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Research Article

Analysis of air-conditioning and drying processes using spreadsheet add-in for psychrometric data

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Abstract

A spreadsheet add-in for the psychrometric data at any barometric pressure and in the air-conditioning and drying temperature ranges was developed using appropriate correlations. It was then used to simulate and analyse air-conditioning and drying processes in the Microsoft Excel environment by exploiting its spreadsheet and graphic potentials. The package allows one to determine the properties of humid air at any desired state, and to simulate and analyse air-conditioning as well as drying processes. This, as a teaching tool, evokes the intellectual curiosity of students and enhances their interest and ability in the thermodynamics of humid-air processes.

Keywords: Psychrometry, air-conditioning, drying, spreadsheet add-in, Microsoft Excel.

1. Introduction

The properties of humid air are very important in air-conditioning and drying process analysis and system design. The property data are usually provided as tables and charts of properties. But, reading the psychrometric charts is strenuous, time consuming and always prone to errors, and the use of property tables frequently requires interpolation between the tabulated data, which is also manual and time consuming activity. However, the proliferation of computer technology in contemporary engineering practice ensures greater speed and accuracy, and thus should limit or even eliminate the use of property charts and tables in engineering analysis. The present trend in engineering practice is, therefore, towards the development of computer packages that are capable of automatic generation of the values of the desired thermodynamic properties, and thus, facilitating their use in engineering analysis [1].

Many computer software packages are now available for engineering analysis, which have the facility for providing the thermodynamic properties of working fluids [1, 2]. But these packages are not available in most computers; they must be bought and installed; they cannot be modified by their users, say, to account for varying barometric pressure; special training is usually required for their users; and internet connectivity may be necessary. But these shortcomings can be overcome if computer packages that are easy to develop, modify and exploit by users are available. The Microsoft (MS) Excel offers a suitable environment for the development of such packages [3, 4, 5].

Therefore, it is possible to develop computer procedures in Visual Basic for Applications (VBA) for generating the psychrometric data as spreadsheet add-ins. Such a procedure would then be used in the MS Excel environment for the simulation and analysis of air-conditioning and drying processes in an interactive fashion and in a manner that fully exploits the spreadsheet and graphic potentials of MS Excel. Such tool would assist the design engineer in his work, especially when incorporated into a larger plant design software. It would also be tool an easily affordable tool for the effective teaching of air-conditioning and drying engineering principles to students of mechanical and chemical engineering. The use of the MS Excel environment for enhancing the learning process in engineering is not new [6, 7, 8, 9]. Our experience has also shown that students exhibit greater interest, commitment and ability in using the spreadsheet for problem solving, especially when graphical output is involved, than in the traditional approach.

This paper, therefore, presents a spreadsheet add-in for the psychrometric data for any barometric pressure and in the dry bulb temperature range of 0 to 550 (^{0}C), and uses it to illustrate the interactive determination of the state properties of humid air, and simulation and analysis of air-conditioning and drying processes.

2. Governing Equations

Following the works of [10, 11, 12], the basic psychrometric properties are related as follows:

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Specific humidity (g):

$$g = 0.622 \frac{P_{wv}}{(P_b - P_{wv})} \quad (1)$$

where P_b and P_{wv} are the barometric pressure and partial pressure of the water vapour, respectively.

If the temperature of humid air (t) is higher than the temperature of saturation (t_s) of water vapour (wv) at the dry air (da) pressure ($P_{d.a}$), that is, $t > t_s$, then $P_{wv} = P_{da}$ and

$$g = 0.622 \frac{RH}{(1 - RH)} \quad (1a)$$

where RH is the relative humidity of the air, given as

$$RH = \frac{P_{wv}}{P_s} 100 \quad (2)$$

where P_s is the saturation pressure of the water vapour.

Enthalpy of Moist Air (h):

$$h = c_{p_{da}} t + g(2501 + c_{p_{wv}} t) \quad (3)$$

where t, $c_{p_{da}}$, and $c_{p_{wv}}$ are the dry bulb temperature, specific heat capacity of the dry air, and specific heat capacity of the water vapour, respectively.

The average specific heat capacities are given, respectively for air-conditioning and drying processes as $c_{p_{da}}$ =1.005 (*kJ/kgK*) and $c_{p_{wv}}$ =1.88 (*kJ/kgK*), and $c_{p_{da}}$ =1.01 (*kJ/kgK*) and $c_{p_{wv}}$ =1.97 (*kJ/kgK*).

