

CHAPTER-7

CONCLUSION AND SCOPE FOR FUTURE WORK

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7.1 Conclusion

In this thesis, energy and exergy based parametric analyses are carried out first in a single effect vapor absorption refrigeration system (VARS) to evaluate the effect of operating temperatures on system performance with H₂O–LiCl as working solution. In a VARS, the salt concentration in the solution should never exceed its crystallization limit and this is mainly controlled by the operating temperatures of the VARS components. Unfortunately, for H₂O–LiCl, the risk of crystallization is high compared to that of H₂O–LiBr. The mathematical correlations available in the literature which are proposed for calculation of thermodynamic properties of H₂O–LiCl solutions are mostly valid for maximum up to 50 wt. % concentration of LiCl in the solution. At some combinations of VARS component temperatures, the concentration might exceed the 50% limit and therefore, prior to conduction of the exergy based parametric analysis for the H₂O–LiCl operated single effect VARS, an inverse method is used to estimate the VARS component temperatures considering a weak solution concentration of below 50% as objective function. For the inverse estimation of the operating temperatures a differential evolution (DE) based optimization algorithm is used to minimize the objective function. Total 34 different combinations of VARS components' temperatures are estimated from within the given range of lower and upper limits of the component temperatures. Based on estimated combinations of temperatures, the energetic and exergetic performance of the H₂O–LiCl operated single effect VARS is evaluated at a fixed evaporator cooling load of 350 kW. A performance comparison between the single effect H₂O–LiCl and H₂O–LiBr systems is also provided under identical conditions in this thesis.

Next, the series, parallel and reverse parallel configurations of double effect VARS configurations are considered for thermodynamic modeling, analysis and performance comparison among the three under identical operating conditions using H₂O–LiCl as working fluid. Parametric analysis is performed to investigate the effect of component temperatures and distribution ratio on COP, solution concentrations and component's heat load of the double effect VARS configurations. The parametric analysis considers four different cases of fixed condenser (also equal absorber) and

evaporator temperatures viz. Case 1: fixed $T_C = T_A = 33^\circ\text{C}$ and $T_E = 8^\circ\text{C}$; Case 2: fixed $T_C = T_A = 35^\circ\text{C}$ and $T_E = 8^\circ\text{C}$; Case 3: fixed $T_C = T_A = 38^\circ\text{C}$ and $T_E = 8^\circ\text{C}$ and Case 4: fixed $T_C = T_A = 35^\circ\text{C}$ and $T_E = 5^\circ\text{C}$. Under identical operating conditions, a performance comparison between the double effect H_2O – LiCl and H_2O – LiBr systems is also provided in this research study.

Further, exergy analysis is carried out separately to evaluate the exergetic performances of the double effect VARS configurations (series, parallel and reverse parallel) with H_2O – LiCl as solution pair. As a part of parametric study, the components' temperature and distribution ratio (in case of the parallel and the reverse parallel system) are varied to investigate their effect on exergy efficiency and irreversibility of the system components. A comparison between double effect H_2O – LiCl and H_2O – LiBr systems is also provided to compare their exergetic performances under identical conditions.

During the energy and exergy based parametric analyses of the H_2O – LiCl operated double effect VARS configurations, it was actually attempted to find out the optimal difference between T_{LPG} and T_{HPG} for four various cases of fixed condenser (also equal absorber) and evaporator temperatures. It was also attempted to determine the optimal distribution ratio in case of the parallel and reverse parallel configurations. This was mainly done through (i) simultaneous change in T_{LPG} and T_{HPG} and (ii) change in T_{HPG} at fixed T_{LPG} with certain degree of uncertainty particularly in the selection of optimal distribution ratios for the double effect parallel and reverse parallel systems. Therefore, this research study also considers an optimization study, using an evolutionary based genetic algorithm (GA), for finding the optimal operating conditions of the double effect series and parallel absorption refrigeration systems both with H_2O – LiCl and H_2O – LiBr as solution pairs. The reverse parallel system is not considered for optimization because it shows the lowest performance among the three. In the optimization, COP and exergy efficiency are maximized while the total system irreversibility rate is minimized. The optimization is done for four different cases of fixed components' temperatures considering the LPG and HPG temperatures and the distribution ratio (in case of the parallel system) as decision variables. Through the GA based optimization study, it was possible to overcome some of the difficulties faced during parametric optimization, particularly in case of the H_2O – LiCl operated double

