, \mathrm{h_v}) \quad (12)$$

Mixture enthalpy per unit mass of dray air is given as

$$\widehat{h} = \frac{H}{m_a} = h_a + \omega h_v \tag{13}$$

Since the enthalpy of ideal gases is a function of temperature only, the enthalpy of water vapor in the mixture can be approximated by the enthalpy of saturated water vapor.

$$h_v \approx h_g(T) \tag{14}$$

Properties defined in this section can be evaluated from properties of air and saturated properties of steam.

To provide students with fundamental understanding of pyschrometric principals, a series exercises are developed and are given as assignments. Instead of using steam tables, or tables for properties of air, appropriate equations are provided to students and they are asked to use Excel spreadsheet as a computational tool to complete the assignment. To evaluate such properties as the humidity ratio, or enthalpy of air water vapor mixture, reasonably accurate equations are necessary for the evaluation of saturated water vapor pressure and enthalpy of saturated water vapor.

3. Examples

As exercises, students were given the following two assignments to determine the accuracy of some available equations for evaluation of saturation pressure and enthalpy of saturated water vapor.

Exercise 1:

The following equations are given for the saturation pressure of water [12].

$$\ln(P_g) = \frac{-3892.7}{T - 42.6776} + 9.48654 \tag{15}$$

and

$$\ln(P_g) = \sum_{0}^{9} A_i T + \frac{A_{10}}{T - A_{11}} \tag{16}$$

A_0	10.4592	A_4	-1.0152x10^{-9}	A_8	7.79287x10^{-22}
A_1	-4.04897x10^{-3}	A_5	8.65310x10^{-13}	A_9	1.91482x10^{-25}
A_2	-4.1752x10^{-5}	A_6	9.03668x10^{-1}6	A_{10}	-3968.06
A_3	3.68510x10^{-7}	A_7	-1.9969x10^{-18}	A_{11}	39.5735

T is in K in Eqs (15) and (16). Using an Excel spreadsheet, evaluate the saturation pressure obtained from each equation for temperatures ranging between 0.01 ^{o}C and 200 ^{o}C. Compare the results with the Steam Tables.

Solution:

Equations (15) and (16) were formulated in an Excel worksheet to evaluate saturation pressure, $P_g(T)$. The values obtained from each equation were compared with the Steam Tables in a thermodynamic textbook [1]. The results are shown in Fig. 1. The figure shows that both equations evaluate the saturation pressure accurately. In each case the deviations from steam table data are less than 0.5 %. Since Eq. (15) is of simpler form, it will be used in the proceeding exercises involving pschrometric analysis.

Exercise 2:

The following equations are given (Thomas) for the enthalpies of saturated water vapor.

$$h_g = 2099.3(A + BT_C^{1/3} + CT_C^{5/6} + DT_C^{7/8} + \sum_{1}^{5} E_n T_C^n) \qquad (17)$$

where, $T_C = \dfrac{647.3 - T}{647.3}$ and

A	1.0	D	-1.48513244	E_3	-7.39064542
B	0.457874342[3]	E_1	-4.81351884	E_4	10.4961689
C	5.08441288	E_2	2.69411792	E_5	-5.56840036

