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Energy analysis of quadruple effect series flow vapour absorption system

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ABSTRACT
An energy analysis which based on first law of thermodynamics is carried out for single, double, triple effect series flow vapour absorption system with LiBr-H_2O working fluid pair. The coefficient of performance (COP) for all systems is obtained for specified operating conditions. As expected, the COP increases from single effect to triple effect vapour absorption systems.
Finally, COP for quadruple effect series flow vapour absorption system is evaluated and results show that this system has highest COP among all multi-effect systems. The effect of high temperature generator, evaporator temperature, condenser temperature and heat exchanger effectiveness is also evaluated for triple and quadruple effect series flow vapour absorption system.
Keywords - Absorption system, Energy analysis, LiBr-H_2O, Triple effect, Quadruple effect

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I. INTRODUCTION

Vapour absorption refrigeration technology is an economic and effective alternative to the vapour compression systems. The vapour compression systems require high grade energy. On the other hand, vapour absorption systems are thermally activated, and for this reason, high input (shaft) power is not required. Industrial processes use a lot of thermal energy by burning fossil fuel to produce steam or heat for various purposes. After the processes, heat is rejected to the surrounding as waste. This waste heat from thermal systems can be used to power vapour absorption systems. Many researchers have contributed to this field in order to understand and to improve the performance of heat based vapour absorption systems. The performance and efficiency of absorption system is directly correlated with the chemical, thermo physical and thermodynamic properties of the working fluid. A number of refrigerant–absorbent pairs are possible, out of which the most common ones are LiBr–H_2O and H_2O-NH_3. These two pairs offer good thermodynamic performance, and they are environmentally benign[1]. For large capacity cooling systems, vapour absorption systems are found efficient. For this reasons, it has attracted attention of many researchers. Open literature on the subject presents performance of different vapour absorption cooling systems numerically with respect to the temperature of generator, evaporator and condenser, cooling capacity and coefficient of performance for single effect and double effect series flow vapour absorption system.

II. LITERATURE SURVEY

The mechanism of refrigeration in vapour absorption system is an impressive and interesting phenomenon. There are different types of vapour absorption systems. Most of the work is published regarding single and double effect vapour absorption systems. A number of researchers [1-10] have presented the energy analysis for single effect & double effect series flow for parallel flow absorption refrigeration systems. Some author present the study with LiBr-H_2O as working fluid [1, 2, 6-10] and others [3-5] use H_2O-NH_3 as working fluid. In most of the studies, the authors have investigated the effect of several design and operating parameters viz. the generator, absorber, condenser, evaporator temperatures, solution circulation ratio, heat recovery ratio and effectiveness of solution heat exchanger(s), on the cycle performances. Lee and Sherif [11] utilized a modular computer code design to simulate the absorption system by investigating the COP of single effect cycle using LiBr-H_2O pair and exergetic efficiency with varying operating conditions. They developed performance maps of this system. Saravanan and Maiya [12] numerically compared the performance of a water based single effect vapour absorption refrigeration system with binary to quaternary mixtures. It was deduced that the system operating with alternative mixture may operate with different operating temperatures. Lucas et al. [13] experimentally investigated a new working fluid with constituents like LiBr + CHO_2Na+ H_2O, which can overcome the limitations of lithium bromide, improve mass transfer characteristics and 60% more absorption capacity of the refrigeration cycle. In the study of Rahaman et al. [14] the simple vapour absorption system is designed and fabricated to analyze the performance of the system.

Solar energy is also one of the low grade energy source, by using solar panel Sharma et al. [15] have proposed 2 kW single effect vapour absorption system with series flow and this can

different working fluids. The studies presented in references [18-20] pertain to the exergy analysis of single effect to multi effect absorption refrigeration systems using LiBr-H_2O pair. Some authors [21-23] have proposed triple effect vapour absorption system to increase the performance of the vapour absorption system. In the study of Kaita (2002) [21] carried out simulation analysis for three kinds of triple effect system using newly developed simulations for parallel flow, series flow and reverse flow system using LiBr-H_2O pair. They computed COP, maximum pressure, maximum temperature for each system. On the basis of energy and exergy analysis, comparison of triple effect parallel and series flow absorption system were carried out in Aghdam et al. [22]. They showed that COP of triple effect system is about 50 % more than that of double effect system and it was about 2.2 times that of the single effect systems. Kaita (2001) [23] reported thermodynamic properties calculation for triple effect system with valid concentration range from 40-65 wt % and temperature range from 40-210^{0}C, equation was developed for calculation of vapour pressure, enthalpy and entropy of LiBr solutions.

