

A Multi-Substance Add-in for the Analyses of Thermo-fluid Systems using Microsoft Excel

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Abstract— Analyses of thermo-fluid systems require the thermo-physical properties of the working fluids to be repetitively determined at different conditions of pressure and/or temperature. However, relevant computer applications may not be available to many engineering students and practicing engineers particularly in developing countries. This paper presents an add-in that determines these properties for various fluids by using Microsoft Excel. Developed with Microsoft VBA, the add-in provides property functions for ideal gases, saturated and superheated water, saturated and superheated refrigerants for vapour-compression (VC) systems, binary solutions of ammonia-water and water-lithium bromide for vapour-absorption (VA) refrigeration systems, reacting mixtures, and atmospheric air. With its comprehensive library of functions, the add-in enables Microsoft Excel to be used as a modelling platform for conducting parametric and optimisation analyses of advanced power generation and refrigeration cycles, air-conditioning systems, and combustion processes. The present paper highlights the general features of the add-in before focussing on the set of functions that deal with the analyses of VC and VA refrigeration cycles. For the analyses of VC systems, the add-in currently supports ten synthetic and natural refrigerants (R12, R22, R32, R123, R134a, R152a, R717, R290, R600, R600a). The paper verifies the add-in functions for VC analyses by comparing its results with those obtained from relevant published research that used the well recognised REFPROP software. Similarly, the paper verifies the add-in functions for both ammonia-water and water-lithium bromide VA systems. The results obtained for both VC and VA cycles show that the add-in gives reasonably accurate estimations.

Index Terms— Excel add-in; refrigeration cycles; refrigerants; ThermoX; thermo-fluid systems.

I. INTRODUCTION

In introductory courses of thermodynamics, fluid mechanics, and heat-transfer, fluid properties are usually interpolated from relevant tables and charts. The interpolation of tabulated data and the ability to locate states on property diagrams are important skills for engineering students [1]. However, engineering students are also required to undertake design assignments and parametric studies that help them to gain deeper understanding of the basic concepts and their applications to the design of efficient thermo-fluid systems. Apart from the need for repetitive evaluations of fluid properties, such analyses may also involve iterative solutions or the solution of linear or non-linear systems of algebraic and differential equations. Since using property tables and charts becomes both time-consuming and error-prone, a number of computer applications are used by popular textbooks in this field for automated property evaluation. Computer software is believed to increase the curiosity of students and improve the

learning process [1-3]. Computer software is also needed for the development of innovative methods for efficient use of conventional and renewable energy sources. However, proprietary computer applications may not be available to many engineering students and practicing engineers particularly in developing countries.

Microsoft Excel, which is a widely distributed spread-sheet application, is introduced to students as a pre-requisite to most engineering disciplines. With its availability and simplicity of use, Excel can be a valuable education tool for the analyses of thermo-fluid systems. However, the lack of fluid-property built-in functions limits its use to certain cases that do not involve significant property variations. Realising the advantages of using Excel for the analyses of thermo-fluid systems, a number of add-ins have been developed which are dedicated to the calculation of thermo-physical properties of working fluids. REFPROP, which is developed by NIST [4], is probably the most famous among these add-ins that are mainly aimed at industrial applications. Reference [5] also focussed on developing Excel add-ins for thermodynamic properties of working fluids. A number of other property add-ins for Excel have also been developed by individual researchers. Jack [6] presented an Excel add-in for the thermo-physical properties of steam and air and Oke and Diemuodeke [7] developed a similar tool for thermodynamic properties of refrigerant R-152a. However, these add-ins are more tailored towards research applications than educational purposes.

The Mechanical Engineering Department at Alabama University [8] contributed significantly to the development of Excel add-ins for academic purposes. Under the project "Excel in ME", they developed a number of add-ins that can be used for thermodynamic and heat-transfer analyses. Their thermo-dynamic add-ins deal with ideal gases, water, and two refrigerants R134a and R22. They also developed a separate add-in that deals with psychrometric analyses. In its website, the University of Virginia also provides Excel-based models for thermodynamics analyses of Rankine, Brayton, Otto, and Diesel Cycles [9]. Caretto et al [10] developed an Excel-based tool for thermodynamic analyses that can be used to determine individual state points by a graphical user interface calculator and to build models of thermodynamic systems involving various fluids. Goodwin [11] developed an educational Excel add-in, called *TPX* (Thermodynamic Properties for Excel), that determines the thermodynamic properties of selected substances: H₂O, H₂, O₂, N₂, CH₄, and refrigerant R-134a. Rivas et al [12] used *TPX* to demonstrate the capability of current spread-sheets to define, analyse and optimise models of thermo-fluid systems and processes. They used Excel's built-in Solver to analyse and optimise two systems and processes of medium complexity: a regenerative

Rankine cycle with three closed feed-water heaters and a pipe network carrying water that has 13 nodes and 16 pipes.

