AC 2010-2042: APPLICATION OF EXCEL IN PSYCHROMETRIC ANALYSIS

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Application of Excel in Psychrometric Analysis

Abstract

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 usually employed in conjunction with property values from the steam tables and ideal gas tables (or equations) in design and analysis of air conditioning systems, cooling towers, 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.

We have found that Microsoft Excel is a useful tool for teaching students the fundamental psychrometric concepts and its application in solution of problems requiring repeated evaluation of psychrometric parameters or recurring use of psychrometric charts. To reinforce students' understanding of the fundamental concepts we have designed a series of exercises requiring students to use simple equations available for ideal gases in Excel spreadsheets to evaluate such psychrometric parameters as relative humidity, humidity ratio, dew point temperature, and the enthalpy of air-water vapor mixtures. Goal Seek, or Solver functions of Excel are introduced to aid the solution process for problems requiring iterative processes. This paper provides several examples to demonstrate the effectiveness of Excel in teaching and learning the fundamentals of psychrometric principles and its application in solution of problems requiring the recurring evaluation of psychrometric parameters.

Introduction

All mechanical engineering degree programs require either a single course consisting of 3-4 semester credit hours (SCH) or a two-course sequence in thermodynamics, each consisting of 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, mixtures of ideal gases, including psychrometric analysis of moist air. The moist air properties are usually obtained from using steam tables in combination with the properties of air.

Many modern thermodynamic textbooks provide a software packages to aid students with property evaluation[1-3]. Some of these 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 variation of parameters 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.

Another useful available tool is The Expert System for Thermodynamics (TEST), which is available to educators free of charge[6]. TEST is a visual platform tool for thermodynamic analyzing thermodynamic problems. It can be used for the property evaluation, and the thermodynamic analysis of closed or open systems as well as power and refrigeration cycles. It contains useful modules, video clips, charts, and tables.

When IT or EES are not provided as a package with a textbook, to avoid additional expenses to students, Microsoft Excel 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 are very useful in solving problems requiring iterative processes. The effectiveness of these tools has been demonstrated in recent studies in solving heat transfer and thermodynamic problems[7-12].

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

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 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:

$$PV = n\bar{R}T = mRT \tag{1}$$

where, $\bar{R}$ is the universal gas constant, $R = \bar{R}/M$, and M is the molecular weight of the substance. For the moist air, the total pressure can be expressed as

$$P = P_a + P_v \tag{2}$$

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

Relative humidity, ϕ, is defined as

$$\phi \equiv \frac{P_v(T)}{P_g(T)} \tag{3}$$

where, P_g denotes the saturation pressure of water vapor evaluated at the temperature of mixture, T.

Humidity ratio or absolute humidity is defined as

$$\omega \equiv \frac{m_v}{m_a} = 0.622\frac{P_v(T)}{P_a(T)} = 0.622\frac{P_v(T)}{P - P_v(T)} = 0.622\frac{\phi P_g(T)}{P - \phi P_g(T)} \tag{4}$$

The mass of mixture can be expressed as

$$m = m_a + m_v = m_a(1+\omega) \tag{5}$$

The enthalpy of the air water vapor mixture can be expressed as

$$H = H_a + H_v = m_a h_a + m_v h_v = m_a(h_a + \omega h_v) \tag{6}$$

The enthalpy of mixture per unit mass of dry air is given as

$$\hat{h} = \frac{H}{m_a} = h_a + \omega h_v \tag{7}$$

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.

$$h_v \approx h_g(T) \tag{8}$$

For an adiabatic saturation process, the humidity ratio of moist air is expressed as[1]

$$\omega = \frac{h_a(T_{as}) - h_a(T) + \omega'\lfloor h_g(T_{as}) - h_f(T_{as})\rfloor}{h_g(T) - h_f(T_{as})} = \frac{c_{pa}(T_{as} - T) + \omega'\lfloor h_g(T_{as}) - h_f(T_{as})\rfloor}{h_g(T) - h_f(T_{as})} \tag{9}$$

where,

$$\omega' = 0.622\frac{P_g(T_{as})}{P - P_g(T_{as})} \tag{10}$$

T_{as} denotes adiabatic saturation temperature, T is the temperature of the mixture, subscript a refers to the properties of air, subscripts f and g denote the properties of water in the saturated liquid and vapor states, respectively.

For moist air at atmospheric pressure and normal temperature range (0.1°C to 60 °C) of pyschrometric application, the wet-bulb temperature and adiabatic saturation temperature are nearly the same. Therefore, Eqs. (9) and (10) can be used to evaluate the wet-bulb temperature.

Properties defined in this section can be evaluated from properties of air and saturated properties of steam given in standard property tables. They could also be evaluated from the available equations given for the properties of air and saturated properties of water.

To give students a better understanding of pyschrometric principals, a series of exercises were developed and assigned. Instead of using steam tables, or tables for properties of air, appropriate equations for the thermodynamic properties were given to students and they were asked to use Microsoft Excel as a computational tool to complete the exercises. To evaluate such properties as the humidity ratio, or enthalpy of air-water vapor mixture, reasonably accurate equations are necessary for the evaluations of water vapor pressure and enthalpies of water in saturated liquid and vapor states.

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. The objectives of these exercises were to demonstrate to students that the complexity of equations for accurate evaluation of thermodynamic properties depends on the range of applications and sometimes an equation with as few as three terms can represent the properties quite accurately within a 200 ^{o}C temperature range. A case in point is Exercise 1.

<u>Exercise 1:</u>

The following equations are given for the saturation pressure of water[13].

$$\ln(P_g) = \frac{-3892.7}{\mathrm{T} - 42.6776} + 9.48654 \tag{11}$$

and

$$\ln(P_g) = \sum_{n=0}^{9} A_i T^n + \frac{\mathrm{A}_{10}}{\mathrm{T} - \mathrm{A}_{11}} \tag{12}$$

where, the values of A_1, through A_{11} are given in the following table

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

T, in Eqs. (11) and (12) is in K. Using MS Excel, 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.

<u>Solution:</u>

Equations (11) and (12) 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 provided in the Thermodynamic textbook by Moran/Shapiro[1]. The results are shown in Table 1. The table shows that both equations represent the saturation pressure accurately. In each case the deviations from the steam table data are less than 0.5 %. This demonstrates that, in the given range of temperatures, the three-term Eq. (11) is almost as accurate as the twelve-term Eq. (12). Since Eq. (11) is of simpler form, it was used in the proceeding exercises involving psychrometric analysis.