assists the economic analysis for manufacturing of absorption chillers. All components of vapour absorption system are equally important but Deng and Ma [16] focused on the absorber in absorption machines and presented that its characteristics have significant effect on the overall efficiency of absorption machines with modified Reynolds number and Prandtl number using inlet solution concentration. Somers et al. [17] developed ASPEN model for single and double effect system with LiBr-H_2O working fluid which had important advantages over models created in EES and the model showed discrepancy between 3% and 5% after verification with reference data. In some of the above referred studies, the authors have emphasized the computation of COP, operating temperatures,

Obviously significant amount of work has been carried out on the energy and exergy analysis of both single and double effect series and parallel vapour absorption systems. However, fewer studies are reported on performance evaluation of triple and quadruple effect vapour absorption systems. This has provided motivation for carrying out the presented work in this paper. Triple and quadruple effect systems are modelled for their energy analysis and their performance is evaluated with respect to important system parameters.

III. MODELLING AND SIMULATION

All multi-effect systems (Fig. 1 and Fig. 2) are logical extension of single effect vapour absorption system. The performance of the system increases with the number of generators and heat exchangers increases. Here, quadruple effect series flow vapour absorption system (Fig. 3) is introduced with more efficiency. This system has same working as the triple effect series flow vapour absorption system only difference is that one more

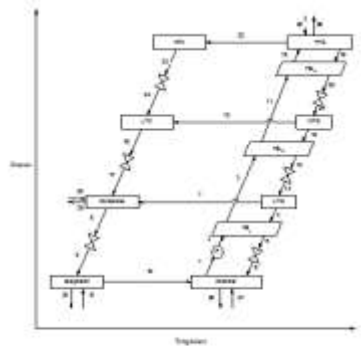

Fig. 2 Triple effect series flow vapour absorption system [20]

generator and heat exchanger is added to triple effect system. These multi effect systems obtain higher COP than single effect system, but they required high temperature ranges. The mathematical model for this investigation has been developed with the following assumptions:

1. The heat losses and pressure drop occurring in the pipelines and system components are negligible.

2. The refrigerant leaving the condenser and
3. Circulating pump is assumed to do work is isentropically.
4. All solution heat exchangers have same effectiveness.
5. Heat transfer from the system to the surroundings and from the surroundings to the system is neglected.
6. The processes at all expansion valves are assumed to be adiabatic.
7. The refrigerant leaving the high temperature generator is assumed to be superheated.
8. The solution leaving the absorber and the generator are assumed to be saturated in equilibrium conditions.

A computer code for performance calculation of all systems has been established using

where ṁ is the mass flow rate and X is the concentration of lithium bromide in the solution and the subscripts in and out are inlet and outlet flow in control volume. The model solves the governing equations for

the system's components and incorporates the chemical and thermodynamic properties of the LiBr-H_2O solution.

So, enthalpy data must be available for the working pair at all state points in the cycle. The enthalpies of the lithium bromide solution at different state points of the system are obtained using the equations of the lithium bromide enthalpy concentration diagram with the pressure-temperature correlations [24] as well as saturated water enthalpy and superheated steam enthalpy correlations [25],

To calculate the concentration of aqueous lithium bromide solution in all generators and absorber, the following equation is obtained with the help of equilibrium diagram for LiBr-H_2O solution.

evaporator is assumed to be saturated.

the MATLAB 7.9.0 software. For the thermodynamic analysis of the absorption system, the principle of mass conservation is applied to each component of the system. Each component is treated as a control volume with inlet and outlet streams, mass conservation include mass balance of the total mass and each material species (e.g. refrigerant and absorbent in an absorption cycle).

