Design of Thermodynamic Data of a Solar Powered Ammonia–Water Vapour Absorption Refrigeration System with Storage Units using EES

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Abstract— The aim of this paper is to estimate of energy analysis of ammonia-water vapour absorption refrigeration (VAR) system using EES (Engineering Equation Solver) software. Engineering Equation Solver makes available many built-in thermo-physical properties mathematical relations useful for thermal systems. Systematic procedure is presented for predicting thermodynamic properties of ammonia-water. Under energy analysis, specific enthalpy is evaluated at every thermodynamic state of vapour absorption refrigeration cycles and heat transfer rate or heat load are also estimated for major components of vapour absorption refrigeration systems which are represented in tabular form. Heat load in major components of absorption refrigeration system is compared with the past published work. Comprehensive thermodynamic design data are also estimated and obtained under the energy analysis of vapour absorption refrigeration system. These thermodynamic design data can also be used in fixing operating setting for existing or future systems and maintain automatic control on optimum operation of the systems. First law performance parameters coefficient of performance is also calculated for different refrigerant operated vapour absorption refrigeration system. Literature of Engineer's Equation Solver software is also presented in this work. This Engineer's Equation Solver software is very user friendly and it can be used by any non-technical person for estimating coefficient of performance of any single stage vapour absorption refrigeration (VAR) system.

Key words: Energy Analysis, Ammonia-Water, VAR, EES

I. INTRODUCTION

Refrigeration is the process of keeping the temperature of any thermodynamic body or system lower than that of atmospheric temperature [1-4]. Refrigeration is used in many applications of human life like food procurement, pharmaceutical and human comfort [5-6]. The conventional refrigeration cycles are driven by electricity or heat energy from fossil fuel, which results in more consumption of electricity and fossil energy day by day. Approximately 15% of the total electricity produced in the whole world is used in the refrigeration and air-conditioning purpose which is revealed by International Institute of Refrigeration , Paris (IIF/IIR) in their report [7].International Institute of Refrigeration, Paris (IIF/IIR) also evaluated that 45% of the total energy consumed in refrigeration is used for air-conditioning systems of overall households and commercial buildings [8].Therefore, the demand of energy is increasing continuously for refrigeration because global warming is increasing day by day in the world. Most popular commercial refrigeration systems work on VCR (vapour compression refrigeration) cycle which runs on electricity. The vapour absorption refrigeration (VAR) cycle uses combination of two eco-friendly chemical fluids and some quantity of heat whereas commercially popular VCR (vapour compression refrigeration), requires more and continuous supply of electricity. Working principle of both (VAR & VCR) cycles are based on the principle that heat is removed at low pressure through evaporation process and heat is rejected through condensation at high pressure. It means that pressure difference is required to flow the refrigerant in cycle. Compressor is used to create the pressure difference in vapour compression refrigeration cycle to circulate the refrigerant which consumes electricity. In case of vapour absorption refrigeration cycle, a fluid named absorbent, is used to circulate refrigerant by the use of renewable energy sources like solar energy or wind energy or geothermal energy or waste heat etc. Vapour absorption refrigeration system is also free from any hazardous impact on environment like ozone depletion and also does not contribute in global warming. In modern era of research, scientists are taking interest to develop the technologies to reduce the energy consumption, peak electricity demand and cost of energy without reducing the human comfort[4-8].

II. SYSTEM DESCRIPTION

A typical Ammonia-Water (NH_3-H_2O) vapour absorption refrigeration system (VAR) system is illustrated in Figure 1. Strong ammonia solution is pumped to the generator through solution heat exchanger at high pressure. It is assumed that generator leaves 0.999 ammonia concentration vapour to the condenser and ammonia vapour leaves condenser at saturated state. Saturated ammonia vapour passes through the expansion valve and it gets converted into low pressure liquid ammonia. This low pressure liquid ammonia is used to refrigerate desired space in evaporator and vaporized water absorbs the vapor to form a strong ammonia solution in the absorber. Weak solution leaves the generator to the absorber through refrigerant heat exchanger and pressure reducing valve.