Wet Bulb Temperature (t_{wb}) *and Thermodynamic Wet Bulb Temperature* (t^*):

$$t_{wb} = t - \frac{k_M}{\alpha_a} \frac{h_{(fg)wb}}{} (g_{wb} - g) \quad (4)$$

and

$$t^* = t - \frac{h^*_{fg}}{c_p} (g^* - g) \quad (5)$$

where

$$c_p = c_{p_{d.a}} + g c_{p_{w.v}} \quad (6)$$

Le = 0.945 is the Lewis number for humid air, in which case $t_{wb} \approx t^*$; α_α [W/m^2K], k_M [$kg_{w.v}/m^2s$], and c_p [$kJ/kg_{d.a}K$] are the heat transfer coefficient of the air film around the wetted surface, the mass transfer coefficient based on the specific humidity (g) and the humid specific heat, respectively; $h_{(fg)wb}$ and g_{wv} are the specific latent enthalpy and specific humidity at the wet bulb temperature, respectively; and R_{da}= 0.2873 [kJ/kgK] is the dry air gas constant; the superscript "*" denotes adiabatic saturation properties and the indices "*fg*" and "*wb*" denote latent conditions and wet bulb temperature, respectively.

The Carrier's equation for the partial pressure of the water vapour, P_{wv}, is given as

$$P_{wv} = P_{(s)\,wb} - \frac{1.8\,(P_{wv} - P_{(s)wb})(t - t_{wb})}{2800 - 1.3\,(1.8\,t + 32)} \quad (7)$$

where $P_{(s)wb}$ [kPa] is the saturation pressure at the wet bulb temperature.

Specific volume (v):

$$v = \frac{R_{d.a} T}{P_b - P_{w.v}} \quad (8)$$

where T [K] is the absolute temperature of humid air, $T = 273 + t$; t is temperature in degree celsius.

The humid air analysis is carried out using the following *algorithm*:

start

input data:

i. obtain the prevailing barometric pressure;
ii. obtain the desired (unknown) property (specific enthalpy, dry bulb temperature, wet bulb temperature, specific volume, specific humidity, relative humidity or dew point temperature);
iii. obtain two known properties and their values;

compute (using the relevant relationships for the psychrometric properties) the specific humid volume, specific enthalpy, specific humidity, dry-bulb, wet-bulb or dew-point temperature;

output the desired data (property name and numerical value);

use the output for process simulation and analysis, if desired;

plot psychrometric charts, if desired;

stop.

The software was developed in MS Excel Visual Basic for Application Integrated Development Environment (Excel-VBA IDE) as an Excel add-in, called Psychrometric_data, using all the relevant correlations for the thermodynamic analysis of humid air, given in the *governing equations*, and following the *computational algorithm*. Some of the procedures are iterative with an error bound of 0.01%. The interface retrieves and supplies information on any of the humid air properties. A command button control on the Excel form is used to run the macro that implements a particular function.

After a successful installation of the Excel add-in, the *Psychrometric_data menu* is seen on the standard menu bar. By clicking on the Start button of the *Psychrometric_data menu*, the window shown in Figure 1 appears. Select the process type (*Drying* or *Air Conditioning*) by clicking on the relevant *OptionButton*. If the barometric pressure is different from the standard, P_b= 101.325 [kPa], check the *No* box, and enter the prevailing barometric pressure in the *TextBox* provided. Select the unknown property from the *ComboBox* captioned *Unknown Property*. In the *ComboBox* captioned *Function*, ℘ (…,…), select the known properties. Key in the numerical values of the known properties into the *TextBoxes* in the *Frame* captioned *Input the known data*. By clicking on the *CommandButton* captioned *Read*, the Psychrometric_data uses the relevant correlations to obtain the numerical value of the desired property, which is displayed in the *Output Data Frame* and is also automatically transferred to a pre-selected cell in the worksheet for further use. The process continues for another state by clicking on the *Continue* drop menu of the *Psychrometric_data menu*.

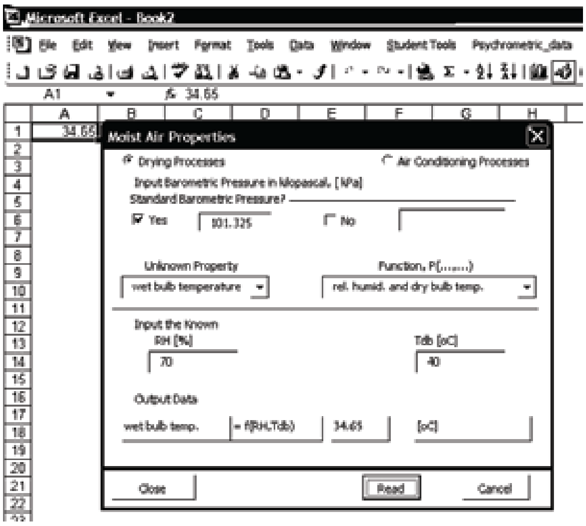

Figure 1. The add-in (Psychrometric_data) window.