This present paper presents an Excel add-in that provides a comprehensive library of user-defined functions for determining the thermo-physical properties of a wide range of substances. The add-in, called *ThermaX*, has been developed by using Visual Basic for Applications (VBA) that comes as part of Microsoft Office. *ThermaX* functions, which can be used via Excel's user interface just like Excel's own built-in functions, enable parametric studies and design optimisation of most types of thermal systems to be easily performed via Excel's user-interface and iterative tools (Solver and Goal Seek). The automation of property determination by *ThermaX* also enables engineering students to deal with thermo-fluid analyses that require iterative solutions (e.g. determination of the adiabatic flame temperature, solution of type 2 and type 3 flow problems, and heat-exchanger analyses). The paper describes the various functions supported by the add-in before focussing on the validity of the set of functions that deal with the analyses of vapour-compression (VC) and vapour-absorption (VA) refrigeration cycles.

II. THERMAX PROPERTY FUNCTIONS

ThermaX provides seven groups of user-defined functions that estimate the thermo-physical properties of most fluids usually used in thermo-fluid systems. As shown in Table I, the functions included in each group carry a common name that indicates the subject(s) of their application. For example, all functions in the group whose name starts with "Gas" deal with properties of ideal gases and the functions whose names start with "Wat" deal with the properties of saturated and superheated water. In addition to thermodynamic properties, some groups also estimate other thermo-physical properties such as the viscosity and thermal conductivity which are needed for fluid flow and heat transfer analyses. The add-in functions for determining the thermo-physical properties of saturated water, saturated refrigerants, and atmospheric air do that by interpolation of tabulated data obtained from standard textbooks and reference books [13,14]. However, the functions used to determine the thermodynamic properties of ideal gases, superheated water, superheated refrigerants, and aqua solutions of ammonia and Li-Br are formulated on the basis of relevant property relationships [13-19].

TABLE I. GROUPS OF THERMAX PROPERTY FUNCTIONS

Group	Group subject	Group name	No. of functions
1	Ideal gases (28)	Gas...	10
2	Saturated and superheated water	Wat...	30
3	VC refrigerants (10)	Ref...	25
4	VA binary solutions (2)	Bin...	9
5	Psychrometry (humid air)	Psy...	11
6	Combustion substances (25)	Com...	4
7	Air at 1 atm pressure	Air...	7

The following lines illustrate how the add-in functions are used in an Excel cell:

=GasT_cp("Air";350)
 =WatP_h(90;0.8)

=WatPT_h(90;150)
 =RefPT_s("R134a";100;25)
 =BinTX_v("LiBr";40;50)
 =PsyPTo_Phi(101;30; 0.001)
 =Com_hf0("Acetylene")
 =Air_kvisc(30)

The first line determines the specific heat (c_p) for air at 350K. The second and third lines determine the enthalpy (h) of saturated water at 90 kPa and quality 0.8 and the enthalpy of superheated water at 90kPa and 150°C. The fourth line determines entropy (s) of refrigerant R-134a at 100 kPa, 25°C. The fifth line determines the specific volume (v) of a water-LiBr binary solution at 40°C and 50% concentration. The six line determines relative humidity (ϕ) of humid air at 101 kPa, 30°C, and absolute humidity (ω) of 0.001 kg/kg. The seventh line determines the molar enthalpy of formation at 25°C (\tilde{h}_f^0) for acetylene. The function in the eighth line determines the kinematic viscosity (ν) of atmospheric air at 30°C. Note that name of each functions consists of three letters that refer to its group followed by the input properties. The functions' output follows the underscore.

III. THERMAX FUNCTIONS FOR VC REFRIGERANTS

This group deals with the thermo-physical properties of ten conventional and natural refrigerants (Table II) as saturated liquids, saturated vapours, subcooled liquids, and superheated vapours. The group consists of 25 functions that can be divided into three subgroups:

- (1) Eight functions determine the properties of saturated refrigerants from a given temperature (T) and quality (x),
- (2) Eight functions determine the properties of saturated refrigerants from a given pressure (P) and quality (x),
- (3) Seven functions determine the properties of superheated refrigerants given the pressure and temperature (P,T), pressure and enthalpy (P,h) or pressure and entropy (P,s).