Table 1 Calculate values of saturated pressure of water from Eqs. (11) and (12) and their comparison with the Steam Tables[1]

T, °C	**T, K**	**P_g, MPa Steam Tables**	**P_g, MPa Eq. (11)**	**% difference**	**Pg, MPa Eq. (12)**	**% difference**
0	273.16	0.000611	0.000610	-0.24	0.000609	-0.31
5	278.15	0.000872	0.000872	-0.02	0.000870	-0.26
10	283.15	0.001228	0.001229	0.11	0.001225	-0.25
20	293.15	0.002339	0.002346	0.31	0.002335	-0.19
30	303.15	0.004246	0.004261	0.35	0.004239	-0.18
40	313.15	0.007384	0.007404	0.27	0.007369	-0.20
50	323.15	0.01235	0.012369	0.15	0.01232	-0.22
60	333.15	0.01994	0.019945	0.03	0.01990	-0.22
70	343.15	0.03119	0.031155	-0.11	0.03112	-0.23
80	353.15	0.04739	0.047288	-0.21	0.04729	-0.21
90	363.15	0.07014	0.06993	-0.30	0.07001	-0.19
100	373.15	0.1014	0.1010	-0.40	0.1012	-0.21
120	393.15	0.1985	0.197798	-0.35	0.1983	-0.11
140	413.15	0.3613	0.3603	-0.28	0.3609	-0.10
160	433.15	0.6178	0.6171	-0.11	0.6172	-0.10
180	453.15	1.002	1.003	0.10	1.001	-0.09
200	473.15	1.554	1.558	0.28	1.552	-0.12

<u>Exercise 2:</u>

The following equation is given for the enthalpy of saturated liquid water[13].

$$h_f = 2099.3\sum_{n=0}^{7} A_n T_C^n) \tag{13}$$

where, $T_C = \dfrac{647.3 - T}{647.3}$, T is in K, and the coefficients in Eq. (13) are given in the following table

A_0	0.8839230108	A_2	6.22640035	A_4	-1.9132244	A_6	-124.81990600
A_1	-2.67172935	A_3	-13.17895730	A_5	68.79376530	A_7	72.14354040

The equation for the saturated water vapor is given as[13].

$$h_g = 2099.3(A + BT_C^{1/3} + CT_C^{5/6} + DT_C^{7/8} + \sum_{n=1}^{5} E_n T_C^n) \tag{14}$$

where, $T_C = \dfrac{647.3 - T}{647.3}$, T is in K, and the coefficients in Eq. (14) are given in the following table.

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	-5.46840036

Using Microsoft Excel, determine the values of the enthalpies of saturated liquid and water vapor from Eqs. (13) and (14) for temperatures ranging between 5 °C and 200 °C. Compare the results with the Steam Tables.

Solution:

Equations (13) and (14) were entered in an Excel worksheet to evaluate the enthalpies of saturated liquid water, h_f and saturated vapor, h_g, for temperatures ranging from 5 °C to 200 °C. The values obtained from these equations were compared with the data from the Steam Tables given in the Thermodynamics textbook by Moran Shapiro[1]. The results are presented in Table. 2. The table shows that Eq. (13) gives a good approximation of the enthalpies for the saturated liquid water. It also shows that Eq. (14) gives highly accurate representation of the enthalpies of saturated water vapor in the temperature range. The deviations of calculated values from the data from the Steam Tables are less than 2.7% for saturated liquid water and less than 0.012 % for the saturated water vapor.

Table 2 Calculated values of h_f and h_g of water from Eqs. (13) and (14) and their comparison with Steam Table data[1]

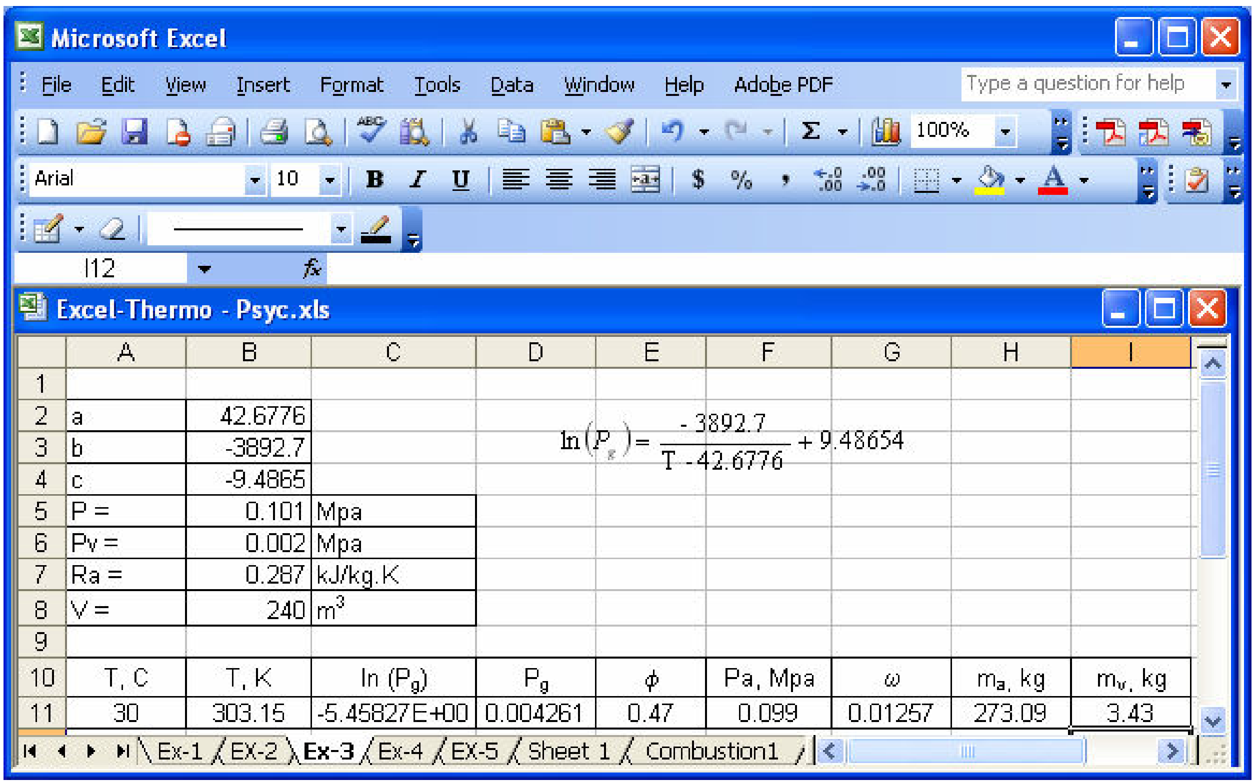
T, °C	T, K	h_f, kJ/kg Steam Tables	h_f, kJ/kg Eq. (13)	% difference	h_g, kJ/kg Steam Tables	h_g, kJ/kg Eq. (14)	% difference
5	278.15	0.01	0.02	133.5313	2501.3	2501.29	-0.0004
10	283.15	20.98	20.43	-2.6116	2510.6	2510.64	0.0018
20	293.15	42.01	41.10	-2.1547	2519.8	2519.95	0.0060
30	303.15	83.96	82.91	-1.2517	2538.1	2538.38	0.0109
40	313.15	125.79	125.06	-0.5840	2556.3	2556.57	0.0104
50	323.15	167.57	167.32	-0.1509	2574.3	2574.53	0.0088
60	333.15	209.33	209.56	0.1088	2592.1	2592.25	0.0056
70	343.15	251.13	251.71	0.2310	2609.6	2609.71	0.0041
80	353.15	292.98	293.76	0.2659	2626.8	2626.87	0.0028
90	363.15	334.91	335.73	0.2436	2643.7	2643.71	0.0002
100	373.15	376.92	377.66	0.1954	2660.1	2660.15	0.0019
120	393.15	419.04	419.61	0.1361	2676.1	2676.15	0.0017
140	413.15	503.71	503.85	0.0276	2706.3	2706.51	0.0077
160	433.15	589.13	588.93	-0.0332	2733.9	2734.17	0.0098
180	453.15	675.55	675.25	-0.0438	2758.1	2758.41	0.0111
200	473.15	763.22	763.07	-0.0194	2778.2	2778.42	0.0080