3. Results and Discussion

As an Excel add-in, Psychrometric_data is designed to aid students as well as practicing air conditioning or drying plant engineers in their design/performance analysis by automatically providing the desired property data in the environment, for the relevant spreadsheet analysis. To illustrate how this is achieved, we consider the following problems:

1. A room for process work is maintained at 20°C dry bulb (db) temperature and 25% relative humidity (RH). The outside air is at 40°C db and 25°C wet buld (wb) temperature. Twelve cubic metre per minute (cmm) of fresh air is mixed with a part of the recirculated air, and another passed over the adsorption dehumidifier. It is then mixed with another part of the recirculated air, and sensibly cooled in the cooler before being supplied to the room at 14°C. The room sensible and latent heat gains are 6 and 0.8 kW, respectively. The performance of the dehumidifier (adsorbent material) is characterized by the inlet and exit humidity ratios of the air flowing through it, which are tabulated below. Assume the heat of adsorption of moisture to be 390 kJ/kg$_{w.v}$ Determine the volume flow rate of the air through the dehumidifier and the heat transfer rate in the cooler [10].

inlet humidity ratio, $g_1 x10^3$ [g/kg$_{d.a}$]	exit humidity ratio, $g_2 x10^3$ [g/kg$_{d.a}$]
2.86	0.43
4.29	0.57
5.70	1.00
7.15	1.57
8.57	2.15
10.00	2.86
11.43	3.57
12.86	4.57
14.29	5.23

Solution: (*The following solution steps are carried out on the MS Excel worksheet*)

Input data: (*the given data in the problem*)

S/No	Quantity	Symbol	Units	Value
1	dry bulb temperature of room	t_{dbi}	°C	20
2	relative humidity of room	RH_i	%	25
3	dry bulb temperature of outside air	t_{dbo}	°C	40
4	wet bulb temperature of outside air	t_{wbo}	°C	25
5	volume flow rate of outside air	V_o	m³/s	0.2
6	dry bulb temp. of air leaving the cooler	t_{dbs}	°C	14
7	room sensible heat	Q_{RS}	kW	6.0
8	room latent heat	Q_{RL}	kW	0.8

Sketches/Diagrams:
(*Figure 2 shows the plant flow sheet and process diagram*).

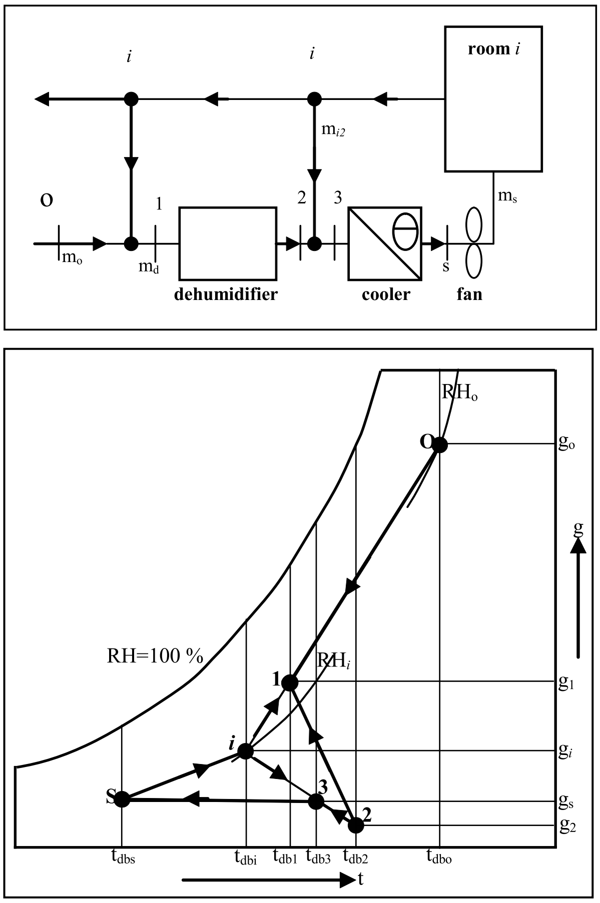

Figure 2. The air-conditioning plant and processes.