TABLE II. REFRIGERANTS SUPPORTED BY THERMAX

Refrigerant name and designation	ThermaX name
Dichlorodifluoromethane (R-12)	R12
Chlorodifluoromethane (R-22)	R22
Methylene fluoride (R-32)	R32
Dichlorotrifluoroethane (R-123)	R123
Tetrafluoroethane (R-134a)	R134a
Difluoroethane (R-152a)	R152a
Ammonia (R-717)	R717
Propane (R-290)	R290
Butane (R-600)	R600
Isobutane (R-600a)	R600a

Table III lists the functions that determine the refrigerants' properties of saturated refrigerants at a given pressure. The names of these functions are shown together with their input and output arguments. These functions use interpolation functions [20] to interpolate the tabulated data provided by

ASHRAE [14]. A similar set of functions determine the same properties at a given temperature. These functions return warning messages if the given value of pressure (temperature) or quality is beyond the expected range. Properties of subcooled refrigerants are approximated by their values as saturated liquids at the given temperature. The seven functions that deal with superheated vapours are listed in Table IV. Unlike the functions for saturated and subcooled refrigerants, the functions for superheated refrigerants apply property formulae as described in the following section.

IV. PROPERTY FORMULAE FOR SUPERHEATED VC REFRIGERANTS

1. Specific volume

The molar specific volume (\tilde{v}) of a superheated refrigerant is obtained from the Soave-Redlich-Kwong equation of state [13, 16]:

$$P = \frac{R_u T}{\tilde{v} - b} - \frac{a\alpha}{\tilde{v}(\tilde{v} + b)} \quad (1)$$

where, R_u is the universal gas constant, P is the absolute pressure, and T is the absolute temperature. The constants a , b and α , which depend on the refrigerant's pressure and temperature at the critical point, are given by:

$$a = 0.4278 R_u^2 T_c^2 / P_c \quad (2)$$

$$b = 0.0867 R_u T_c / P_c \quad (3)$$

$$\alpha = \left[1 + S \left(1 - \sqrt{\frac{T}{T_c}} \right) \right]^2 \quad (4)$$

where, T_c and P_c are the temperature and pressure at the critical point and S is a function of the acentric factor (ω) for the given refrigerant:

$$S = 0.48508 + 1.55171 \omega - 0.15613 \omega^2 \quad (5)$$

Equation (1), which is non-linear, is solved by using Newton-Raphson method. The specific volume (v) is then obtained by dividing the molar volume \tilde{v} by the molar mass (M) of the refrigerant.

2. Enthalpy

Enthalpy of superheated refrigerant at a given pressure (P) and temperature (T) is determined from [16]:

$$h = h_g + C p_g (T - T_s) \quad (6)$$

Where h_g , $C p_g$, and T_s are the enthalpy, specific heat, and temperature of the saturated vapour refrigerant at the given pressure. Values of h_g , $C p_g$, and T_s are obtained by using the add-in functions for the properties of saturated refrigerant shown in Table III.

3. Entropy

Entropy of superheated refrigerant at a given pressure (P) and temperature (T) is determined from [16]:

$$s = s_g + \frac{C p_g (T - T_s)}{(T_{av} + 273)} \quad (7)$$

Where s_g is the entropy of saturated vapour refrigerant at the given pressure and T_{av} is the average temperature:

$$T_{av} = \frac{T + T_s}{2} \quad (8)$$

TABLE III. PROPERTIES OF SATURATED REFRIGERANTS GIVEN THE PRESSURE AND QUALITY

Property	Function	Input	Output
Saturation pressure	RefP_Tsat	Refrigerant name, P[kPa], x	T_{sat} [°C]
Specific volume	RefP_v	Refrigerant name, P[kPa], x	v [m ³ /kg]
Enthalpy	RefP_h	Refrigerant name, P[kPa], x	h [kJ/kg]
Entropy	RefP_s	Refrigerant name, P[kPa], x	s [kJ/kg.K]
Specific heat	RefP_cp	Refrigerant name, P[kPa], x	c_p [kJ/kg.K]
Velocity of sound	RefP_vsound	Refrigerant name, P[kPa], x	C [m/s]
Dynamic viscosity	RefP_visc	Refrigerant name, P[kPa], x	μ [μPa.s]
Thermal conductivity	RefP_thermk	Refrigerant name, P[kPa], x	k [mW/(m.K)]
Surface tension	RefP_surft	Refrigerant name, P[kPa], x	σ [mN/m]