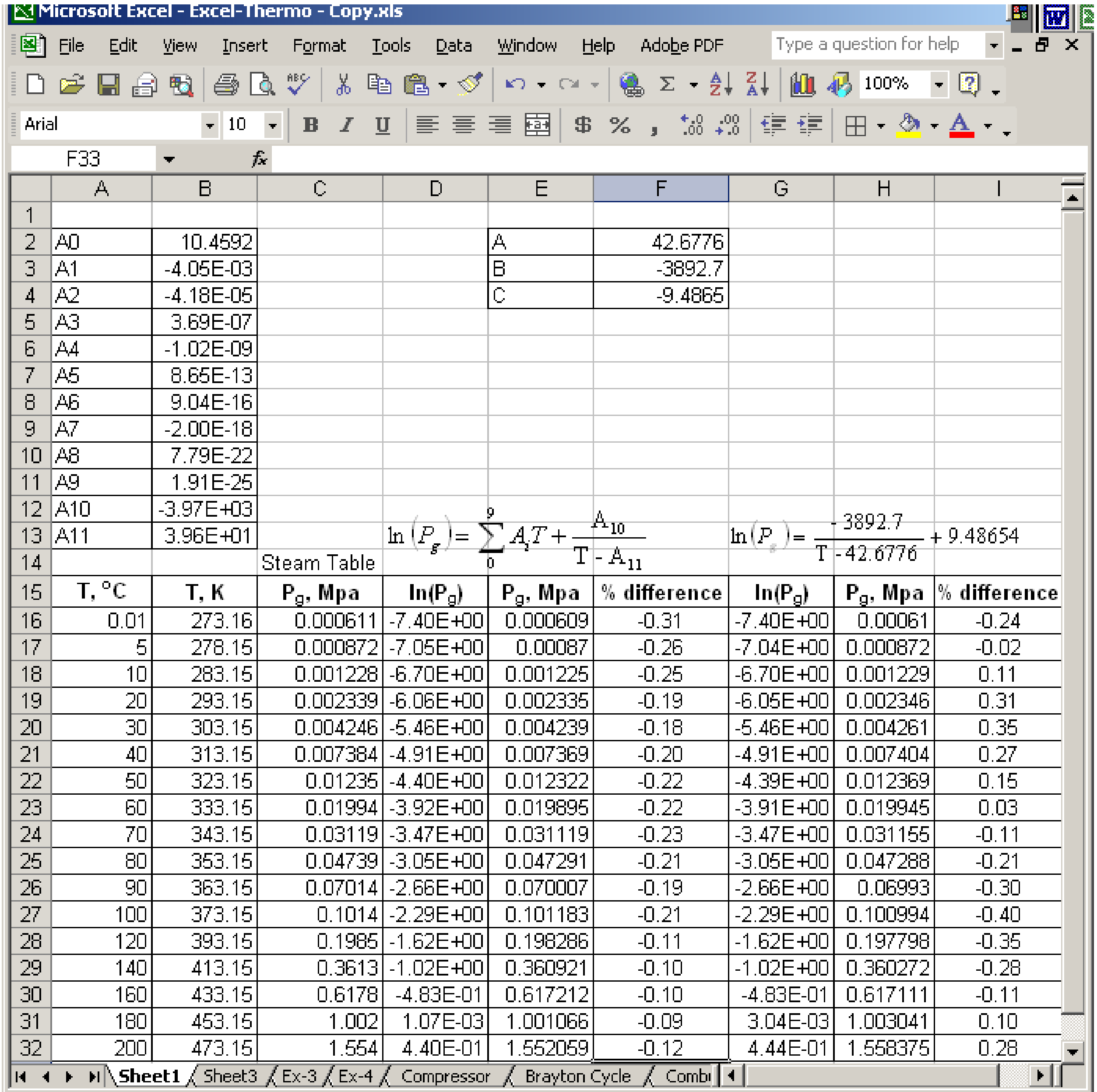
T is in K in Eq. (17). Using an Excel spreadsheet, evaluate the enthalpies of saturated water vapor obtained from Eq. (17) for temperatures ranging between 0.01 ^oC and 200 ^oC. Compare the results with the Steam Tables.

Solution:

Equations (17) was formulated in an Excel worksheet to evaluate enthalpies of saturated water vapor, hg, in a range of temperature from 0.01 ^oC and 200 ^oC. The values obtained from Eq. (17) were compared with the data from Steam Tables in a thermodynamic textbook [1]. The results are presented in Fig. 1, where it shows that Eq. (17) gives highly accurate results for the enthalpies of saturated water vapor. The deviations of calculated values from the data from the Steam Tables are less than 0.012 %.

Exercise 3:

A room having a volume of 240 m^3 contains moist air at 30 ^oC, 0.101 MPa. The partial pressure of water vapor is 2.0 kPa. Using an appropriate equation for saturation pressure in an Excel spreadsheet, evaluate relative humidity, humidity ratio, the mass of dry air, and the mass of water vapor in the room.