Exercise 3:

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

Solution:

Equation (11) was formulated in an Excel worksheet to evaluate saturation pressure of water, P_g, at 30 °C. The result was used in Eq. (3) to evaluate the relative humidity ϕ. The calculated values of P_g and ϕ were used in Eq. (4) to determine the humidity ratio, ω. The partial pressure of air was calculated, using Eq. (2). The values of partial pressure of air, the ideal gas constant, the total volume, and the mixture temperature were used in Eq. (1) to evaluate the mass of dry air. The mass of vapor was calculated using the calculated values of ω and m_a in Eq. (1). The results are presented in Fig. 1.



	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

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

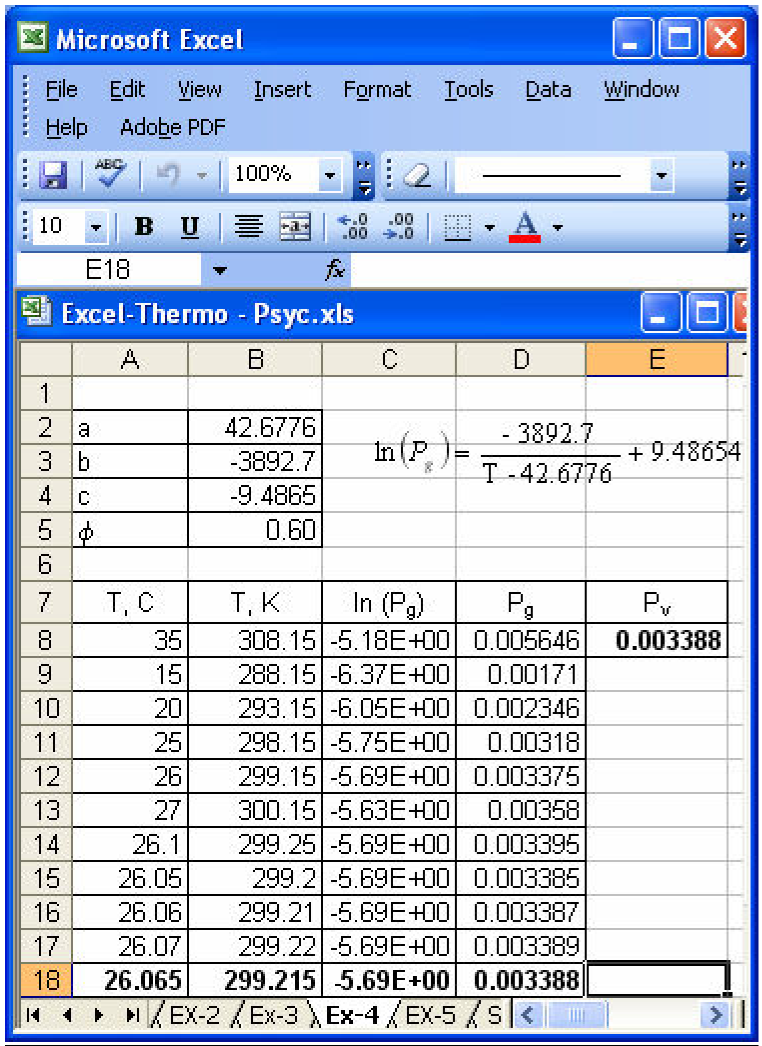
Fig. 1 Evaluation of ϕ, ω, m_a, and m_v in Exercise 3

Exercise 4:

Consider moist air at 35 °C, and 60% relative humidity. Using an appropriate equation for saturation pressure in an Excel worksheet, evaluate the dew point temperature.

Solution:

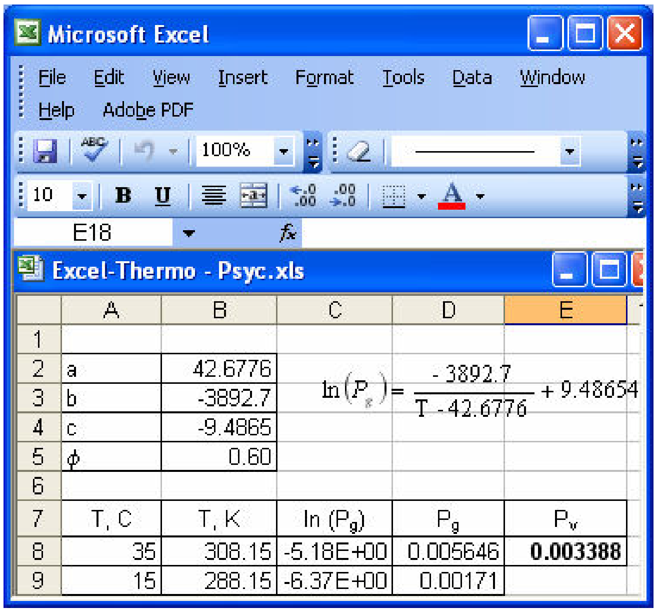
Equation (11) was used in an Excel worksheet to evaluate saturation pressure of water at 35 °C. The calculated value of saturation pressure was used in Eq. (3) to evaluate the partial pressure of water vapor in the mixture. Figure 2 shows a calculated value 0.003388 MPa for P_v. The dew point temperature 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. 2. 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.



	A	B	C	D	E
1					
2	a	42.6776	$\ln(P_g) = \dfrac{-3892.7}{T - 42.6776} + 9.48654$		
3	b	-3892.7			
4	c	-9.4865			
5	ϕ	0.60			
6					
7	T, C	T, K	ln (P_g)	P_g	P_v
8	35	308.15	-5.18E+00	0.005646	**0.003388**
9	15	288.15	-6.37E+00	0.00171	
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**	

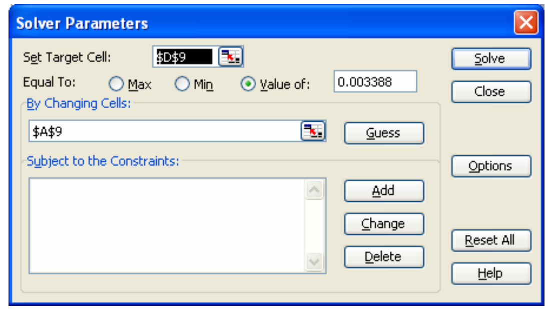
Fig 2. Evaluation of dew point temperature in exercise 4, using trial and error process

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, Fig 3-a), the tool menu is used to select Solver. A dialog box appears as shown in Fig. 3-b. In the dialog box, cell D9 is selected as the target cell and its value is set to the desired solution value (0.003388). The cell that's value must be changed during the iteration process is identified (A9). By clicking on the Solve button, the values of the cells are automatically changed for the desired solution. A new dialog box opens confirming that the Solver found a solution, as shown in Fig. 3-c. The Solver returns a value of 26.067 ^{o}C for the dew point temperature, as shown in Fig. 3-d.