TABLE IV. PROPERTIES OF REFRIGERANTS GIVEN THE PRESSURE AND ANOTHER PROPERTY

Property	Function	Input	Output
Specific volume	RefPT_v	Refrigerant name, P[MPa], T[°C]	v [m ³ /kg]
Enthalpy	RefPT_h	Refrigerant name, P[MPa], T[°C]	h [kJ/kg]
Entropy	RefPT_s	Refrigerant name, P[MPa], T[°C]	s [kJ/kg.°C]
Enthalpy	RefPs_h	Refrigerant name, P[MPa], s[kJ/kg.°C]	h [kJ/kg]
Entropy	RefPh_s	Refrigerant name, P[MPa], h [kJ/kg]	s [kJ/kg.°C]
Temperature	RefPh_T	Refrigerant name, P[MPa], h[kJ/kg]	T [°C]
Temperature	RefPs_T	Refrigerant name, P[MPa], s[kJ/kg.°C]	T [°C]

4. Temperature at a given pressure and enthalpy or entropy

The analysis may require the temperature of superheated refrigerant to be determined given its pressure and enthalpy. In this case, (6) is rearranged as follows:

$$T = T_s + \frac{(h - h_g)}{Cp_g} \quad (9)$$

Similarly, when the pressure and entropy of the superheated refrigerant are known, the temperature is determined from [16]:

$$T = (T_g + 273.15)e^{\frac{s-s_g}{Cp_g}} - 273.15 \quad (10)$$

Where s_g is the entropy of saturated vapour refrigerant at the given pressure.

V. VERIFICATION OF THERMAX FUNCTIONS FOR VC REFRIGERATION ANALYSES

The add-in functions for the analyses of vapour-compression refrigeration cycles are validated in this section by considering the cascade refrigeration system shown in Fig. 1. Compared to a simple VC refrigeration system, the cascade system increases the coefficient of performance (COP) by simultaneously increasing the refrigeration capacity and decreasing the compressor work. Using the notation of Fig. 1, the cycle's COP is determined from [13]:

$$COP = \frac{Q_L}{w_{CA} + w_{CB}} \quad (11)$$

where Q_L is the rate of heat removal in the evaporator of the bottom cycle and w_{CA} and w_{CB} are power consumed in the compressors of the top and bottom cycles, respectively. Given the evaporator and condenser temperatures (or pressures) and the intermediate temperature, the values of Q_L , w_{CB} , and w_{CA} can be determined from:

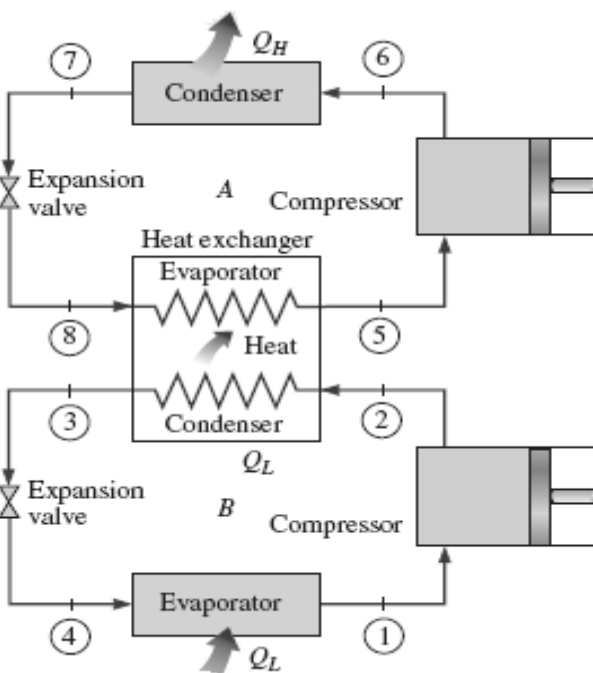


Fig. 1. The cascade refrigeration system (adapted from Cengel and Boles [13])