The governing equations of mass and species conservation for system are as follows:

Mass conservation:

$$\Sigma\ (\dot{m})_{in} - \Sigma\ (\dot{m})_{out} = 0 \quad (1)$$

Species Conservation:

$$\Sigma\ (\dot{m}.X)_{in} - \Sigma\ (\dot{m}.X)_{out} = 0 \quad (2)$$

and lithium-bromide solution enthalpy correlations [26]. To calculate the concentration of aqueous lithium bromide solution in all generators and absorber, the the following equation is obtained with the help of equilibrium diagram for LiBr-H_2O solution. The fitted equation has correlation coefficient of 0.9985. solution. The fitted equation has correlation coefficient of 0.9985.

a = 23.1158, b = 1.6079915, c = -1.6072595, d = -0.02148598, e = -0.020998852,

f = 0.04180901, g = 0.00010657, h = -0.000053511975, i = 0.00023897972,

j = -0.00028637431

x = temperature of generator and absorber, y = temperature of condenser and evaporator,

z = concentration of lithium bromide in %

The fitted equation has correlation coefficient of 0.9985.

$$z = a + bx + cy + dx^2 + ey^2 + fxy + gx^3 + hy^3 + ixy^2 + jx^2y \quad (4)$$

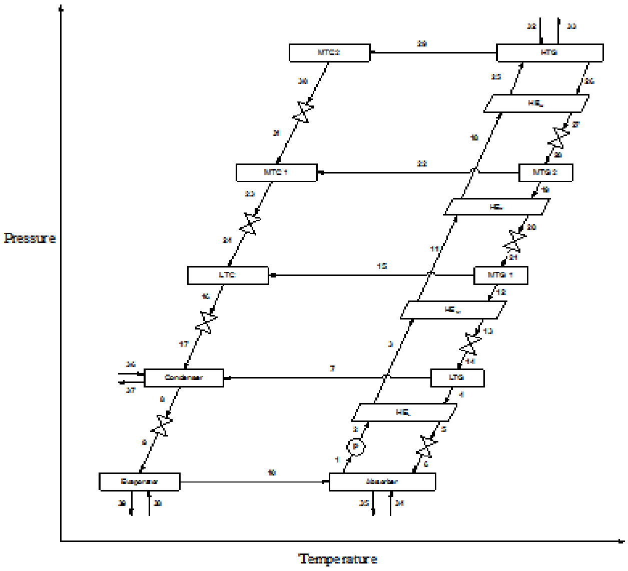

Fig. 3 Quadruple effect series flow vapour absorption system

IV. RESULTS AND DISCUSSION

Modeling of a single effect series vapour absorption system has been carried out using ASHRAE equations [ASHRAE Handbook, 1997]. The results have been compared with ASHARE Handbook [24] and Arora and Kaushik [8], for single and double effect vapour absorption system respectively; the results showed good agreement for the input parameters given in Table 1 and 2.

Table 1: Input parameters for the single effect LiBr-H_2O vapour absorption system

Parameters		Example-value
Capacity,	Qe	1760 kW
Evaporator Temperature,	T_{10}	5.1°C
Generator solution exit temperature,	T_4	98.8 °C
Weak solution mass fraction,	X_1	59.5% LiBr
Strong solution mass fraction,	X_4	64.6% LiBr
Solution heat exchanger exit temperature,	T_3	76.8 °C
Generator vapour exit temperature,	T_7	93.3 °C
Liquid carryover from evaporator,	$\dot{m}_{11}$	2.5% of $\dot{m}_{10}$

Table 2: Input parameters for the double effect series flow LiBr-H_2O vapour absorption system

Parameters		Example Value
Generator Temperature,	T_{12}	138.15°C
Low Temperature Generator,	T_4	87.8°C
Evaporator Temperature,	T_{10}	7.2 °C
Absorber Temperature,	T_1	37.8 °C
Condenser Temperature,	T_8	37.8 °C
Effectiveness of the solution heat exchanger,	ϵ	0.7
Mass flow rate of the refrigerant,	ṁ	1 kg/s

4.1 Triple effect series flow vapour absorption system

A computer code is developed with following input parameters (Table 3) and calculated operating conditions and COP are represented in Table 4 and Table 5 respectively.

Table 3: Input parameters for the triple effect series flow LiBr-H_2O vapour absorption system

Parameters		Example Value
High Temperature Generator,	T_{19}	180°C
Evaporator Temperature,	T_{10}	5°C
Absorber Temperature,	T_1	30°C
Condenser Temperature,	T_8	30°C
Low Temperature Generator,	T_4	80°C
Medium Temperature Generator,	T_{12}	129.6°C
Effectiveness of the solution heat exchanger,	ϵ	0.7
Mass flow rate of the refrigerant,	ṁ	1 kg/s

Table 4: Estimated data for triple effect LiBr-H_2O absorption system

State Point Number	T (°C)	P (kPa)	X (% LiBr)	ṁ (kg/s)	h (kJ/kg)
1	30	0.8717	51.4896	5.5478	62.8351
2	30	276.9042	51.4896	5.5478	62.8351
3	54.6054	276.9042	51.4896	5.5478	115.8890
4	80	4.4384	62.8115	4.5478	205.9003