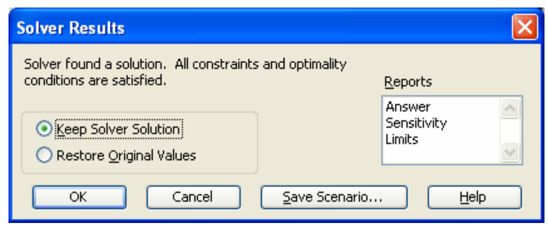


	A	B	C	D	E
1					
2	a	42.6776	$\ln(P_g) = \frac{-3892.7}{T - 42.6776} + 9.48654$		
3	b	-3892.7			
4	c	-9.4865			
5	ϕ	0.60			
6					
7	T, C	T, K	ln (P_g)	P_g	P_v
8	35	308.15	-5.18E+00	0.005646	**0.003388**
9	15	288.15	-6.37E+00	0.00171	

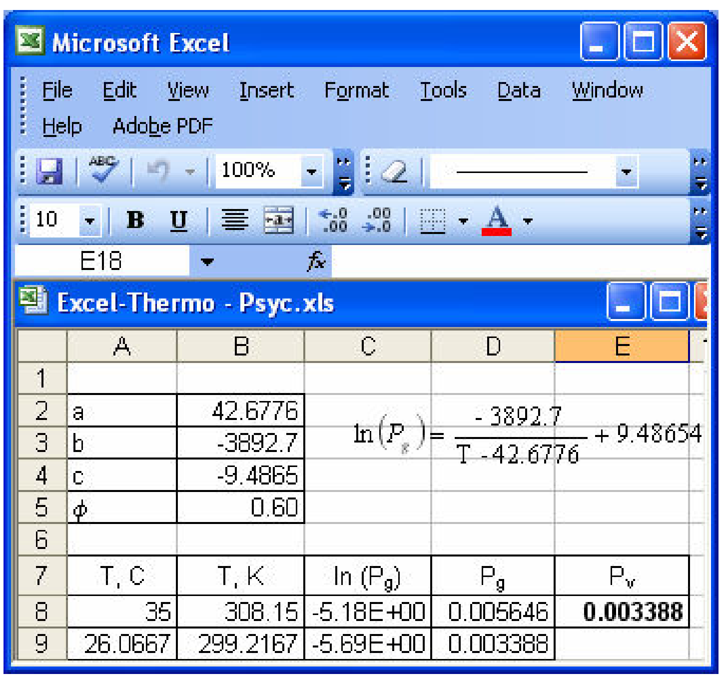
(a)



(b)



(c)



	A	B	C	D	E
1					
2	a	42.6776	$\ln(P_g) = \frac{-3892.7}{T - 42.6776} + 9.48654$		
3	b	-3892.7			
4	c	-9.4865			
5	ϕ	0.60			
6					
7	T, C	T, K	ln (P_g)	P_g	P_v
8	35	308.15	-5.18E+00	0.005646	**0.003388**
9	26.0667	299.2167	-5.69E+00	0.003388	

(d)

Fig.3. Evaluation of dew point temperature in exercise 4, using Solver

Figures 1 through 3 were produced using the 1997-2003 version of Microsoft Office. Solutions to problems in 2007 version of MS Office look very similar to those shown in Figs. 1 and 2. However, when using Solver, the menu bar and the tool menu of the MS Office-2007 does not look the same as those in 1997-2003 version of MS Office.

The *Ribbon* is a new feature in MS Office containing a number of tabs (Home, Insert, Page Layout, formulas, Data, Review, and View). By clicking on each, a group of related tabs will be displayed. The Solver is an Add-In function that needs to be activated when it is first used. To check whether solver is activated, one needs to click on the Data tab. If Solver is activated, it will appear in the Analysis group. If Solver is not already activated, one needs to click on the Microsoft Office button. By clicking on the Excel Options button, a dialog box opens. On the left panel, the Add-Ins should be selected. Using the Manage drop down menu, select the Excel Add-Ins and click on go. This will activate the Solver.

The solution of Exercise 4, using Solver in MS Excel 2007 is presented in Fig. 4. After entering the formulas for solving the problem in a worksheet and entering an initial guess for the dew point temperature (cell A9, Fig 4-a), the Data tab is used to select Solver from the analysis group. A dialog box appears as shown in Fig. 4-b. In the dialog box, cell D9 is selected as the target cell and its value is set to the desired solution value (0.003388). The cell that's value must be changed during the iteration process is identified (A9). By clicking on the Solve button, the values of the cells are automatically changed for the desired solution. A new dialog box opens confirming that the Solver found a solution, as shown in Fig. 4-c. The Solver returns a value of 26.063 ^{o}C for the dew point temperature, as shown in Fig. 4-d.

<u>Exercise 5:</u>

Moist air enters a duct at 10 ^{o}C, 0.101 MPa, 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 through the duct. No moisture is added or removed during this process. Evaluate the temperature and relative humidity of the exit.

<u>Solution:</u>

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.