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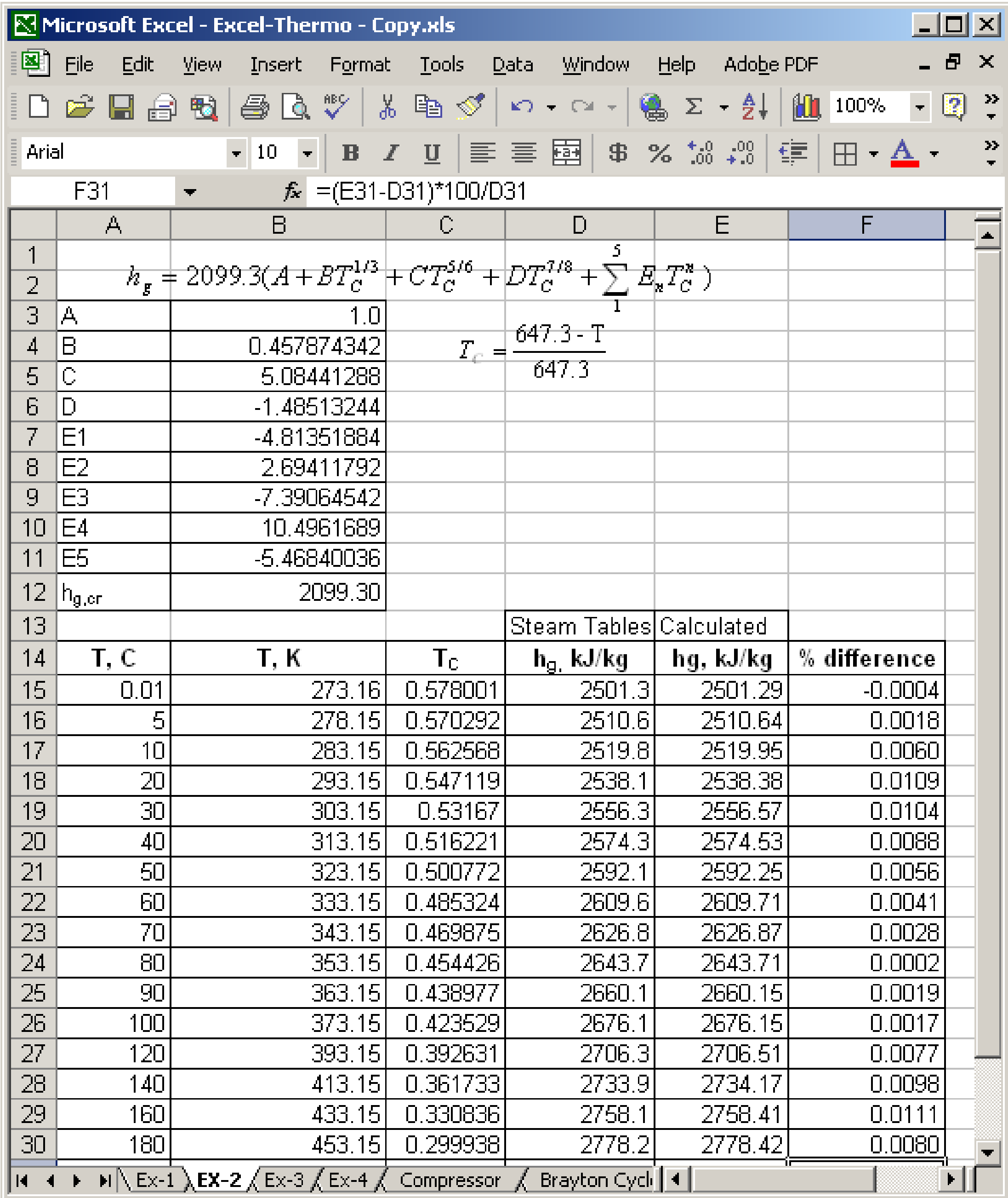
	A	B	C	D	E	F	G	H	I
1									
2	A0	10.4592			A	42.6776			
3	A1	-4.05E-03			B	-3892.7			
4	A2	-4.18E-05			C	-9.4865			
5	A3	3.69E-07							
6	A4	-1.02E-09							
7	A5	8.65E-13							
8	A6	9.04E-16							
9	A7	-2.00E-18							
10	A8	7.79E-22							
11	A9	1.91E-25							
12	A10	-3.97E+03							
13	A11	3.96E+01		$\ln(P_g)=\sum_0^9 A_i T^i+\frac{A_{10}}{T-A_{11}}$			$\ln(P_g)=\frac{-3892.7}{T-42.6776}+9.48654$		
14			Steam Table						
15	T, °C	T, K	P_g, Mpa	$\ln(P_g)$	P_g, Mpa	% difference	$\ln(P_g)$	P_g, Mpa	% difference
16	0.01	273.16	0.000611	-7.40E+00	0.000609	-0.31	-7.40E+00	0.00061	-0.24
17	5	278.15	0.000872	-7.05E+00	0.00087	-0.26	-7.04E+00	0.000872	-0.02
18	10	283.15	0.001228	-6.70E+00	0.001225	-0.25	-6.70E+00	0.001229	0.11
19	20	293.15	0.002339	-6.06E+00	0.002335	-0.19	-6.05E+00	0.002346	0.31
20	30	303.15	0.004246	-5.46E+00	0.004239	-0.18	-5.46E+00	0.004261	0.35
21	40	313.15	0.007384	-4.91E+00	0.007369	-0.20	-4.91E+00	0.007404	0.27
22	50	323.15	0.01235	-4.40E+00	0.012322	-0.22	-4.39E+00	0.012369	0.15
23	60	333.15	0.01994	-3.92E+00	0.019895	-0.22	-3.91E+00	0.019945	0.03
24	70	343.15	0.03119	-3.47E+00	0.031119	-0.23	-3.47E+00	0.031155	-0.11
25	80	353.15	0.04739	-3.05E+00	0.047291	-0.21	-3.05E+00	0.047288	-0.21
26	90	363.15	0.07014	-2.66E+00	0.070007	-0.19	-2.66E+00	0.06993	-0.30
27	100	373.15	0.1014	-2.29E+00	0.101183	-0.21	-2.29E+00	0.100994	-0.40
28	120	393.15	0.1985	-1.62E+00	0.198286	-0.11	-1.62E+00	0.197798	-0.35
29	140	413.15	0.3613	-1.02E+00	0.360921	-0.10	-1.02E+00	0.360272	-0.28
30	160	433.15	0.6178	-4.83E-01	0.617212	-0.10	-4.83E-01	0.617111	-0.11
31	180	453.15	1.002	1.07E-03	1.001066	-0.09	3.04E-03	1.003041	0.10
32	200	473.15	1.554	4.40E-01	1.552059	-0.12	4.44E-01	1.558375	0.28