5	45	4.4384	62.8115	4.5478	141.1805
6	45	0.8717	62.8115	4.5478	141.1805
7	80	4.4384	0	0.2828	2642.8
8	30	4.4384	0	1	124.8478
9	5	0.8717	0	1	124.8478
10	5	0.8717	0	1	2509.8
11	95.8784	276.9042	51.4896	5.5478	205.3495
12	129.6	49.2026	59.1338	4.8306	286.4541
13	77.1037	49.2026	59.1338	4.8306	183.7121
14	77.1037	4.4384	59.1338	4.8306	183.7121
15	129.6	49.2026	0	0.2911	2723.1
16	80	49.2026	0	0.7172	336.0872
17	30	4.4384	0	0.7172	336.0872
18	147.2270	276.9042	51.4896	5.5478	317.4671
19	180	276.9042	55.7729	5.1217	384.3197
20	121.1149	276.9042	55.7729	5.1217	262.8752
21	121.1149	49.2026	55.7729	5.1217	262.8752
22	180	276.9042	0	0.4261	2798.3
23	129.6	276.9042	0	0.4261	545.6367
24	80	49.2026	0	0.4261	545.6367

Note: State points are defined in Fig. 2.

Table 5: Results of triple effect series flow LiBr-H_2O absorption system

Component	Calculated Values
Qe	2384.9 kW
Qa	2803.2 kW
Q_{HTG}	1399.4 kW
Qc	863.6659 kW
COP	1.7043

4.3 Quadruple effect series flow vapour absorption system

To calculate the COP a computer code is developed using input parameters given in Table 6. Table 7 and Table 8 shows that the evaluated data at each state point and COP respectively.

Table 6: Input parameters for the quadruple effect series flow LiBr-H_2O vapour absorption system

Parameters		Example Value
High Temperature Generator,	T_{26}	180^0C
Medium Temperature Generator 2,	T_{19}	138.5^0C
Medium Temperature Generator 1,	T_{12}	100^0C
Low Temperature Generator,	T_4	65^0C
Evaporator Temperature,	T_{10}	5^0C
Absorber Temperature,	T_1	30^0C
Condenser Temperature,	T_8	30^0C
Effectiveness of the solution heat exchanger,	ϵ	0.7
Mass flow rate of the refrigerant,	$\dot{m}$	1 kg/s

Table 7: Evaluated data for quadruple effect series flow LiBr-H_2O absorption system

State Point Number	T (^oC)	P (kPa)	X (% LiBr)	ṁ (kg/s)	h (kJ/kg)
1	30	0.8717	51.4896	10.7469	62.8351
2	30	359.39	51.4896	10.7469	62.8351
3	50.8311	359.39	51.4896	10.7469	107.7374
4	65	4.43	56.7722	9.7469	150.8469
5	40.5	4.43	56.7722	9.7469	101.3379
6	40.5	0.8717	56.7722	9.7469	101.3379
7	65	4.43	0	0.4397	2617.3
8	30	4.43	0	1	124.8478
9	5	0.8717	0	1	124.8478
10	5	0.8717	0	1	2509.8
11	82.3817	359.39	51.4896	10.7469	176.0304
12	100	26.03	54.3217	10.1866	216.8934
13	65.5817	26.03	54.3217	10.1866	144.8440
14	65.5817	4.43	54.3217	10.1866	144.8440
15	100	26.03	0	0.1978	2675.9
16	65	26.03	0	0.5603	272.7154
17	30	4.43	0	0.5603	272.7154
18	119.5430	359.39	51.4896	10.7469	256.9075
19	138.5	105.12	53.2871	10.3844	297.6196
20	99.2172	105.12	53.2871	10.3844	213.9191
21	99.2172	26.03	53.2871	10.3844	213.9191
22	138.5	105.12	0	0.1118	2736.8
23	100	105.12	0	0.3625	420.5830
24	65	26.03	0	0.3625	420.5830
25	159.9120	359.39	51.4896	10.7469	345.3040
26	180	359.39	52.7196	10.4962	386.4587
27	137.6801	359.39	52.7196	10.4962	295.9506
28	137.6801	105.12	52.7196	10.4962	295.9506
29	180	359.39	0	0.2507	2798.3
30	138.5	359.39	0	0.2507	583.2373
31	100	105.12	0	0.2507	583.2373

Note: State points are defined in Fig. 3.