$$\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a \tag{15}$$

$$\dot{m}_{v1} = \dot{m}_{v2} = \dot{m}_v \tag{16}$$

$$\omega_1 = \omega_2 = \omega \tag{17}$$

$$\dot{m} = \dot{m}_a + \dot{m}_v = \dot{m}_a (1+\omega) \tag{18}$$

$$\dot{m}_a = \frac{\dot{m}}{(1+\omega)} \tag{19}$$

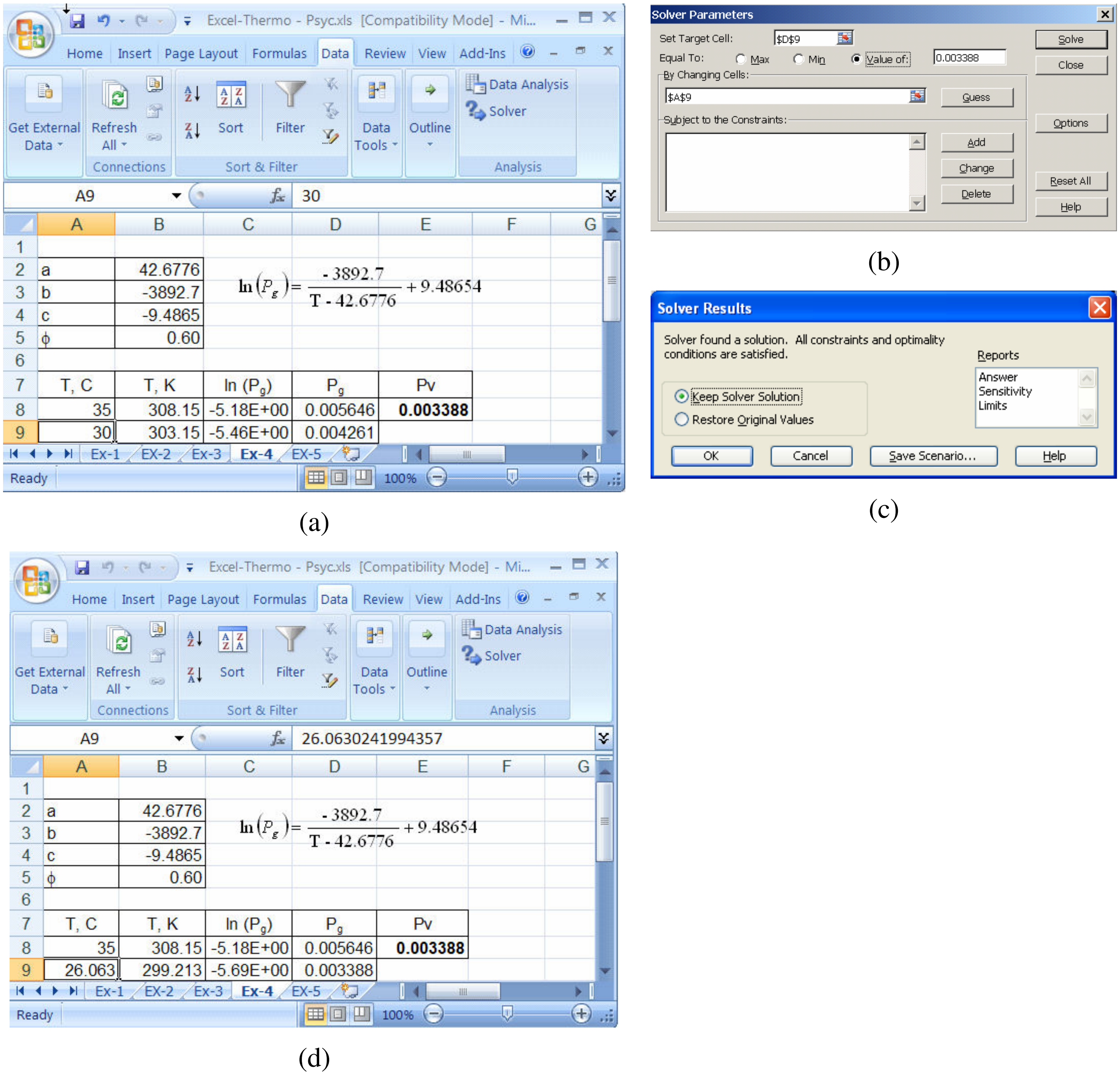


Fig.4. Evaluation of dew point temperature in exercise 4, using Solver in MS Excel 2007

Using Eq. (11), the saturated pressure of water at T_1 is calculated. Using the calculate value of P_{g1} in Eq. (3), the partial pressure of water vapor is determined. The result is used in Eq. (4) to determine ω. Then the mass flow rate of dry air is calculated from Eq. (19).

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

$$\dot{Q} = \dot{m}_a\left(h_{a2} - h_{a1}\right) + \dot{m}_v\left(h_{v2} - h_{v1}\right) = \dot{m}_a\left[c_{pa}\left(T_2 - T_1\right) + \omega\left(h_{v2} - h_{v1}\right)\right] \tag{20}$$

Since $h_v \approx h_g(T)$, it can be used for the evaluation of h_{v1} and h_{v2} in Eq. (20). To evaluate h_{g2} the value of T_2 is necessary. Therefore, to evaluate T_2 from Eq. (20) a trial and error procedure needs to be used. The Goal Seek tool of Excel may be employed to evaluate T_2.

After entering the applicable formulas, P_{g1}, P_v, ω, $\dot{m}_a$, and h_{g1} are evaluated at T_1, using Eqs. (11), (3), (4), (19), and (14), respectively. By assuming a temperature of 25 °C for T_2, P_{g2}, h_{g2}, ϕ_2, and the rate of heat transfer were calculated from Eqs. (11), (14), (4), and (20), respectively. The assumed value of $T_2 = 25$ °C yields a value of 45.4 kW for the rate of heat transfer. The results of calculations in an Excel worksheet are shown in Fig. 5a. To find the correct temperature for T_2, the tool menu in Excel 1997-2003 is used to select the Goal Seek function. By selecting Coal Seek option from the Tools menu, a dialog box appears as shown in Fig. 5b. In the dialog box cell G19 is set a value of 60. The cell that its value must be changed is identified (A19). By clicking on the Ok button, the values of the cells are automatically changed for the desired solution. The Goal Seek returns a value of 29.8 °C for T_2. This temperature yields a value of 17.5% for the relative humidity ϕ_2 as shown in Fig. 5d.

The solution of Exercise 5 in Excel 2007 is presented in Fig. 6. The formulation of problem is the same as that described for the Excel 1997-2003. Figure 6a shows the calculation results for P_{g1}, P_v, ω, $\dot{m}_a$, and h_{g1} at T_1. It also shows the results for P_{g2}, h_{g2}, ϕ_2, and the rate of heat transfer based on the assumed value of $T_2 = 25$ °C. To use the Goal Seek function in Excel 2007, the Data tab is clicked and after clicking on the What-If Analysis button, the Goal Seek option is selected. The remaining steps for completing the Goal seek process are the same as those described for Excel 1997-2003.

<u>Exercise 6:</u>

Using an MS Excel, determine the humidity ratio, mixture specific enthalpy, and wet-bulb temperature of moist air at 101 kPa, corresponding to the dry-bulb temperature of 32°C and 50% relative humidity.

<u>Solution:</u>

The values of dry-bulb temperature, T_{db}, an assumed value for wet-bulb temperature, T_{wb} ($T_{wb} < T_{db}$), total pressure, P, the constant pressure specific heat of air, c_{pa}, relative humidity, ϕ, Eqs. (4), (10),(11), (13), and (14) are entered in an Excel worksheet for the evaluation $P_g(T_{db})$, $P_g(T_{wb})$, $\omega(T_{db})$, $\omega'(T_{wb})$, $h_f(T_{wb})$, $h_g(T_{db})$, and $h_g(T_{wb})$. In these equations T is replaced by T_{db} and T_{as} is replaced by T_{wb}. The results are used in Eq. (9) to calculate the value of humidity ratio $\omega(T_{wb})$ which is based on the assumed value of T_{wb}. The results are shown in Fig. 7a. The results show $\omega(T_{db}) = 0.01506$. This value used in Eq. (7) to evaluate the specific enthalpy of the mixture, in kJ/kg of dry air. The value of ha in Eq. (7) is evaluated by the multiplying the constant pressure specific heat of air, c_{pa}, by T_{db} (°C). The results shows that

$$\hat{h} = h_a + \omega h_v = c_{pa} T_{db} + \omega(T_{db}) h_g(\mathrm{T}_{db}) = 70.71 \text{ kJ/kg of dry air.}$$