Fig. 1 Evaluation of saturated pressure of water from Eqs. (15) and (16) and comparison with Steam Tables

Solution:

Equation (15) was formulated in an Excel worksheet to evaluate saturation pressure of water at 30 °C. The result was used in Eqs. (7) and (9) to evaluate the relative humidity ϕ and the humidity ratio, ω, respectively. Equation (5) was employed to evaluate the mass dry air. The mass of vapor was calculated using the calculated values of ω and m_a in Eq. (8). The results are presented in Fig. 3.



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F31 =(E31-D31)*100/D31

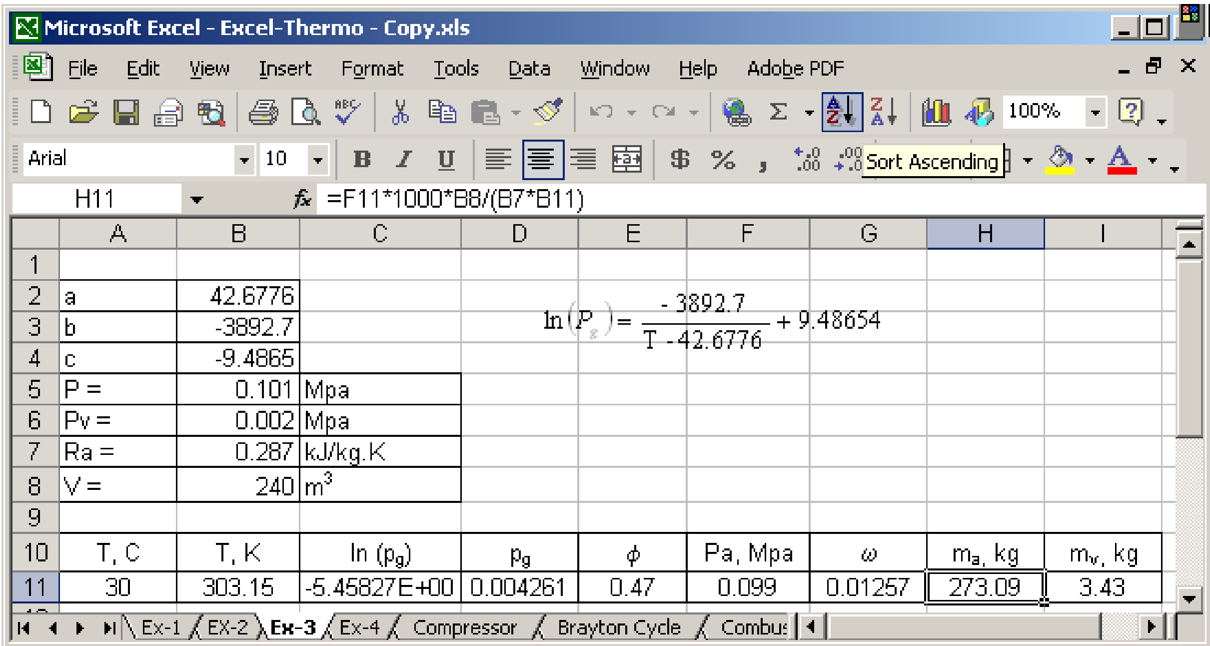
$$h_g = 2099.3(A + BT_C^{1/3} + CT_C^{5/6} + DT_C^{7/8} + \sum_{1}^{5} E_n T_C^n)$$

$$T_c = \frac{647.3 - T}{647.3}$$

	A	B	C	D	E	F
3	A	1.0				
4	B	0.457874342				
5	C	5.08441288				
6	D	-1.48513244				
7	E1	-4.81351884				
8	E2	2.69411792				
9	E3	-7.39064542				
10	E4	10.4961689				
11	E5	-5.46840036				
12	$h_{g,cr}$	2099.30				
13				Steam Tables	Calculated	
14	**T, C**	**T, K**	**T_C**	**h_g, kJ/kg**	**hg, kJ/kg**	**% difference**
15	0.01	273.16	0.578001	2501.3	2501.29	-0.0004
16	5	278.15	0.570292	2510.6	2510.64	0.0018
17	10	283.15	0.562568	2519.8	2519.95	0.0060
18	20	293.15	0.547119	2538.1	2538.38	0.0109
19	30	303.15	0.53167	2556.3	2556.57	0.0104
20	40	313.15	0.516221	2574.3	2574.53	0.0088
21	50	323.15	0.500772	2592.1	2592.25	0.0056
22	60	333.15	0.485324	2609.6	2609.71	0.0041
23	70	343.15	0.469875	2626.8	2626.87	0.0028
24	80	353.15	0.454426	2643.7	2643.71	0.0002
25	90	363.15	0.438977	2660.1	2660.15	0.0019
26	100	373.15	0.423529	2676.1	2676.15	0.0017
27	120	393.15	0.392631	2706.3	2706.51	0.0077
28	140	413.15	0.361733	2733.9	2734.17	0.0098
29	160	433.15	0.330836	2758.1	2758.41	0.0111
30	180	453.15	0.299938	2778.2	2778.42	0.0080