Table 8: Results of quadruple effect series flow LiBr-H_2O absorption syste

Component	Calculated Values
Qe	2384.9 kW
Qa	2822.2 kW
Q_{HTG}	1047.0 kW
Qc	1178.8 kW
COP	2.2778

4.4 Effect of high temperature generator on COP

The effect of high temperature generator on COP is shown in Fig. 5. The generator temperature is varied from 150^{0}C of 210^{0}C. The absorption system is not a reversible cycle. It has degree of irreversibility due to mixing of absorbent and refrigerant. That's why COP first increases with increase in generator temperature upto an optimum value and then decreases in response of increase in irreversibility at high generator temperature. For triple effect system the maximum COP is obtaining at generator temperature of 180^{0}C and then it drops down slowly to near about 1.75. For quadruple effect system COP varies from 1.14 to 2.26. Initially the COP increases with generator temperature and then reaches a maximum value of 2.30 at 190^{0}C. Afterwards, it falls down slowly to 2.26 as temperature increases. Further increase in generator temperature will give rise to risk of crystallisation for LiBr-H_2O solution.

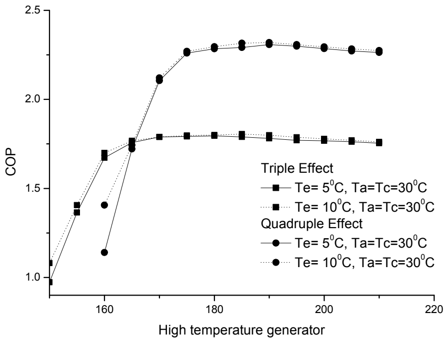

Fig. 5 Influence of high temperature generator on COP

4.5 Effect of evaporator temperature on COP

Figure 6 shows variation of COP with evaporator temperature. As the evaporator temperature increases, COP also increases it is due to the fact that temperature increases refrigerant potential to extract heat from evaporator and cooling capacity also increases. The evaporator temperature increases from 1^{0}C to 10^0 with that COP also increases from 1.70 to 1.71 for triple effect system and 2.27 to 2.29 for quadruple effect system. This is due to the fact that with respect to evaporator temperature cooling capacity also increases. It is important to note that the improvement in COP is not substantial.

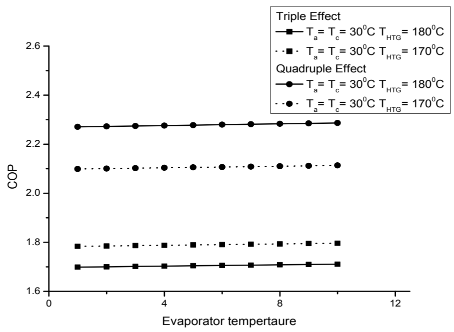

Fig. 6 Influence of evaporator temperature on COP

4.6 Effect of condenser temperature on COP

Figure 7 shows the performance of the system with respect to condenser temperature. Same results are obtained for absorber temperature also because condenser and absorber both components reject heat at the temperature of the environment. When condenser is since maintained at lower temperature, the generation of water vapour is easy and hence performance of system is increases. That's why as per increasing condenser temperature COP is decreases. By increasing temperature from 15^0C to 60^0C performance for triple and quadruple effect system is found to decrease from 1.7301 to 1.6512 and 2.32 to 2.17 respectively. Higher condenser temperature will mean less heat remove from the refrigerant in condenser. This will lead to lower heat carrying capacity of the refrigerant with its same mass flow rate which will reduce the COP.

4.6 Effect of heat exchanger effectiveness on COP

From Fig. 8 it is easy to understand that COP of a vapour absorption system will depend on effectiveness of heat exchanger (s) used in triple and quadruple effect series flow vapour absorption system. The COP keep increasing as effectiveness of all heat exchangers is increased simultaneously. The effectiveness varies from 0.5 to 0.95 for both the systems. It should be noted that higher improvement in COP with effectiveness is quite logical since in a triple effect, there are three and in a quadruple effect, there are four heat exchangers. It is observed that COP increases substantially with increase in heat exchanger effectiveness; from 1.41 to 2.1 for triple effect system and 1.56 to 3.52 for quadruple effect system.