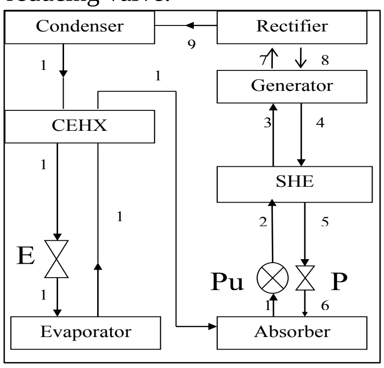

Fig. 1: Schematic diagram of Ammonia-Water (NH_3-H_2O) operated vapour absorption refrigeration system

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VAR	Vapour Absorption Refrigeration
VCR	vapour compression refrigeration
X	Solution Concentration, (%)
T	Temperature, ^{0}C
SHE	Solution Heat Exchanger
F	Circulation Ratio
M	Mass flow rate, kg/s
Q	Heat transfer rate, Kw
Q_a	Absorption Heat, w
W	Work transfer rate, Kw
H	Specific Enthalpy,(kJ/kg)
COP	Coefficient of Performance
P	Pressure, (kPa)
EES	Engineering Equation Solver
PRV	Pressure Reducing Valve
EV	Expansion Valve

Table 1: Nomenclature

III. Energy Analysis of Absorption Refrigeration System

Fundamental expressions for carrying out energy analysis involve principle of mass conservation, concentration balance and energy balance. The same is presented in Eq. (1) to Eq. (3).

To perform the energy analysis of ammonia-water vapour absorption system using ammonia as refrigerant, following assumptions are taken-

1) Thermodynamic system operates in steady state.
2) There are no pressure drops except through pump.
3) Refrigerant condenses to a saturated liquid in the condenser, while refrigerant evaporates to saturated vapor in the evaporator.

Mass balance equations of the working fluid and refrigerant at any major component of vapour absorption refrigeration system, can be written as:

$$\sum \dot{m}_i = \sum \dot{m}_o \qquad (1)$$

Similarly, doing concentration balance across any major component of vapour absorption refrigeration system, one can write:

$$\sum \dot{m}_i X_i = \sum \dot{m}_o X_o \qquad (2)$$

$$\sum Q - \sum W = \sum \dot{m}_i h_i - \sum \dot{m}_o h_o \qquad (3)$$

Where, m is the mass flow rate, Subscript i is input and Subscript o is the output flow. Q is the heat transfer rate, W is the work transfer, X is the concentration of working fluid and h is the specific enthalpy. In this analysis, the parameter circulation ratio (f) is defined as the ratio of mass flow rate of the solution through the pump to the mass flow rate of the working fluid.

$$f = \frac{X_9 - X_4}{X_3 - X_4} = \frac{0.9996 - 0.3709}{0.3709 - 0.2709} = 6.287 \qquad (4)$$

By using I Law of Thermodynamics, energy balance equations for the major components of the vapour absorption refrigeration system are given below.

The energy balance in absorber is given by Eq. (5) below

$$\dot{Q}_{AB} = \dot{m}_{14}\left[h_{14} + (h_6 - h_1)f - h_6\right] \qquad (5)$$

The energy balance in condenser is given by Eq. (6) below

$$\dot{Q}_{CO} = \dot{m}_9 (h_9 - h_{10}) \qquad (6)$$

The energy balance in generator is given by Eq. (7) below

$$\dot{Q}_{GE} = \dot{m}_7 [h_7 + (h_4 - h_3)f - h_4] \qquad (7)$$

The energy balance in evaporator is given by Eq. (8) below

$$\dot{Q}_{EV} = \dot{m}_9 [h_{13} - h_{12}] \qquad (8)$$

The energy balance in solution heat exchanger is given by Eq. (9) below

$$\dot{Q}_{SHE} = \dot{m}_1 (h_3 - h_2) \qquad (9)$$

Energy balance in condenser evaporator solution heat exchanger is Eq. (10) below

$$\dot{Q}_{CEHX} = \dot{m}_{13} (h_{14} - h_{13}) \qquad (10)$$

The energy balance in rectifier is given by Eq. (11) below

$$\dot{Q}_{Rect} = \dot{m}_7 h_7 - \dot{m}_8 h_8 - \dot{m}_9 h_9 \qquad (11)$$

Work supplied to the pump is given by Eq. (12)

$$\dot{W}_P = \frac{\dot{m}_R v \left(P_{high} - P_{low}\right)}{\eta_{pump}} \qquad (12)$$