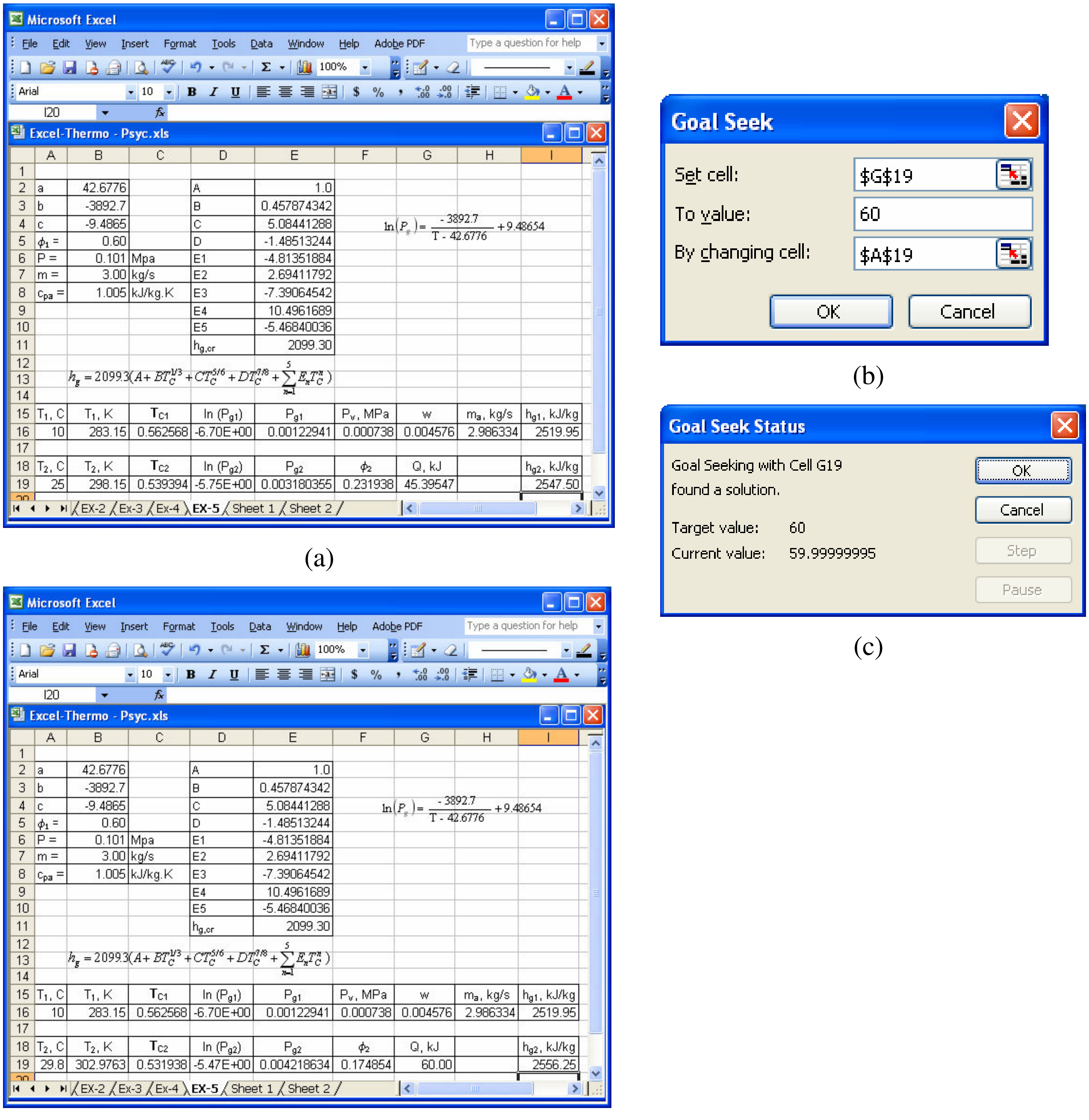


Fig. 5. Solution of Exercise 5 using the Goal Seek Function of Excel (1997-2003 versions)

Figure 7a also shows that the value of $\omega(T_{db})$ evaluated from Eq. (4) differs from the value of $\omega(T_{wb})$ calculated from Eq. (9). Therefore, the value of T_{wb} needs to be changed in a trial and error process until $\omega(T_{db}) = \omega(T_{wb})$. To complete the Iteration process, the Solver tool of Excel is employed. The results are presented in Fig. 7d. The solver yields a value of 23.64 ^{o}C for the wet-bulb temperature. Equation