$$Q_L = \dot{m}_B(h_1 - h_4) \quad (12)$$

$$w_{CB} = \dot{m}_B(h_2 - h_1) \quad (13)$$

$$w_{CA} = \dot{m}_A(h_6 - h_5) \quad (14)$$

Where \dot{m}_A and \dot{m}_B are the refrigerant mass flow rates in the top and bottom cycles, respectively. Assuming no heat-loss to the surrounding from the heat-exchanger (i.e. an adiabatic heat exchanger), the mass flow rates in the top and bottom cycles are related by the law of energy conservation:

$$\dot{m}_A(h_5 - h_8) = \dot{m}_B(h_1 - h_4) \quad (15)$$

Dalkilic [21] conducted an extensive theoretical study on the two-stage cascade refrigeration system by comparing the performance of three conventional refrigerants, CFC-12, HCFC-22, CFC-502, with that of alternative refrigerants such as HFC-134a, HFC-152a, HFC-404A, HFC-407C, HC-290, HC-600a, ammonia (R717), and three mixtures of HFC and hydrocarbon (HC) refrigerants with different compositions of HFC-134a, HFC-152a, HC-600a, and HC-290. The heat exchanger temperature was kept constant at 1°C, but the condensing temperatures were varied between 40 and 60°C and the evaporating temperatures varied between -50 and -10°C. In his study, Dalkilic [21] initially assumed the refrigerants in the top and bottom cycles to be the same and then considered the separate usage of the refrigerants R717 and R152a for the high- and low-pressure sections of the cascade system. He concluded that the best combination, in terms of coefficient of performance and refrigerant charge rate, is the combination of R717 for the high-pressure section and HFC-152a for the low-pressure section. Dalkilic [21], who determined the physical properties of the various refrigerants by using REFPROP 7 [4], provided part of his results in a tabulated form that makes it possible to compare his results with those obtained by the present add-in.

Fig. 2 shows the Excel sheet developed for the analysis of the cascade cycle by using the add-in functions to determine properties of the refrigerants. The input data and calculations parts are split such that the top part deals with the top cycle and the bottom part deals with the bottom cycle. Therefore, FluidA and FluidB represent the refrigerants in the top and bottom cycles, respectively. The states in the two cycles are designated with numbers that refer to their corresponding numbers shown in Fig. 1. The mass flow rate in the bottom cycle is calculated according to (15) and the COP of the cascade system is calculated according to (11). All the points in the top and bottom cycles lie in the saturated liquid-vapour region except points 2 and 6. Therefore, the accuracy of the add-in function in determining the refrigerant's properties for six points is derived from that of the property tables provided by ASHRAE [14] since they only apply interpolation of these data. However, points 2 and 6 apply the approximate formulae (1)-(10) described in the previous section for superheated refrigerants. The accuracy of the add-in functions that calculate the refrigerant's properties at these two points determine the accuracy of calculating the compressors work and COP of the cascade cycle.