Ex-1 | EX-2 | Ex-3 | Ex-4 | Compressor | Brayton Cycl

Fig. 2 Evaluation of h_g of saturated water vapor from Eq. (17) and comparison with Steam Tables



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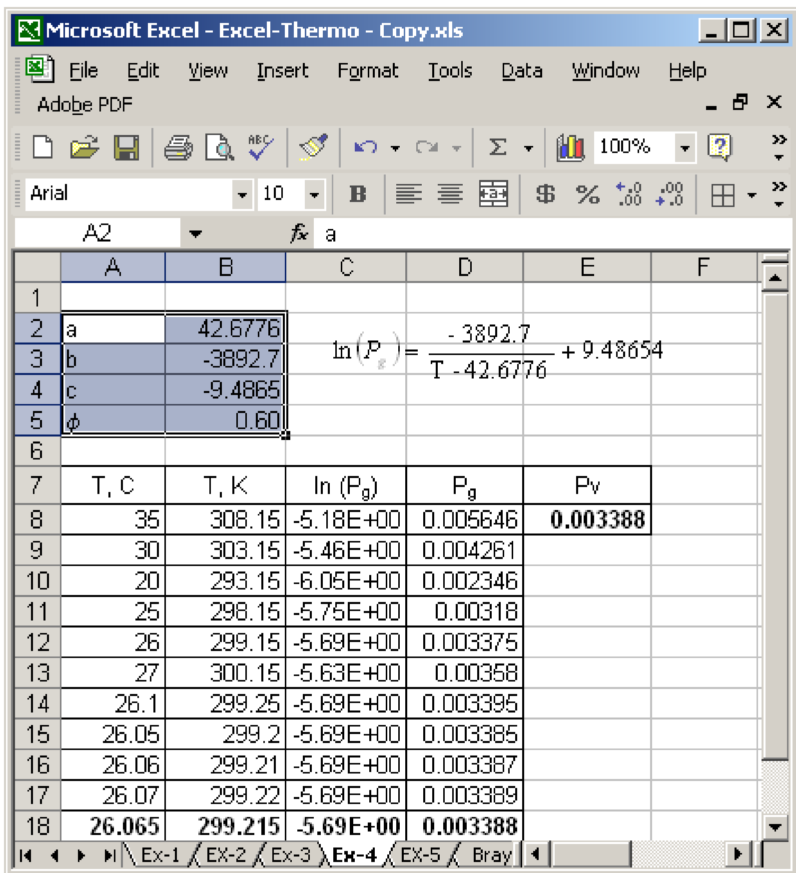
H11 =F11*1000*B8/(B7*B11)

	A	B	C	D	E	F	G	H	I
1									
2	a	42.6776							
3	b	-3892.7							
4	c	-9.4865							
5	P =	0.101	Mpa						
6	Pv =	0.002	Mpa						
7	Ra =	0.287	kJ/kg.K						
8	V =	240	m^3						
9									
10	T, C	T, K	ln (p_g)	p_g	ϕ	Pa, Mpa	ω	m_a, kg	m_v, kg
11	30	303.15	-5.45827E+00	0.004261	0.47	0.099	0.01257	273.09	3.43

$$\ln(P_g) = \frac{-3892.7}{T - 42.6776} + 9.48654$$

Fig. 3 Evaluation of ϕ, ω, m_a, and m_v in Exercise 3



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A2 a

	A	B	C	D	E
1					
2	a	42.6776			
3	b	-3892.7			
4	c	-9.4865			
5	ϕ	0.60			
6					
7	T, C	T, K	ln (P_g)	P_g	Pv
8	35	308.15	-5.18E+00	0.005646	**0.003388**
9	30	303.15	-5.46E+00	0.004261	
10	20	293.15	-6.05E+00	0.002346	
11	25	298.15	-5.75E+00	0.00318	
12	26	299.15	-5.69E+00	0.003375	
13	27	300.15	-5.63E+00	0.00358	
14	26.1	299.25	-5.69E+00	0.003395	
15	26.05	299.2	-5.69E+00	0.003385	
16	26.06	299.21	-5.69E+00	0.003387	
17	26.07	299.22	-5.69E+00	0.003389	
18	**26.065**	**299.215**	**-5.69E+00**	**0.003388**	

$$\ln(P_g) = \frac{-3892.7}{T - 42.6776} + 9.48654$$

Fig 4. Evaluation of dew point temperature in exercise 4, using trial and error process

Exercise 4:

Consider moist air at 35 ^{o}C, and 60% relative humidity. Using an appropriate equation for saturation pressure in an Excel spreadsheet, evaluate the dew point temperature.