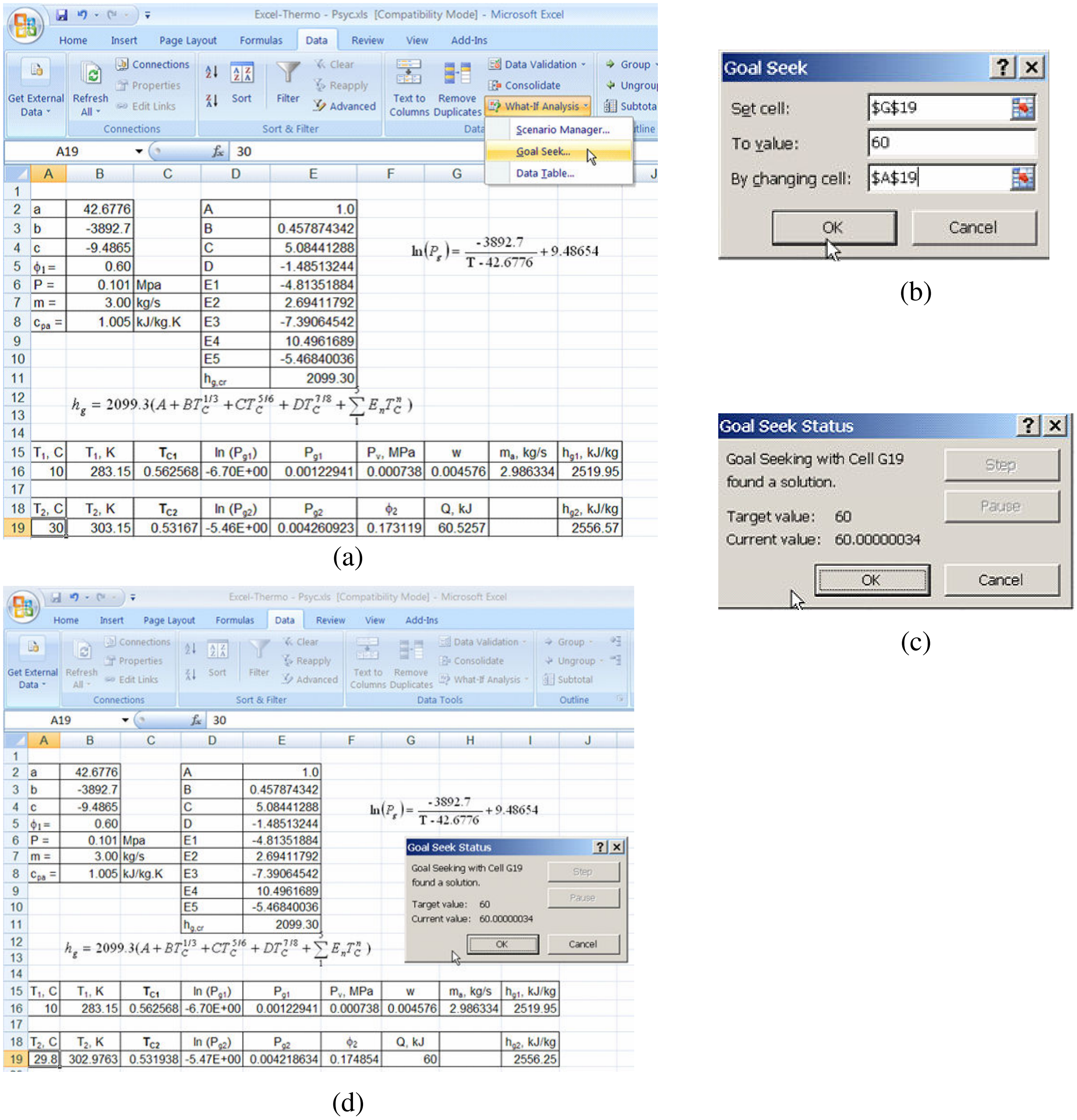
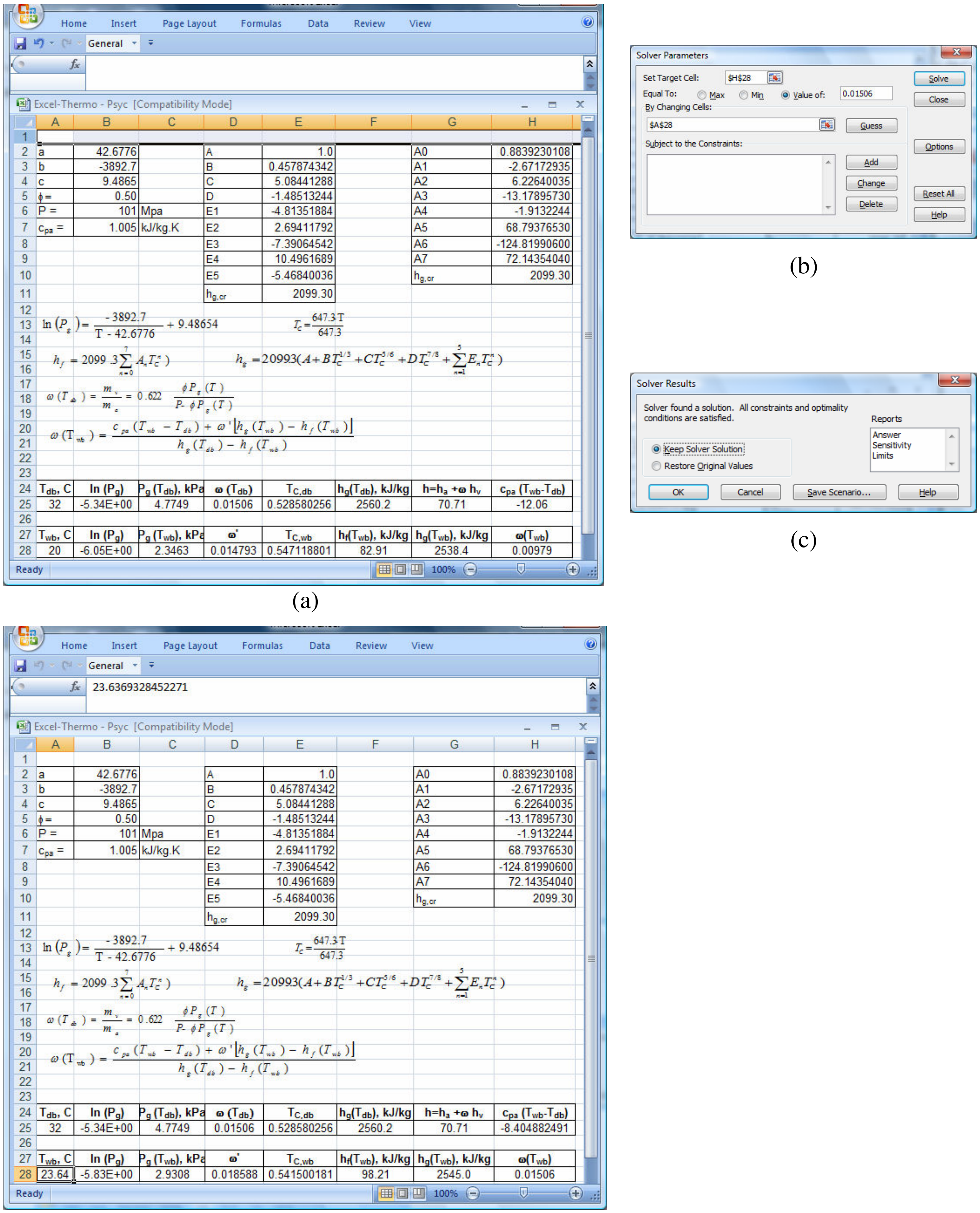


Fig. 6. Solution of Exercise 5 using the Goal Seek Function of Excel 2007

Student Survey and Assessment

Students enrolled in Thermodynamic-II were assigned the exercises described in this paper. After completing the assignment, a survey was conducted to obtain feedback on the students' experience in using MS Excel. Table 3 shows the summary of the survey results. For each question in the survey students were asked to use the following scale in responding to each question: 1 = definitely yes; 2 = yes; 3 = maybe; 4 = no; and 5 = definitely no.



	A	B	C	D	E	F	G	H
2	a	42.6776		A	1.0		A0	0.8839230108
3	b	-3892.7		B	0.457874342		A1	-2.67172935
4	c	9.4865		C	5.08441288		A2	6.22640035
5	ϕ =	0.50		D	-1.48513244		A3	-13.17895730
6	P =	101	Mpa	E1	-4.81351884		A4	-1.9132244
7	c_{pa} =	1.005	kJ/kg.K	E2	2.69411792		A5	68.79376530
8				E3	-7.39064542		A6	-124.81990600
9				E4	10.4961689		A7	72.14354040
10				E5	-5.46840036		$h_{g,cr}$	2099.30
11				$h_{g,cr}$	2099.30			

$$\ln(P_g) = \frac{-3892.7}{T - 42.6776} + 9.48654 \qquad T_c = \frac{647.3 - T}{647.3}$$

$$h_f = 2099.3\sum_{n=0}^{7} A_n T_c^n \qquad h_g = 20993(A + BT_c^{1/3} + CT_c^{5/6} + DT_c^{7/8} + \sum_{n=1}^{5} E_n T_c^n)$$

$$\omega(T_{db}) = \frac{m_v}{m_a} = 0.622\,\frac{\phi P_g(T)}{P - \phi P_g(T)}$$

$$\omega(T_{wb}) = \frac{c_{pa}(T_{wb} - T_{db}) + \omega'[h_g(T_{wb}) - h_f(T_{wb})]}{h_g(T_{db}) - h_f(T_{wb})}$$