(*psychrometric data obtained using the add-in,* $\wp(\ldots,\ldots)$

S/No	Quantity	Symbol	Units	Function	Value
1	wet bulb temperature of room	t_{wbi}	^oC	$\wp(t_{dbi},RH_i)$	11.210
2	specific enthalpy of outside air	h_o	$kJ/kg_{d.a}$	$\wp(t_{dbo},t_{wbo})$	75.760
3	specific enthalpy of room air	h_i	$kJ/kg_{d.a}$	$\wp(t_{dbi},RH_i)$	29.010
4	specific humidity of outside air	g_o	$kg_{w.n}/kg_{d.a}$	$\wp(t_{dbo},t_{wbo})$	0.014
5	specific humidity of room air	g_i	$kg_{w.n}/kg_{d.a}$	$\wp(t_{dbi},RH_i)$	0.003
6	specific volume of outside air	v_o	$m^3/kg_{d.a}$	$\wp(t_{dbo},t_{wbo})$	0.907
7	relative humidity of outside air	RH_o	%	$\wp(t_{dbo},t_{wbo})$	29.570
8	specific volume of room air	v_i	$m^3/kg_{d.a}$	$\wp(t_{dbi},RH_i)$	0.835

Data read from literature:

1	isobaric specific heat capacity of air	c_p	kJ/kg	1.024
2	Specific heat of vaporization	h_{fgref}	kJ/kg	2500
3	reference temperature	t_{ref}	^oC	25
4	Reference density	ρ_{ref}	kg/m^3	1.2
5	heat of adsorption	Q_a	kW	390
6	Iteration error	ε	-	0.000005

Computation: (*provides answers the questions asked*)

S/No	Quantity	Symbol	Units	Function	Value
1	mass flow rate of fresh air	m_o	kg/s	$m_o=V_o/v_o$	0.221
2	temperature rise of supply air in the room	Δt_{dbs}	^oC	$\Delta t_s=t_{dbi}-t_{dbs}$	6.000
3	sensible volumetric heat constant	K_S	kJ/m^3	$K_s=\rho_{ref}c_p(273+t_{ref})$	366
4	volume flow rate of supply air	V_s	m^3/s	$V_s=Q_{RS}(t_{dbs}+273)/(K_S\Delta t_{dbs})$	0.784
5	Latent volumetric heat constant	K_L	kJ/m^3	$K_L=\rho_{ref}h_{fgref}(273+t_{ref})$	894000
6	specific humidity of supply air	g_s	$kg_{w.v}/kg_{d.a}$	$g_s=g_i-Q_{RL}(t_{dbs}+273)/(K_L V_s)$	0.003
7	heat taken by the supply air per unit mass	q_s	kJ/kg	$q_s=c_p\Delta t_{dbs}$	6.144
8	mass flow rate of fresh air	m_s	kg/s	$m_s=Q_{RS}/q_s$	0.977
9	mass flow rate of the recirculated air	m_i	kg/s	$m_i=m_s-m_o$	0.756
10	specific humidity of air at the inlet of the dehumidifier	g_1	$kg_{w.v}/kg_{d.a}$	$g_1= \varphi(g_1,\varepsilon)^*$	0.010^*
11	mass flow rate of recirculated air mixing before the cooler	m_{i2}	kg/s	$m_{i2}=m_i-m_{i1}$	0.614
12	mass flow rate of air entering the dehumidifier	m_d	kg/s	$m_d=m_s-m_{i2}$	0.363
13	recirculation/fresh air mass mixing ratio	$\gamma_{i1,o}$	-	$\gamma_{i1,o}=m_{i1}/m_o$	0.644
14	temperature of air entering the dehumidifier	t_{db1}	^oC	$t_{db1}=(t_{dbo}+\zeta_{i1,o}t_{dbi})/(1+\zeta_{i1,o})$	32.165
15	specific volume of air entering the dehumidifier	v_1	$m^3/kg_{d.a}$	$\wp(t_{db1},g_1)$	0.878
16	volume flow rate of air through the dehumidifier	V_d	m^3/s	$V_d=m_d v_1$	0.318
17	specific humidity of air at the exit of the dehumidifier	g_2	$kg_{w.v}/kg_{d.a}$	$g_2= -0.1273g_1+0.00382$	0.003^*
18	mass flow rate of recirculated air before the dehumidifier	m_{i1}	kg/s	$m_{i1}=m_o(g_1-g_o)/(g_i-g_1)$	0.142
19	specific humidity drop in the dehumidifier	Δ_{gd}	$kg_{w.v}/kg_{d.a}$	$\Delta g_d=g_2-g_1$	-0.007
20	heat transfer rate due to condensation in dehumidifier	Q_{cond}	kW	$Q_{cond}=2500m_d I\Delta g_d I$	6.345
21	heat transfer rate due to adsorption of moisture in the dehumidifier	Q_{ads}	kW	$Q_{ads}=Q_a m_d I\Delta g_d I$	0.990
22	total heat transfer rate in the dehumidifier	Q_d	kW	$Q_d=Q_{cond}+Q_{ads}$	7.335
23	temperature rise in the dehumidifier	Δt_{dbd}	^oC	$\Delta t_{dbd}=Q_d/(m_d c_p)$	19.756
24	temperature of air exiting the dehumidifier	t_{db2}	^oC	$t_{db2}=t_{db1}+\Delta t_{dbd}$	51.920
25	dehumidifier/recirculation air mass mixing ratio	$\gamma_{i2,2}$	-	$\gamma_{i2,2}=m_{i2}/m_d$	1.693
26	temperature of air entering the cooler	t_{db3}	^oC	$t_{db3}=(t_{db2}+\gamma_{i2,2}t_{dbi})/(1+\gamma_{i2,2})$	31.851
27	specific enthalpy of air entering the cooler	h_3	$kJ/kg_{d.a}$	$\wp(t_{db3},g_s)$	41.260
28	specific enthalpy of the supply air	h_s	$kJ/kg_{d.a}$	$\wp(t_{dbs},g_s)$	22.120
29	heat transfer rate in the cooler	Q_c	kW	$Q_c=m_s I h_s-h_3 I$	18.691