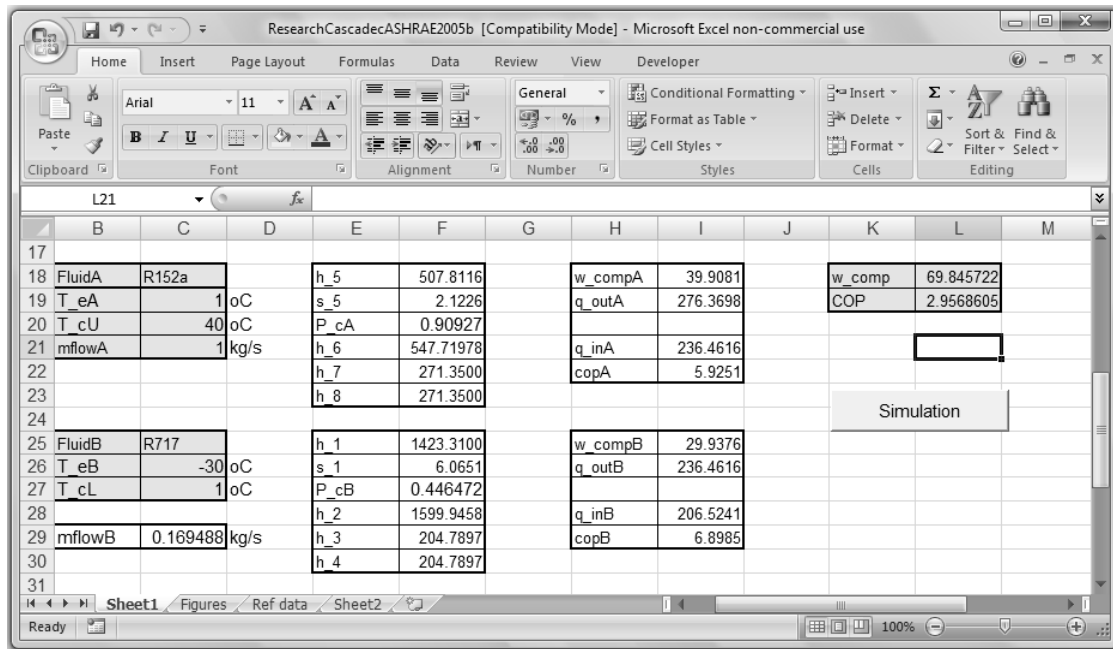


Fig. 2. Excel sheet developed for the analysis of the cascade-cycle with different refrigerants

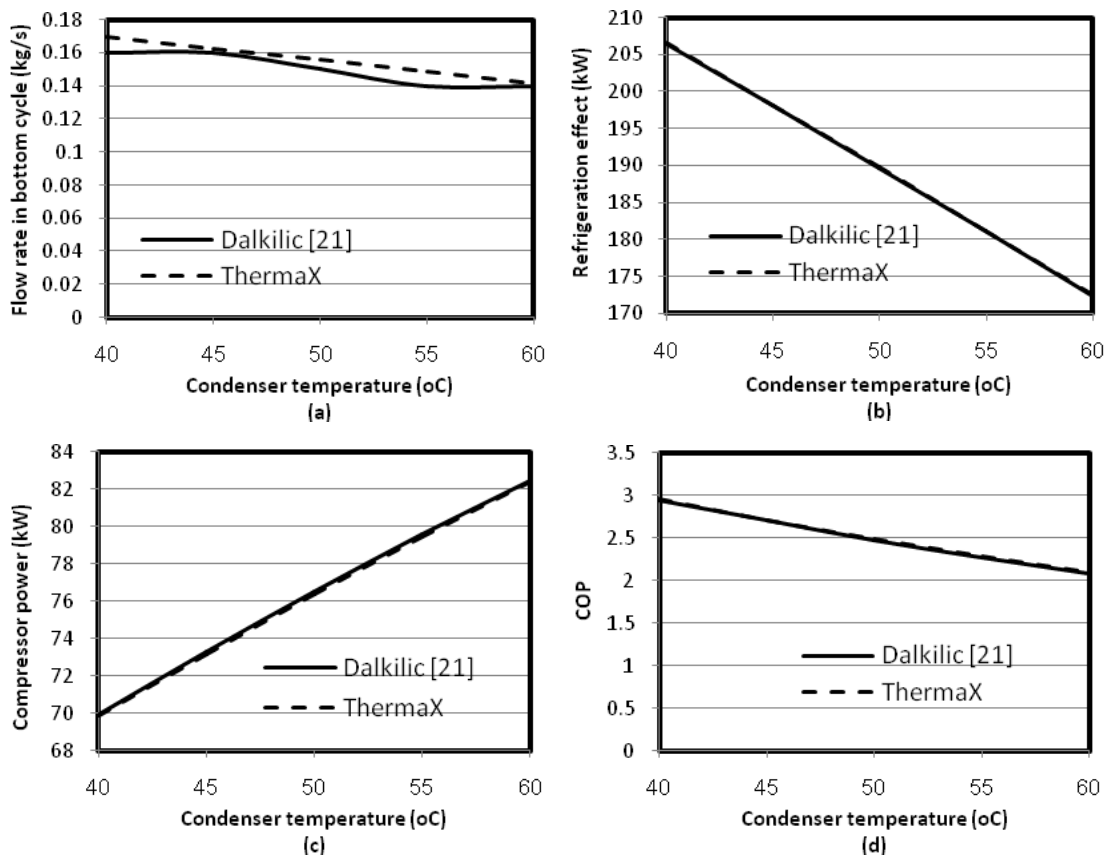


Fig. 3. Cycle performance with R-152a in the top and R-717 in the bottom cycles of the cascade system

By suitably adjusting the input data parts of the sheet, it can be used to analyse the performance of the cascade system with different refrigerants in the top and bottom cycle at different condenser and evaporator pressures. Fig. 3 compares the performance parameters of the cascade system with R-152a in the top cycle and R-717 in the bottom cycle with those provided by Dalkilic [21] at an evaporating temperature of -30°C and various condensing temperatures. With the exception of the mass flow rate, the figures show close agreements between the estimations of the present

add-in with those obtained by Dalkilic [21]. Comparison was also made with the data provided by Dalkilic [21] for other arrangements of the cascade system in which the same refrigerant (R-12, R-22, R-290, R-152a, or R-717) was used in both the top and bottom cycles and for the case when R-717 was used in the top cycle and R-152a in the bottom cycle. In all these cases, the results obtained by *ThermaX* functions were in good agreement with those obtained by REFPROP.