(a)

	A	B	C	D	E	F	G	H
24	T_{db}, C	ln (P_g)	P_g (T_{db}), kPa	ω (T_{db})	$T_{C,db}$	h_g(T_{db}), kJ/kg	h=h_a +ω h_v	c_{pa} (T_{wb}-T_{db})
25	32	-5.34E+00	4.7749	0.01506	0.528580256	2560.2	70.71	-12.06
27	T_{wb}, C	ln (P_g)	P_g (T_{wb}), kPa	ω'	$T_{C,wb}$	h_f(T_{wb}), kJ/kg	h_g(T_{wb}), kJ/kg	ω(T_{wb})
28	20	-6.05E+00	2.3463	0.014793	0.547118801	82.91	2538.4	0.00979

(b)

(c)

(d)

	A	B	C	D	E	F	G	H
24	T_{db}, C	ln (P_g)	P_g (T_{db}), kPa	ω (T_{db})	$T_{C,db}$	h_g(T_{db}), kJ/kg	h=h_a +ω h_v	c_{pa} (T_{wb}-T_{db})
25	32	-5.34E+00	4.7749	0.01506	0.528580256	2560.2	70.71	-8.404882491
27	T_{wb}, C	ln (P_g)	P_g (T_{wb}), kPa	ω'	$T_{C,wb}$	h_f(T_{wb}), kJ/kg	h_g(T_{wb}), kJ/kg	ω(T_{wb})
28	23.64	-5.83E+00	2.9308	0.018588	0.541500181	98.21	2545.0	0.01506

Fig. 7. Solution of Exercise 6 using the Goal Seek Function of Excel 2007

Table 3 Student survey results, with 68 students participating in the survey
Response: 1 = definitely yes; 2 = yes; 3 = maybe; 4 = no; 5 = definitely no

	Question	1	2	3	4	5
1	Have you used thermodynamics software such as IT (Interactive Thermodynamics), EES (Engineering Equation Solver) or CATT3 (Computer Aided Thermodynamics Tables 3)?	44%	15%	3%	23%	15%
2	If yes, did the software program help you solve complex thermodynamic problems?	51%	30%	11%	2%	6%
3	If yes, was the software easy to use?	45%	32%	11%	2%	9%
4	Have you used thermodynamics software available on the internet?	33%	31%	3%	13%	20%
5	If yes, did the internet software help you solve more complex thermodynamics problems?	31%	33%	21%	6%	8%
6	If yes, was the internet software easy to use?	36%	39%	16%	2%	7%
7	Prior to this course, did you use Excel to solve engineering homework problems or engineering class projects?	50%	17%	12%	12%	9%
8	Is Excel easy to use?	44%	34%	22%	0%	0%
9	Is Excel a useful tool?	66%	29%	3%	1%	0%
10	Is Excel readily available for you to use?	67%	23%	5%	3%	2%
11	Prior to this course, did you use the “Solver” function of Excel?	7%	7%	6%	32%	47%
12	Prior to this course, did you use the “Goal Seek” function of Excel?	0%	8%	0%	35%	56%
13	Did you find “Solver” to be useful?	36%	27%	22%	11%	5%
14	Did you find “Goal Seek” to be useful?	43%	37%	8%	10%	2%
15	Did you try to solve the last two problems by hand (without using Excel)?	9%	23%	5%	28%	34%
16	Have you used other software (other than Excel) which could be used to solve the last two problems requiring iteration?	11%	27%	8%	29%	26%

Nearly 70 students anonymously participated in the survey. The survey shows that about 40% of the students have not used IT, EES, or CATT3 software to assist them in solving thermodynamics problems. although these problems can be tedious by hand. Over 60% of the students have used internet-based thermodynamics software. The majority claimed they have used the property calculator of the Free Steam Tables Online[14]. This tool was used before this assignment primarily for property evaluations. About 20% of the students claim to have not used Excel in their engineering courses before this assignment and most students are within two semesters of graduation. Students viewed Excel as an easy to use and useful tool available in most computers. Very few students had used the “Solver” or Goal Seek capabilities of the MS Excel before this assignment. Both of these capabilities were viewed useful, although 15% responded that it was not useful. Some students stated that Goal Seek was easier to use than the Solver. This was supported by student’s comments, such as:

- “Both Goal Seeker and Solver are useful, but the Goal Seeker is much more intuitive.”
- “Solver was harder to use and I felt I could do it by hand in the time it took me to figure it out. But Goal Seek was easy and quick and made my work a lot easier.”

- “Since I hadn’t used solver or goal seek before, I tried looking at tutorials online, and found that looking at the tutorials was a waste of time because both solver and goal seek were easy to use.”
- “This is a more practical approach to applying available technology to solve engineering problems.”
- “this was the first time I used Excel in thermodynamics.”
- “yay, I learned something new about Excel.”
- “Solver and Goal Seek were extremely useful. I will definitely use them in the future.”
- “would like to do more problems such as this assignment, using Excel.”
- “More assignments should include software use, since it is more practical for real world applications. Testing our competency in software use and knowledge will be more beneficial for job skills.”

Overall, the students were successful in completing the exercises and most appreciated the exposure to Excel. As in many engineering assignment with a tight schedule, many students worked late the night before it was due. As one might expect, some negative comments were received:

- “Please no more iteration problem.”
- “These problems would have been easier to me in MATLAB because of the sums and iterations.”

Based on student success in completing the exercise and survey feedback, this assignment does help meet the following course objectives:

- “Develop understanding how thermodynamic relations are used in evaluation of thermodynamic properties”
- “Enhance problem solving skills”

Likewise, this exercise contributed the ABET Program Outcome:

(e) “ability to identify, formulate, and solve engineering problems”

With exposure to Excel and its analysis capabilities, the students are better prepared for more detailed and complicated thermodynamics system analysis and design. Therefore, it strengthens their preparation to achieve design oriented program educational objectives:

(c) ‘ability to design a system, component, or process to meet desired needs within realistic constraints”

Summary

The application of MS Excel in solving problems involving psychrometric principles were demonstrated through several exercises. 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. Student feedback was mostly positive regarding to the use of Excel in solving psychrometric problems, especially those requiring trial and error processes. Excel is accessible to all students and, typically is available on most desktop and laptop

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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
n = number of moles
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
V= volume, m^3
v = specific volume, m^3/kg
Q = heat transfer, kJ
$\dot{Q}$= rate of heat transfer, kW

Greek letters
ϕ = relative humidity
ω = humidity ratio

Subscripts

a= air
as= adiabatic saturation
db= dry-bulb
f= saturated liquid
g = saturated liquid
p = inlet port
v = water vapor
wb= wet-bulb