$$* \quad g_1 = \frac{g_i - g_o}{g_i - \dfrac{(m_s g_s - m_i g_i)}{m_i}} g_2 + \frac{g_o - (1/m_o)(m_s g_s - m_i g_i)}{g_i - (1/m_o)(m_s g_s - m_i g_i)} g_i \quad ;\ or,\ \ g_2 = -0.12732 g_1 + 0.00382 = f(g_1).$$

By curve fitting the experimental data for the dehumidifier performance using MS Excel curve fitting tool, we obtain $g_2 = 20.928\, g_1^2 + 0.08 g_1 - 7 \times 10^{-5} = \varphi(g_1)$, *Figure 3. Equating the last two equations,* $f(g_1) = \varphi(g_1)$, *we get the iteration scheme,* $g_{1,j+1} = -100.989\, g_{1,j}^2 + 0.01877$. *Setting* $g_{1,0} = 0.00286$ *and iterating in Excel environment, within an absolute error bound of* 10^{-5}, *we obtain the values of* g_1 *and* g_2 *as* $g_1=0.0097$ *and* $g_2= -0.1273g_1+0.00382 =0.0027$ (kg_{wv}/kg_{da}).

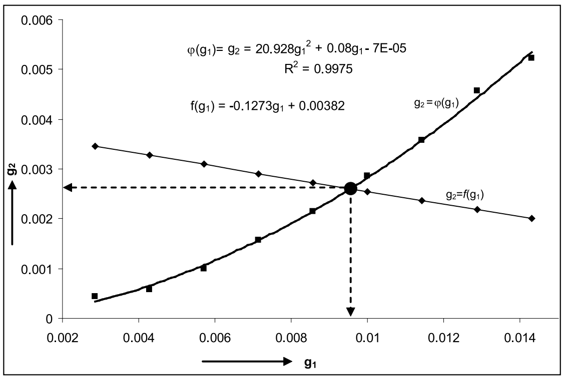

Figure 3. Curve fitting of the dehumidifier data and solution of the equation $f(g_1)= \varphi(g_1)$.

2. One tonne of some moist material is to be dried per hour from an initial moisture content of u_{in} = 50 [%] to a final moisture content of u_{fin} = 6 [%] (wet basis). The temperature and humidity of the outdoor air are t_o = 25 [%] and go = 0.0095 [$kg_{w.v}/kg_{d.a}$], respectively, and those of the air leaving the dryer (spent air) are t_s= 60 [°C] and g_s = 0.041 [$kg_{w.v}/kg_{d.a}$]; where the subscripts "*wv*" and "*da*" denote "water vapour" and "dry air", respectively. The drying of the moist material can be accomplished by any of the following three arrangements:

(a) The temperature of the outdoor air is raised in the heater before it enters the dryer; the humid air leaving the dryer (spent air) is exhausted into the atmosphere.
(b) The temperature of the outdoor air is raised to 100 [°C] in the heater; it enters the dryer and partially dries the moist material; it then enters the reheater, where its temperature is again raised to 100 [°C] before it is reintroduced into the dryer to complete the drying process; the spent air is then exhausted into the atmosphere.
(c) The outdoor air is mixed with 80 [%] recirculated; it is then heated in the heater and introduced into the dryer to process the moist material; the spent air is exhausted into the atmosphere.

Determine the outdoor air flow rate through the dryer, and the power consumption (heat transfer rate) for each of the drying arrangements. Also compare the drying potentials of these arrangements [12].