VI. VERIFICATION OF THERMAX FUNCTIONS FOR VA REFRIGERATION ANALYSES

Fig. 4 shows a schematic diagram of a single-effect VA refrigeration system. By dissolving the refrigerant in a liquid before compression, vapour absorption refrigeration systems require significantly lower pumping work than that of VC systems. To free the refrigerants from the absorbent, VA systems need a low-temperature supply of heat. In power-generation plants, this heat comes from the waste energy of the exhaust gas, but renewable energies, such as solar and biomass, can also be used. Since analyses of VA systems are usually more involved than those of VC systems, most textbooks in engineering thermodynamics deal with VA systems only briefly. Detailed analyses of this system can be found in ASHRAE [14] or Stoecker and Jones [22]. The coefficient of performance of a VA system is defined as:

$$COP = \frac{Q_e}{Q_g + w_p} \quad (16)$$

Where Q_e is heat absorbed in the evaporator, Q_g the heat provided to the generator, and w_p is the pump work. In terms of flow rates and fluid enthalpies, these quantities are given by [14]:

$$Q_e = \dot{m}_9(h_{10} - h_9) \quad (17)$$

$$Q_g = \dot{m}_3h_3 - \dot{m}_4h_4 - \dot{m}_7h_7 \quad (18)$$

$$w_p = \dot{m}_1(h_2 - h_1) \quad (19)$$

The present add-in provides functions for two types of VA systems; water-lithium bromide and ammonia-water systems. For the water-lithium bromide system, ThermaX uses the formulae given by ASHRAE [14] and Patek and Klomfar [18]. Abdulateef et al [23] analysed the performance of a water-lithium bromide VA system at $T_e=5^\circ\text{C}$, $T_c=T_a=35^\circ\text{C}$, and various generator temperatures $T_g=70-90^\circ\text{C}$. The refrigerant mass flow rate through the pump was 1 kg/min and the heat exchanger effectiveness was 70%. Fig. 5 compares their estimations for the heat added in the generator (Q_g), the heat removed in the absorber (Q_a), and the cycle's COP with those obtained by the present add-in. Unlike the heat transfer in the evaporator and condenser, both Q_g and Q_a depend on the accuracy of estimating the enthalpy of the water-lithium bromide solution. Fig. 5 shows that the add-in functions give accurate estimations of both Q_g and Q_a as well as the COP.

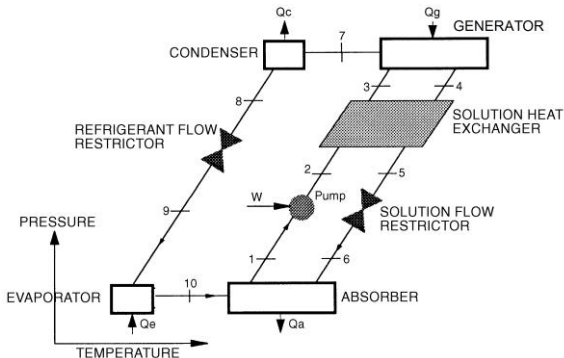


Fig. 4. Single effect VA refrigeration system (adapted from ASHRAE [14])