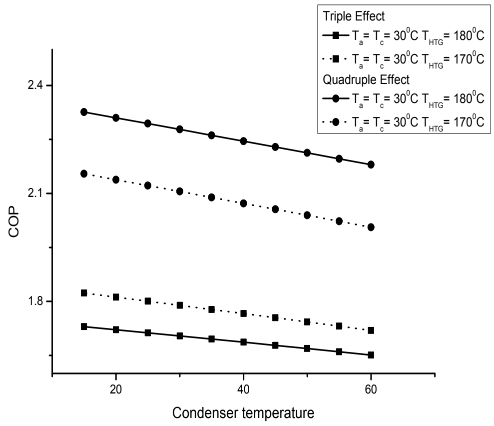

Fig. 7 Influence of condenser temperature on COP

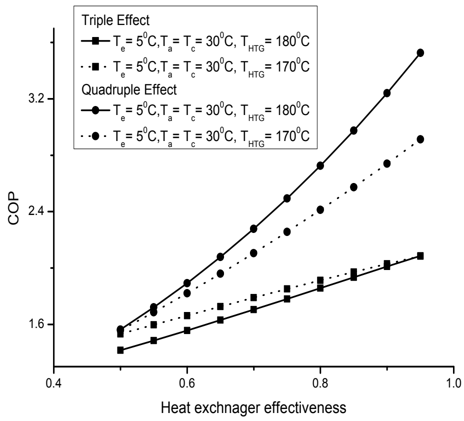

Fig. 8 Influence of heat exchanger effectiveness on COP

4.7 Comparison of single to multi-effect systems

Figure 9 shows the variation in COP with high generator temperature for single, double, triple and quadruple effect systems. It can be seen that as the number of effects increases, COP is also increases. It is obvious that multi effect series flow vapour absorption system need higher operating temperature. This can be treated as their strong point in addition to the characteristic higher COP.

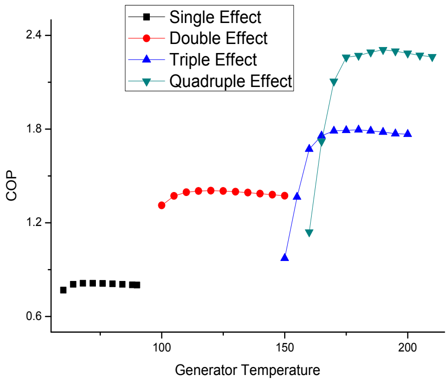

Fig. 9 Variation of the coefficient of performance with generator temperature

V. CONCLUSIONS

1. The calculation of COP for single effect and double effect series flow vapour absorption system was carried out with developed computer code and it was validated using existing data in literature, this validation showed good agreement.
2. As expected, the performance of triple effect series flow vapour absorption system was found better than both single and double effect systems. The COP increases as generator and evaporator temperatures increases and it goes down as condenser temperature increases.
3. The performance of quadruple effect system was found to depend on the same parameters as triple effect systems. However, the operating temperature range for a quadruple effect series vapour absorption system was found to be highest of single and double effect series flow vapour absorption system studied in this work. The COP was found to be highest of all the multi-effect series vapour absorption system – it was between 1.80 and 2.30 for the high temperature generator temperature range of 155^{0}C to 180^{0}C.
4. Because of existence of multiple heat exchangers in higher effect systems; three in triple effect and four in quadruple effect vapour absorption system effectiveness of heat exchanger (s) in single and multi-effect vapour absorption systems affected on coefficient of performance of the system. Increase in effectiveness of heat exchanger increase the COP; for the range of effectiveness from 0.50 to 0.95, the COP was found to raise in triple and quadruple effect vapour absorption systems.
5. At a given generator pressure, addition of heat to the generator beyond a limit gave rise to increased mass flow rate of refrigerant causing the solution in the generator to be more strong in lithium bromide. This can eventually lead to the problem of crystallisation in generator. Thus the generator temperature, pressure and heat input were important parameters in the design of vapour absorption systems.
6. The performance of multi-effect series vapour absorption systems was found to increase as the system goes on becoming the one with higher effect. Obviously, this was due to better utilisation of heat and additional refrigerant mass flow rates available from multiple generators provided. However, higher effect systems will require use of more material for their mechanical construction and maintenance due to their higher operating pressures, temperatures, etc.; their initial cost as well as operating cost will be on the higher side in comparison with a single effect vapour absorption system. Therefore, it will be interesting to study the economical viability of all multiple effect systems. Nevertheless, their existence can be strongly justified not only from the point of view of higher COP but also from the point of view of need of increasingly higher cooling capacities for commercial systems.

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