Solution: (*The following solution steps are carried out on the MS Excel worksheet*)

Input data: (*the given data in the problem*)

S/No	Quantity	Symbol	Units	Value
1	initial mass of moist material	m_{mm}	kg/s	0.278
2	initial moisture content of material	u_{in}	-	0.5
3	final moisture content of material	u_{fin}	-	0.06
4	temperature of air in case (b) heater	t_{dbb}	°C	100
5	fraction of recirculated air	κ	-	0.8
6	outside air dry bulb temperature	t_{dbo}	°C	25
7	outside air specific humidity	g_o	$kg/kg_{d.a}$	0.0095
8	spent air dry bulb temperature	t_{dbs}	°C	60
9	spent air specific humidity	g_s	$kg/kg_{d.a}$	0.041

Sketches/Diagrams:
(*Figure 3 shows the plant flow sheet and process diagram*).

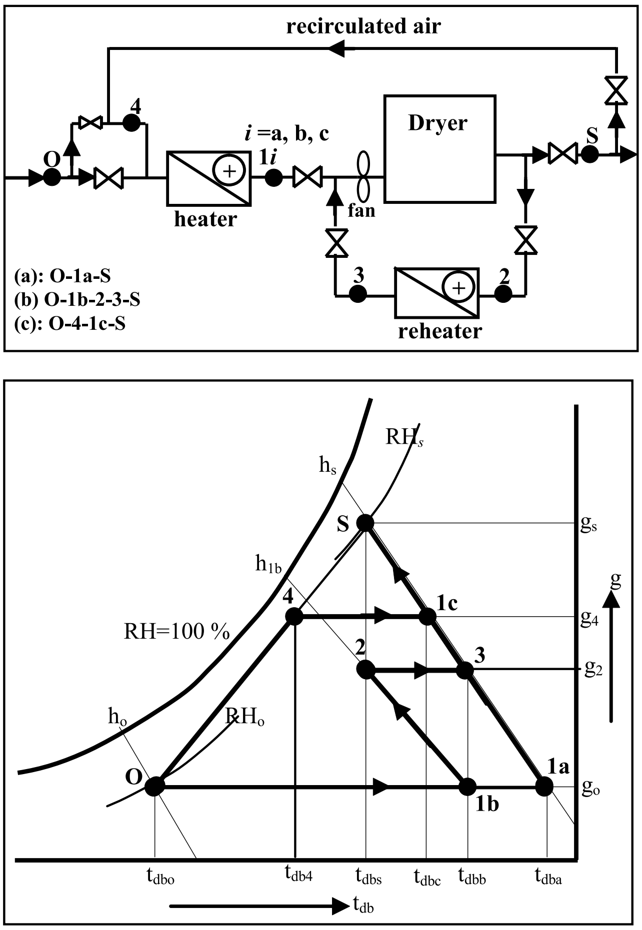

Figure 4. The convective drying plant and processes.

Data read: *(psychrometric data obtained using the add-in)*

S/No	Quantity	Symbol	Units	Value	Value
1	outside air specific enthalpy	h_o	kJ/kg_{da}	$\wp(t_{dbo},g_o)$	46.25
2	spent air specific enthalpy	h_s	kJ/kg_{da}	$\wp(t_{dbs},g_s)$	168.13
3	outside air relative humidity	RH_o	%	$\wp(t_{dbo},g_o)$	43.33
4	spent air relative humidity	RH_o	%	$\wp(t_{dbs},g_s)$	31.09
5	spent air wet bulb temperature	t_{wbs}	°C	$\wp(t_{dbs},g_s)$	39.8
6	case (a) heated air dry bulb temperature	t_{dba}	°C	$\wp(g_o,h_s)$	139.1
7	specific humidity of air in the first process O-1b-2	g_2	kg_{wv}/kg_{da}	$\wp(t_{dbs},h_s)$	0.02528
8	case (b) heated air wet bulb temperature	t_{wbb}	°C	$\wp(t_{dbb},g_o)$	34.68

Computation: (*Answers the question asked*)