First law based analysis is coefficient of performance and it is presented in Eq. (13) below

$$COP = \frac{Q_{EV}}{Q_{GE} + W_P} \qquad (13)$$

IV. Result and Discussion

In this analysis, energy analysis performed for mass of refrigerant equal to 0.137 kg/s and the operational temperature parameters taken as T_{EV}=-10°C, T_{CO}=40°C, T_{AB}= 40°C, T_{GE}=108°C. Operational parameters are selected from the past published work for this study [9-11]. Table 1 shows the chemical composition and mass flow rates along with temperature, pressure, concentration and specific enthalpy of the working fluids. Table 5.2 shows the energy balance and performance parameters of the proposed ammonia-water vapour absorption refrigeration cycle. Ratio of the heat input at the evaporator to that at the generator will be recognized as the coefficient of performance (COP) for the vapour absorption refrigeration cycle. It can be seen from the Table 2 that absorber heat transfer rate is the highest and the solution pump power is the lowest.

State	Pressure (kPa)	Temp (^{0}C)	Mass flow rate m (kg/s)	Solution Concentration (%)	Specific Enthalpy from this study (kJ/kg)
1	244.85	40	1	0.3709	-43.92
2	1555.76	40.1	1	0.3709	-43.92
3	1555.76	110.06	1	0.3709	300.6
4	1555.76	130.31	0.863	0.2709	395.5
5	1555.76	40.45	0.863	0.2709	-1.315
6	244.85	40.71	0.863	0.2709	-1.315
7	1555.76	107.33	0.15	0.9460	1543
8	1555.76	107.36	0.013	0.3709	259.4
9	1555.76	44.07	0.137	0.9996	1305
10	1555.76	40	0.137	0.9996	190
11	1555.76	16.88	0.137	0.9996	78.12
12	244.85	-14.14	0.137	0.9996	78.12
13	244.85	-10	0.137	0.9996	1258
14	244.85	37.39	0.137	0.9996	1371

Table 2: Energy analysis data at various thermodynamic states of Ammonia-Water vapour absorption refrigeration cycle.

Thermodynamic Quantity	Symbol	Energy flow [9]	Energy Flow (kW) from this study
Heat Load in Evaporator	Q_{EV}	162	161.64
Heat Load in Absorber	Q_{AB}	231	230.35
Heat Load in Generator	Q_{GE}	267.9	267.29
Heat Load in Condenser	Q_{CO}	151	152.76
Heat Load in SHE	Q_{SHE}	343.3	344.52
Heat Load in Rectifier	Q_{Rect}	50.7	49.21
Heat Load CEHX	Q_{CEHX}	15.4	15.34
Pump Work	W_P	2.79	2.85
Coefficient of Performance	COP	0.598	0.605 (Dimensionless)
Circulation Ratio	f	6.287	6.287 (Dimensionless)

Table 3: Heat transfer rate in major components of Ammonia-Water vapour absorption refrigeration system and first law based performance parameters.

Figure 2 shows the variations of coefficient of performance (COP) and circulation ratio with generator temperature (T_{GE}) at different values of absorber temperature (T_{AB}) under given evaporator temperature (T_{EV}) and condenser temperature (T_{CO}). As can be seen from the figure, coefficient of performance (COP) initially increases rapidly but tends to attain a limiting value at higher generator temperature (T_{GE}). It is also observed that the coefficient of performance (COP) is higher at lower absorber temperatures. The circulation ratio decreases as the generator temperature (T_{GE}) is increased.