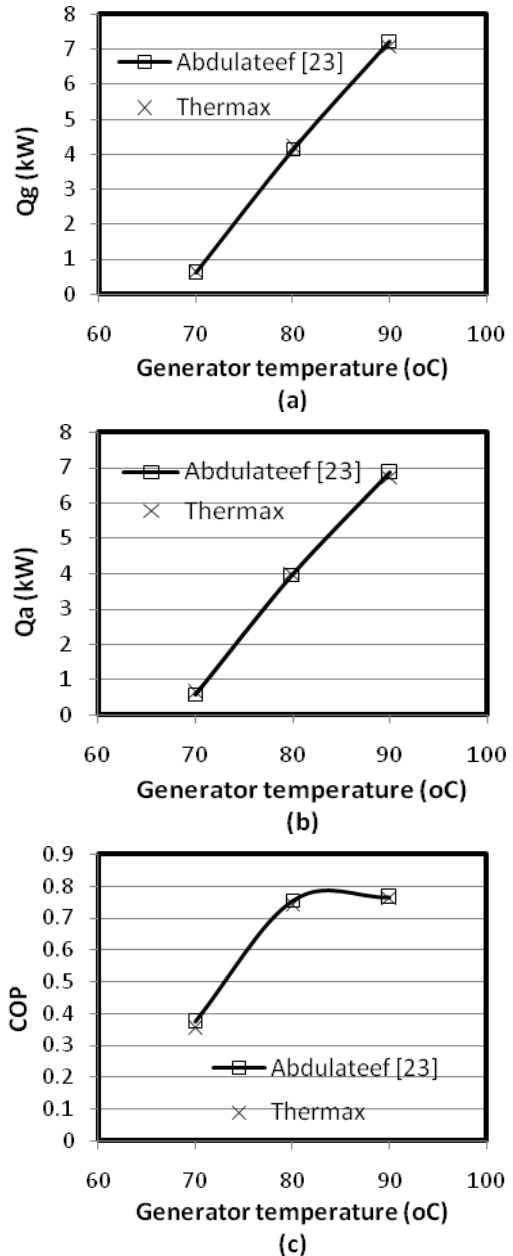


Fig. 5. Validation of add-in functions for H₂O-LiBr

TABLE V. VALIDATION OF THE ADD-IN FUNCTIONS FOR NH₃-H₂O

	Sun [24]	ThermaX	Error (%)
Q_g (kW)	30.1314	30.86	2.42
Q_c (kW)	18.4611	19.07	3.30
Q_e (kW)	18.5974	18.58	-0.09
Q_a (kW)	30.3269	30.38	0.18
w (kW)	0.0592	0.059	-0.34
Q_{ex} (kW)	11.8382	11.86	0.18
COP	0.6160	0.601	-2.44

For the ammonia-water system, the add-in applies the formulae given by Patek and Klomfar [17] and El-Shaarawi et al [18]. For the purpose of verifying the add-in estimates, comparison is made with the data provided by Sun [24] for an ammonia-water VA system operating at $T_g=100^\circ\text{C}$, $T_c=30^\circ\text{C}$, $T_a=25^\circ\text{C}$ and $T_e=-5^\circ\text{C}$. The refrigerant mass flow rate was 1 kg/min and the heat exchanger effectiveness was 80%. Table V compares the cycle parameters as obtained by the present add-in and those given by Sun [24]. The figures show good

agreements between the estimations of the present add-in and those given by Sun [24].

VII. CONCLUSIONS

The paper demonstrated that the present add-in can be used with acceptable accuracy to analyse the performance of vapour-compression and vapour-absorption refrigeration systems under different operating conditions. The functions provided for vapour-compression refrigerants also enable the students to easily analyse multi-stage refrigeration cycles and cycles that involve suction-line heat exchangers. Similarly, double-effect vapour-absorption refrigeration systems involving ammonia-water or water-lithium bromide solutions can be analysed with the present add-in.

The other groups of functions provided by the add-in that have not been considered in the present paper enable students to analyse other types of thermo-fluid systems. For example, using the functions provided for ideal gases and water, students can analyse thermodynamic power cycles such as Brayton, Rankine, Otto, Diesel, and combined cycles. The eleven functions provided by the add-in for psychrometry enable students to analyse different air-conditioning processes. For reacting mixtures, the add-in provides four functions that determine the molar mass (M), molar enthalpy of formation (\bar{h}_f^0), Gibbs function of formation (\bar{g}_f^0), and absolute entropy (\bar{s}^0) at 25°C and 1 atm. Based on the data provided by Cengel and Boles [13], the add-in functions determine these properties for 25 substances that are frequently encountered in combustion analyses.

The addition of other vapour-compression refrigerants presently not included in the add-in library is straightforward since it mainly requires the inclusion of their missing data. However, the addition of refrigerant mixtures or ternary vapour-compression solutions may require further developments with VBA. Finally, although the present paper focussed the use of the add-in for performing parametric studies, it should be mentioned that the add-in is particularly useful for conducting iterative solutions and optimization analyses by means of Excel's two iterative tools, Goal Seek and Solver.

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