Solution:

Equation (15) was used in an Excel worksheet to evaluate saturation pressure of water at 35 ^{o}C. The calculated value of saturation pressure was used in Eq. (7) to evaluate the partial pressure of water vapor in the mixture. Figure 4 shows a calculated value 0.003388 MPa for P_v. The dew point temperature is defined as the saturated temperature of water at a pressure equal to P_v. Therefore, a trial and error procedure is necessary to evaluate the dew point temperature. One method is to evaluate P_g by changing the value of temperature as shown in Fig. 4. When the value of P_g is equal to 0.003388 MPa, the corresponding temperature represents the dew point temperature. Figure shows that dew point temperature for this example is 26.07 ^{o}C.

Alternatively the "Solver" functions of Excel could be used to perform the trial and error process. In this case, after entering the formulas for solving the problem in a worksheet and entering an initial guess for the dew point temperature (cell A9), the tool menu is used to select Solver. A dialog box appears as shown in Fig.5. In the dialog box cell D9 is selected as the target cell and its value is set the desired solution (0.003388). The cell that its value must be changed is identified (A9). By clicking the Solve button, the values of the cells are automatically changed for the desired solution. The Solver returns a value of 26.063 ^{o}C for the dew point temperature.

Exercise 5:

Moist air enters a duct at 10 ^{o}C, 0.101 MpPa, relative humidity of 75%, and a mass flow rate of 3.0 kg/s. Air is heated at a rate of 60 kW as it flows trough the duct. No moisture is added or removed during this process. Evaluate the temperature and relative humidity of the exit.

Solution:

Identifying the duct inlet as state 1 and the exit as state 2, the following relationships can be written for the mass flow rates of dry air and water vapor.