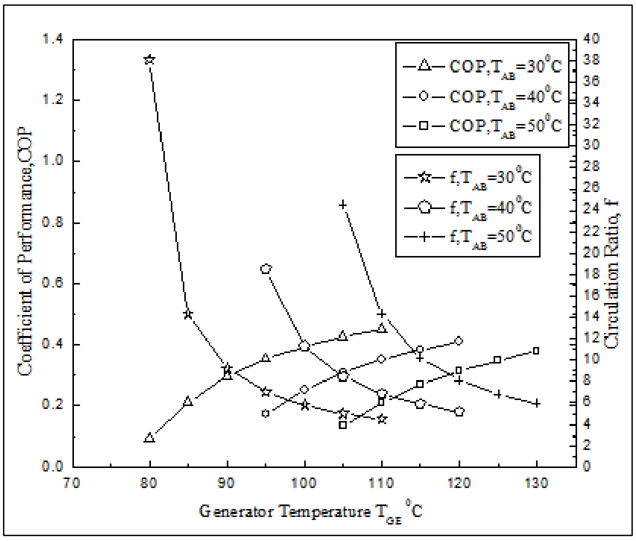

Fig. 2: Variations of Coefficient of Performance and Circulation Ratio with the Generation Temperature (T_{GE}) at different Absorber Temperature (T_{AB})(T_{CO}=30^{0}C, T_{EV}=-10^{0}C).

Figure 3 shows the variations of the coefficient of performance (COP) and circulation ratio with condenser temperature (T_{CO}) at different values of absorber temperature (T_{AB}) under the given generator temperature (T_{GE}) and evaporator temperature (T_{EV}).It can be observed from the figure that the COP of the vapour absorption refrigeration system decreases while circulation ratio (f) of the absorption system increases when condenser temperature (T_{CO}) increases.

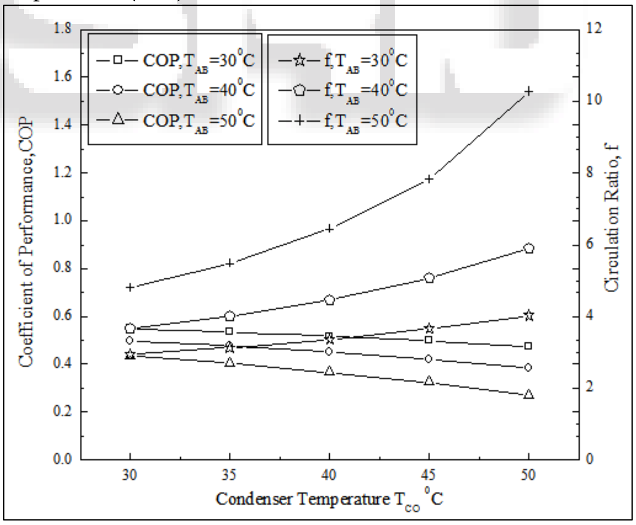

Fig. 3: Variations of Coefficient of Performance and Circulation Ratio with the Condenser Temperature (T_{CO}) at different absorber temperature (T_{AB}). (T_{GE}=140^{0}C,T_{EV}=-10^{0}C).

Figure 4 shows the variations of the coefficient of performance (COP) and circulation ratio with evaporator temperature (T_{EV}) at different values of absorber temperature (T_{AB}) for the given generator temperature (T_{GE}) and condenser temperature(T_{CO}). It can be observed from the figure that the COP of the absorption system increases while circulation ratio (f) of the absorption system decreases when evaporator temperature (T_{EV}) increases. It is also observed that the coefficient of performance (COP) is higher at lower absorber temperature (T_{AB}).