S/No	Quantity	Symbol	Units	Formula	Value
(a)					
1	rate of moisture removal in the dryer	m_{wv}	kg/s	$m_{wv}=m_{mm}(u_{in}-u_{fin})/(1-u_{fin})$	0.130128
2	rise in the specific humidity of the working fluid (air) in the dryer	$\Delta g_{(a)}$	kg_{wv}/kg_{da}	$\Delta g_{(a)}=g_s-g_o$	0.0315
3	mass of dry air per kilogram of moisture evaporated	$x_{(a)}$	kg_{da}/kg_{wv}	$x_{(a)}=1/\Delta g_{(a)}$	31.74603
4	mass flow rate of dry outdoor air through the dryer	$m_{o(a)}$	kg_{da}/s	$m_{o(a)}=m_{wv}*x_{(a)}$	**4.131037**
5	change in the specific enthalpy of air	$\Delta h_{(a)}$	kJ/kg_{da}	$\Delta h_{(a)}=h_s-h_o$	121.88
6	heat consumption per kilogram moisture evaporated	$q_{(a)}$	kJ/kg_{wv}	$q_{(a)}=x_{(a)}*\Delta h_{(a)}$	3869.206
7	power consumption	$Q_{(a)}$	kW	$Q_{(a)}=m_{wv}*q_{(a)}$	**503.4908**
(b)					
8	rise in the specific humidity of the air during the first pass through the dryer, process O-1b-2	Δg_{ib2}	kg_{wv}/kg_{da}	$\Delta g_{ib2}=g_2-g_o$	0.01578
9	mass of dry air per kilogram of moisture evaporated in the first process	$x_{(b)}$	kg_{da}/kg_{wv}	$x_{(b)}=1/\Delta g_{(b)}$	63.37136
10	mass flow rate of dry outdoor air through the dryer	$m_{o(b)}$	kg_{da}/s	$m_{o(b)}=0.5*m_{wv}*x_{(b)}$	**4.123183**
11	change in the specific enthalpy of air	$\Delta h_{(b)}$	kJ/kg_{da}	$\Delta h_{(b)}=h_s-h_o$	121.88
12	heat consumption per kilogram moisture evaporated	$q_{(a)}$	kJ/kg_{wv}	$q_{(b)}=x_{(b)}*\Delta h_{(b)}$	7723.701
13	power consumption	$Q_{(b)}$	kW	$Q_{(b)}=0.5*m_{wv}*q_{(b)}$	**502.5336**
(c)					
14	specific humidity of air after mixing of the outdoor and recirculated air	g_4	kg_{wv}/kg_{da}	$g_4=(1-\kappa)g_o+\kappa*g_s$	0.0347
15	rise in the specific humidity of air in the dryer	$\Delta g_{(c)}$	kg_{wv}/kg_{da}	$\Delta g_{(c)}=g_s-g_4$	0.0063
16	mass of dry air per kilogram of moisture evaporated	$x_{(c)}$	kg_{da}/kg_{wv}	$x_{(c)}=1/\Delta g_{(c)}$	158.7302
17	mass flow rate of dry air through the dryer	m_4	kg_{da}/s	$m_4=m_{wv}*x_{(c)}$	20.65518
18	mass flow rate of dry outdoor air through the dryer	$m_{o(c)}$	kg_{da}/s	$m_{o(c)}=(1-\kappa)*m_4$	**4.131037**
19	specific enthalpy of air after mixing	h_4	$kJ/kg_{d.a}$	$h_4=(1-\kappa)h_o+\kappa*h_s$	143.754
20	change in the specific enthalpy of air	$\Delta h_{(c)}$	kJ/kg_{da}	$\Delta h_{(c)}=h_s-h_4$	24.376
21	heat consumption per kilogram moisture evaporated	$q_{(c)}$	kJ/kg_{wv}	$q_{(c)}=x_{(c)}*\Delta h_{(c)}$	3869.206
22	power consumption	$Q_{(c)}$	kW	$Q_{(c)}=m_{wv}*q_{(c)}$	**503.4908**
23	"big" wet bulb depression for (a)	$\Delta t_{B(a)}$	K	$\Delta t_{B(a)}=t_{dba}-t_{wbs}$	99.3
24	"small" wet bulb depression for (a)	$\Delta t_{S(a)}$	K	$\Delta t_{S(a)}=t_{dbs}-t_{wbs}$	20.2
25	drying potential (logarithmic mean temperature difference (LMTD)) for (a)	$\Delta t_{p(a)}$	K	$\Delta t_{p(a)}=(\Delta t_{B(a)}-\Delta t_{S(a)})/(\ln(\Delta t_{B(a)}/\Delta t_{S(a)}))$	**49.7**
26	drying potential relative to that of (a)	$\varepsilon_{a(a)}$	%	$\varepsilon_{a(a)}=(\Delta t_{p(a)}/\Delta t_{p(a)})*100$	**100**
27	"big" wet bulb depression for (b), first pass through the dryer	$\Delta t_{B(b),1}$	K	$\Delta t_{B(a),1}=t_{dbb}-t_{wbb}$	65.3
28	"small" wet bulb depression for (b), first pass through the dryer	$\Delta t_{S(b),1}$	K	$\Delta t_{S(a),1}=t_{dbs}-t_{wbb}$	25.3
29	drying potential (LMTD) for (b), first pass	$\Delta t_{p(b),1}$	K	$\Delta t_{p(b),1}=(\Delta t_{B(b),1}-\Delta t_{S(b),1})/(\ln(\Delta t_{B(b)},1/\Delta t_{S(b),1}))$	42.2
30	"big" wet bulb depression for (b), second pass through the dryer	$\Delta t_{B(b),2}$	K	$\Delta t_{B(a),2}=t_{dbb}-t_{wbs}$	60.2
31	"small" wet bulb depression for (b), second pass through the dryer	$\Delta t_{S(b),2}$	K	$\Delta t_{S(a),2}=t_{dbs}-t_{wbs}$	20.2
32	drying potential (LMTD) for (b), first pass	$\Delta t_{p(b),2}$	K	$\Delta t_{p(b),2}=(\Delta t_{B(b),2}-\Delta t_{S(b),2})/(\ln(\Delta t_{B(b),2}/\Delta t_{S(b),2}))$	36.7
33	drying potential for (b)	$\Delta t_{p(b)}$	K	$\Delta t_{p(b)}=0,5*(\Delta t_{p(b),1}+\Delta t_{p(b),2})$	**39.5**
34	drying potential relative to that of (a)	$\varepsilon_{a(b)}$	%	$\varepsilon_{a(b)}=(\Delta t_{p(b)}/\Delta t_{p(a)})*100$	**79.5**
35	dry bulb temperature of air after the heater for (c)	t_{dbc}	^oC	$\wp(g_4,h_s)$	73.25
36	"big" wet bulb depression for (b), first pass through the dryer	$\Delta t_{B(c)}$	K	$\Delta t_{B(c)}=t_{dbc}-t_{wbs}$	33.5
37	"small" wet bulb depression for (b), first pass through the dryer	$\Delta t_{S(c)}$	K	$\Delta t_{S(c)}=t_{dbs}-t_{wbs}$	20.2
38	drying potential (LMTD) for (c)	$\Delta t_{p(c)}$	K	$\Delta t_{p(c)}=(\Delta t_{B(c)}-\Delta t_{S(c)})/(\ln(\Delta t_{B(c)}/\Delta t_{S(c)}))$	**26.3**
39	drying potential relative to that of (c)	$\varepsilon_{a(c)}$	%	$\varepsilon_{a(c)}=(\Delta t_{p(c)}/\Delta t_{p(a)})*100$	**52.92**