$$\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a \tag{18}$$

$$\dot{m}_{v1} = \dot{m}_{v2} = \dot{m}_v \tag{19}$$

$$\omega_1 = \omega_2 = \omega \tag{20}$$

$$\dot{m} = \dot{m}_a + \dot{m}_v = \dot{m}_a (1+\omega) \tag{21}$$

$$\dot{m}_a = \frac{\dot{m}}{(1+\omega)} \tag{22}$$

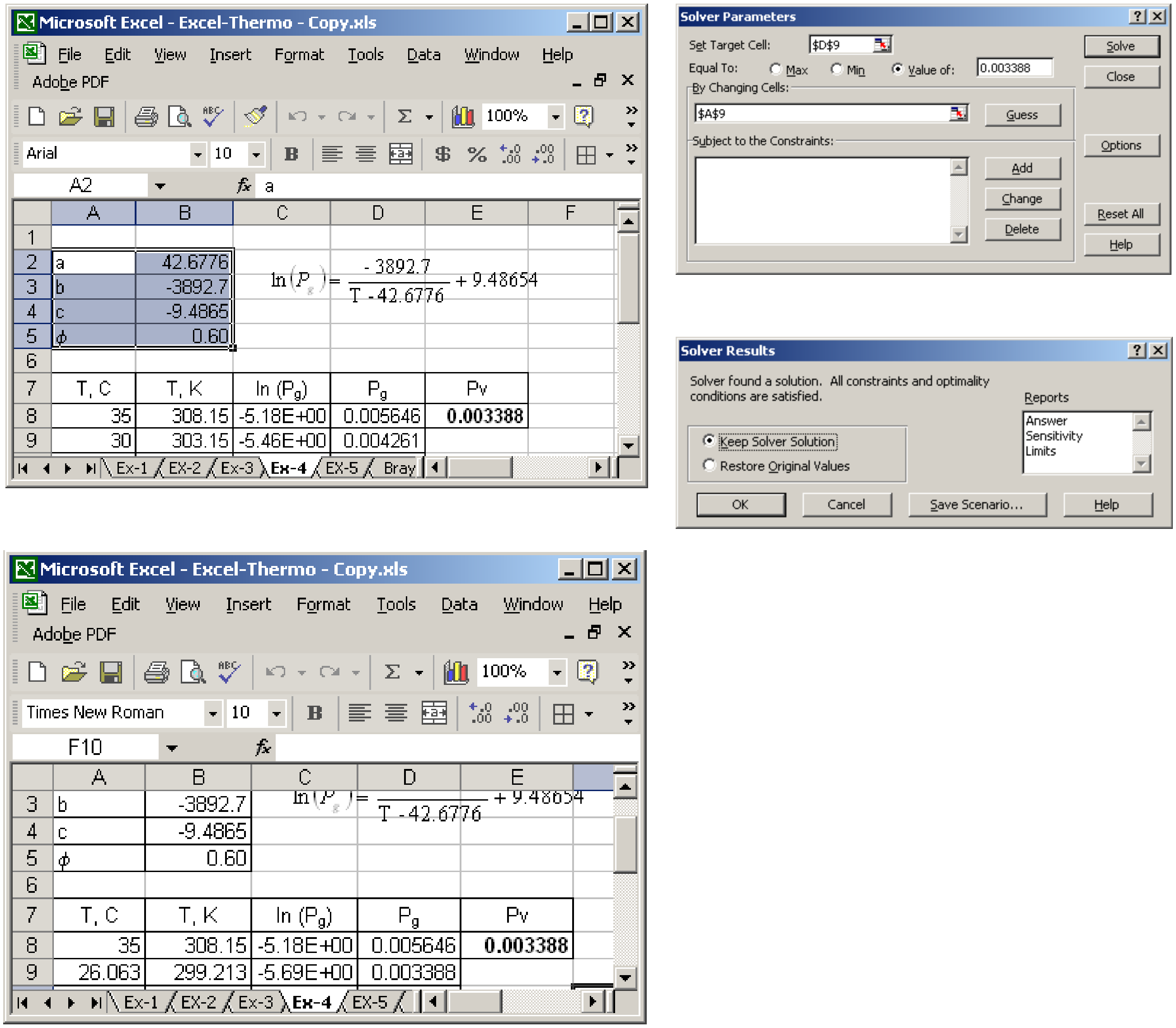

Fig.5. Evaluation of dew point temperature in exercise 4, using Solver

Using Eq. (15), the saturated pressure of water at T_1 is calculated. Using the calculate value of P_{g1} in Eq. (8), the partial pressure of water vapor is determined. The result is used in Eq (8) to determine ω. Then the mass flow rate of dry air is calculated from Eq. (22).

Conducting an energy balance around the duct, the following relation is obtained for the rate of heat transfer.

$$\dot{Q} = \dot{m}_a\left(h_{a2} - h_{a1}\right) + \dot{m}_v\left(h_{v2} - h_{v1}\right) = \dot{m}_a\left[c_{pa}\left(T_2 - T_1\right) + \omega\left(h_{v2} - h_{v1}\right)\right] \qquad (23)$$

Since, $h_v \approx h_g(T)$ Eq. (17) can be used for the evaluation of h_{v1} and h_{v2}. A trail and error process is necessary to complete the solution to this problem, since T_2 is unknown. After entering all necessary formulas, in an Excel worksheet, the Goal Seek tool of Excel is employed to evaluate T_2.

After entering the formulas, P_{g1}, P_v, ω, $\dot{m}_a$, and h_{g1} are evaluated at T_1. By assuming a temperature of 25 ^oC, P_{g2}, h_{g2}, ϕ_2, and the rate of heat transfer were calculated. The assumed temperature of T_2, gives a value of 45. 4 kW for the rate of heat transfer as shown in Fig. 6. To find the correct temperature for T_2, the tool menu is used to select Goal Seek function of Excel. A dialog box appears as shown in Fig. 6. In the dialog box cell G1 is set a value of 60. The cell that its value must be changed is identified (A19). By clicking the Ok button, the values of the cells are automatically changed for the desired solution. The Goal Seek returns a value of 29.8 ^oC for T_2. This temperature gives a value of 17.5% for the relative humidity at state 2.

4. Student Survey

At the end of semester we conducted a course survey to obtain students feedback on their experience with using Excel in solving thermodynamic problems. Table 1 presents students feedback to some of the questions on the on the survey.

5. Summary

The application of Excel spreadsheet in solving problems involving psychrometric principles were demonstrated through several examples. It was shown that Excel is a useful computational tool when the solution to problems requires varying one of the parameters or an iteration process. Excel is accessible to all students and, typically is available on most desktop and laptop