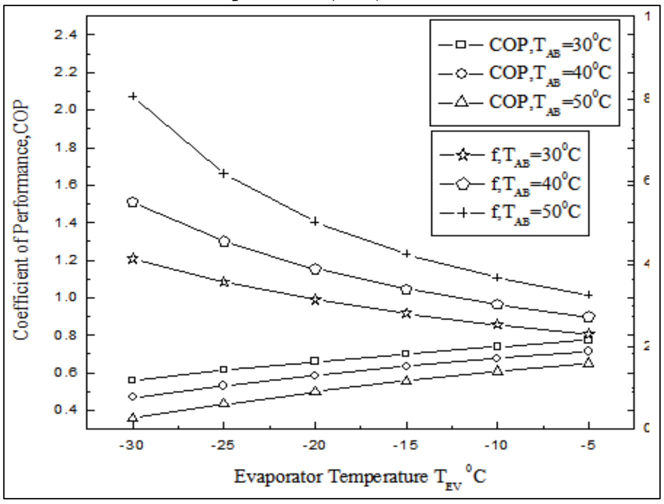

Fig. 4: Variations of Coefficient of Performance and Circulation Ratio with the evaporator temperature (T_{EV}) at different Absorber Temperature (T_{AB}) (T_{GE}=160^{0}C,T_{CO}=30^{0}C).

In the last section of energy analysis of Ammonia-Water (NH_3-H_2O) vapour absorption refrigeration system, thermodynamic design data is also estimated for different operational temperature combinations. Tables 3 presented optimum results of solution concentrations in absorber and generator, flow ratios, coefficient of performance (COP) on possible combinations of operating temperatures. These thermodynamic design data describe thermodynamic condition of proposed vapour absorption refrigeration (VAR) system on particular operational temperature combinations. Thermodynamic design data is estimated at the different temperature combinations and these are presented in the table 3.Thermodynamic design data is tabulated with solution concentration in absorber & generator, circulation ratio and coefficient of performance.

T_{EV}	T_{AB}	T_{CO}	T_{GE}	X_{WS}	X_{SS}	f	COP
-20	30	50	130	38.14	31.01	9.662	0.445
-20	30	50	140	38.15	26.96	6.526	0.552
-20	30	50	150	38.14	22.93	5.063	0.619
-20	30	50	160	38.14	19.04	4.236	0.663
-20	30	40	180	38.14	6.941	2.981	0.728
-20	30	40	190	38.14	3.484	2.783	0.729
-20	30	40	200	38.14	1.817	2.702	0.721
-20	30	50	170	38.14	15.36	3.714	0.691
-20	30	50	180	38.14	11.81	3.348	0.707
-20	30	50	190	38.14	8.181	3.064	0.714
-20	30	50	200	38.14	4.648	2.846	0.712
-10	30	30	90	45.01	38.29	9.18	0.556
-10	30	30	100	45.01	33.53	5.789	0.661
-10	30	30	110	45.01	28.98	4.429	0.715
-10	30	30	120	45	24.67	3.703	0.752
-10	30	30	130	45	20.58	3.25	0.779
-10	30	30	120	45	24.67	3.703	0.752
-10	30	30	130	45	20.58	3.25	0.779
-10	30	30	160	45	9.207	2.535	0.825
-10	30	30	170	45	5.677	2.398	0.83

Table 3: Derived thermodynamic design data for Ammonia-Water (NH_3-H_2O) operated vapour absorption refrigeration system.

V. CONCLUSION

Specific enthalpy of each point in the vapour absorption refrigeration cycle is reported according to the working fluid concentration and temperature at respective thermodynamic state of vapour absorption refrigeration system. Heat flow rate of each component in the cycle and some performance parameters are calculated from the first law analysis. The results show that a high coefficient of performance value is obtained at high generator and evaporator temperatures and also at low condenser and absorber temperatures. The circulation ratio was shown to play an important role in determining the performance of the system. High circulation ratios result in high internal irreversibilities at the absorber and generator. Performance analysis shows that in order to obtain high COP values, it is necessary to operate the cycle at low values of circulation ratio (f).Author is observed that the maximum value of COP (0.995) is achieved with T_{EV} =10^{0}C, T_{AB} =30^{0}C,T_{GE} =120^{0}C,T_{CO} =50^{0}C temperature combination and minimum value of COP (0.122) is achieved with T_{EV} =0^{0}C,T_{AB} =30^{0}C ,T_{GE} =90^{0}C,T_{CO}=50^{0}C temperature combination. Thermodynamic design data is presented and the operating temperature ranges are proposed as follows:

$$-20°C < T_{EV} < 10°C$$
$$30°C < T_{AB} < 50°C$$
$$30°C < T_{CO} < 50°C$$
$$90°C < T_{GE} < 200°C$$

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