The results of the solutions of the illustrative problems 1 and 2 using the add-in are in good agreement with those obtained by [10] and [12], respectively. The psychrometric data provided by the add-in are in agreement with those from the psychrometric charts for air-conditioning processes and drying processes [12] and [13], respectively. It was, however, observed that the maximum relative deviation of 4.5% occurs in the values of the specific enthalpy; but this is within an acceptable limit for most applications. The interactive nature of the MS Excel environment evokes curiosity and participation in students, and its graphic, equation-solving and curve-fitting capabilities permit the student to visualise the humid air processes and appreciate the scope and applications of thermodynamics of humid air. Comparism of process characteristics is relatively simple, and process simulation under a range of varying input parameters is always possible as in Figure 5, which shows the dependence of the outdoor dry air mass flow rate ($\dot{m}_{o(c)}$), mass flow rate of air through the dryer ($\dot{m}_4$) and drying potential ($\Delta t_{p(c)}$) on the fraction of dryer spent air recirculated (κ).

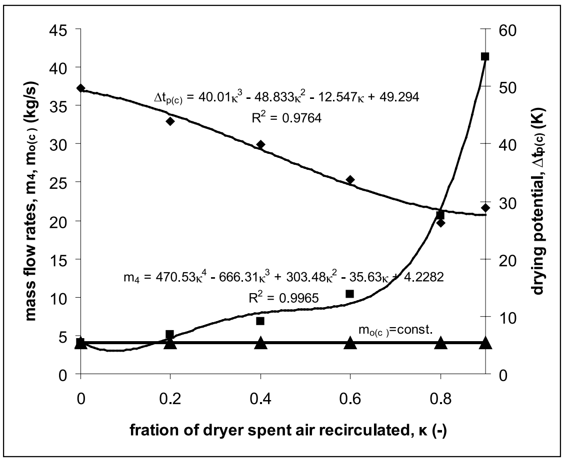

Figure 5. Variation of outdoor air flow rate ($m_{o(c)}$), mass flow rate of air through the dryer (m_4) and drying potential ($\Delta t_{p(c)}$) as function of fraction of dryer spent air recirculated (κ), Problem 2(c).

4. Conclusion

The spreadsheet add-in is provided in an easily accessible MS Excel environment to facilitate process analysis and simulation efforts of students as well as practising air-conditioning and drying engineers. Our experience has shown that students exhibit greater interest, commitment and ability in using the spreadsheet for problem solving, especially when graphical output is involved, than in the traditional approach. The tool proposed in this paper is easy to install, use and modify by engineering students in any computer driven by the MS Office. It is, therefore, strongly recommended as a teaching tool for engineering students, especially in localities with limited access to internet facilities, which may offer alternative tools online.

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