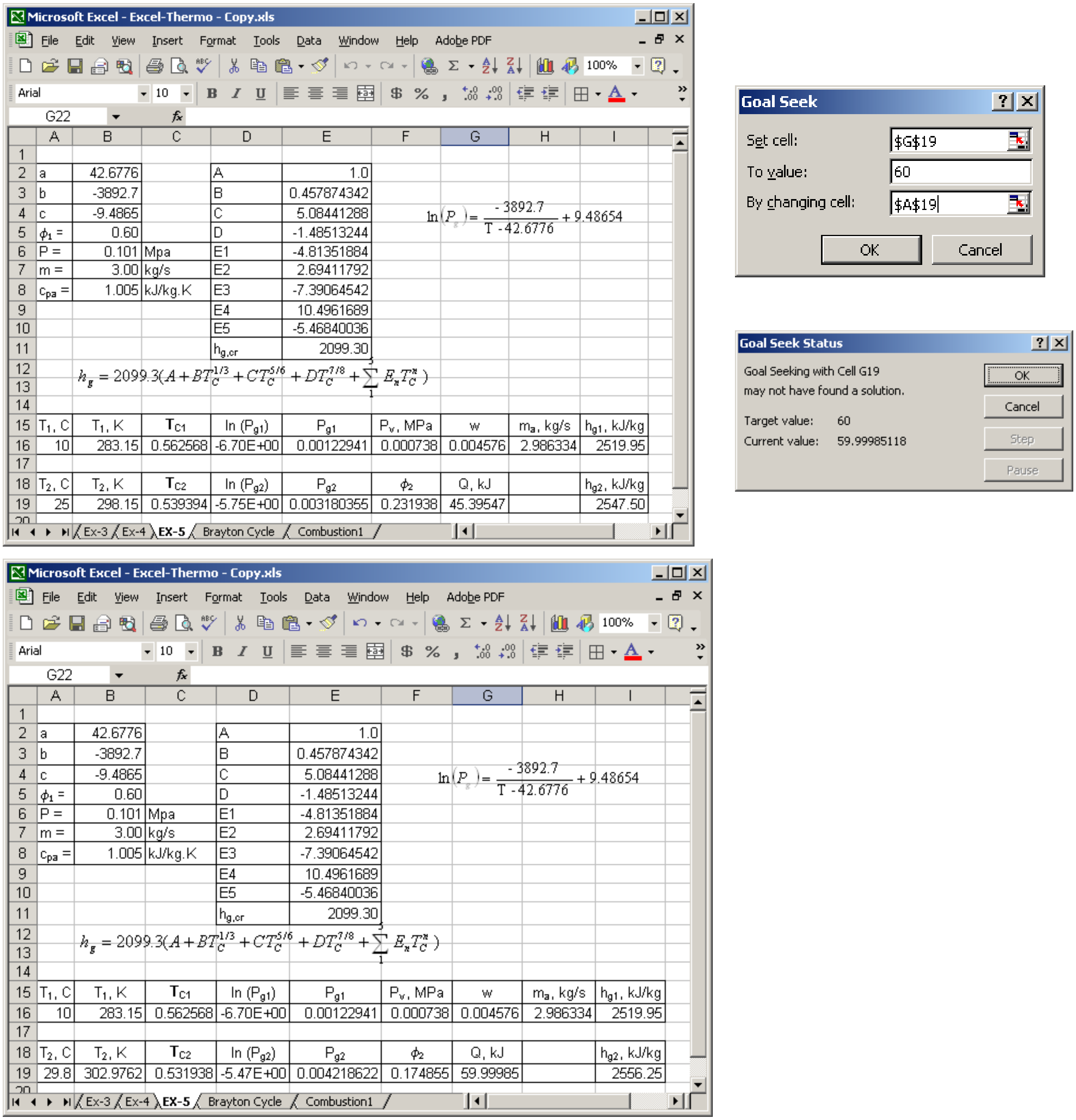

Fig. 6. Solution of exercise 5 using the Goal Seek Function of Excel

Table 1. Student survey results

	Question	% Yes	% No
1	Are you familiar with such thermodynamics software such as IT (Interactive Thermodynamics) or EES (Engineering Equation Solver)?	17	83
2	If you answered yes to question 1, do you think any of these software programs helped you to solve more complex or labor intensive problems?	70	30
3	Have you used Excel spreadsheet in solving any homework problems or completing class projects?	90	10
4	Do you consider Excel to be a useful tool, because it is available on almost all computers?	87	13
	Did you find "Solver" or "Goal Seek" tools of Excel to be useful tools in solving problems requiring a trial and error process?	83	17

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NOMENCLATURE

c_p = constant volume specific heat, kJ/kg.K

c_v = constant pressure specific heat, kJ/kg.K

H = enthalpy, kJ
h = specific enthalpy, kJ/kg
M = Molecular weight, kg/kmol
m = mass, kg
$\dot{m}$ = mass flow rate, kg/s
P = pressure, bar or kPa
Q = heat transfer, kJ
$\dot{Q}$ = rate of heat transfer, kW
$\overline{R}$ = 8.3144 kJ/kmol.K, Universal gas constant
R = $\overline{R}$/M, gas constant, kJ/kg.K
U = internal energy, kJ
u = specific internal energy, kJ/kg
V= volume, m^3
v = specific volume, m^3/kg
W = work, kJ
$\dot{W}$ = power, kW

Greek letters
ϕ = relative humidity
ω = humidity ratio

Subscripts

cv = control volume
e = exit port
i = inlet port