effect parallel configuration. The limitations which were realized during parametric optimization of the distribution ratios for various test cases have been properly addressed through solution of the GA based optimization. The optimal combinations of distribution ratio (D), T_{LPG} and T_{HPG} have been found out more precisely from the GA based optimization study not only for H₂O–LiCl but also for the H₂O–LiBr operated double effect series and parallel configurations. It was also possible through the GA based optimization study to find out better solutions in respect of the H₂O–LiCl operated double effect series and parallel configurations compared to what was obtained during parametric optimization.

From the performance analysis conducted on the single and double effect VARS configurations and the optimization study conducted specifically on the double effect series and parallel systems with both H₂O–LiCl and H₂O–LiBr as solution pairs, the following conclusions are made in this PhD thesis.

1. From inverse analysis of the single effect H₂O–LiCl VARS, it was observed that when the differential evolution (DE) based inverse method estimates a lower generator temperature (T_G), the corresponding condenser temperature (T_C) also reduces proportionately and the vice versa. This difference between T_G and T_C in case of all 34 combinations, was found to be either 38°C or 39°C.
2. In case of the single effect H₂O–LiCl VARS, the estimated combinations of component temperatures corresponding to maximum COP and maximum exergy efficiency (or minimum irreversibility) were different from each other.
3. The COP of the single effect H₂O–LiCl VARS is more at higher evaporator temperature. COP is also more at lower condenser and absorber temperatures. However, this trend was opposite in case of the exergy efficiency and the total system irreversibility. This contradiction aroused mainly due to water temperatures at inlet and outlet of the condenser, absorber and the evaporator, which were considered as function of operating temperature in the respective component. However, instead of variable, if fixed water inlet and outlet temperatures are considered, then the exergy efficiency and total irreversibility also show the same increasing trend with increasing evaporator temperature and reducing condenser and absorber temperatures.

4. From performance comparison between H₂O–LiCl and H₂O–LiBr operated single effect VARS, it was found that the H₂O–LiCl operated single effect VARS performs better than the H₂O–LiBr operated system under identical condition of operating temperatures. The COP and the exergy efficiency of the H₂O–LiCl operated system are higher compared to those of the H₂O–LiBr operated system. Similarly, the total system irreversibility is also less in the H₂O–LiCl operated single effect VARS in comparison to that of the H₂O–LiBr system.

5. In the double effect series configuration, the maximum solution concentration is mainly controlled by T_{LPG} while in the parallel and reverse parallel configurations, additionally the distribution ratio 'D' is also controlling parameter of the maximum solution concentration.

6. The double effect parallel and reverse parallel systems perform better at lower values of 'D', but this lower D limit is fixed by 50% maximum solution concentration limit.

7. For a given set of fixed temperatures in the absorber, condenser and evaporator, the COPs of the double effect H₂O–LiCl VARS configurations are maximized at some particular values of HPG temperature (T_{HPG}) and LPG temperature (T_{LPG}) with an optimal temperature difference between the two.

8. The double effect parallel configuration provides higher COP than those of the series and reverse parallel configurations at certain higher range of T_{LPG} and T_{HPG} values. However at some lower range of T_{LPG} and T_{HPG} values, the series flow configuration was found to perform better than the parallel system. But overall, the performance of the H₂O–LiCl operated double effect parallel and series configurations were found superior to the reverse parallel configuration.

9. During the variation of the distribution ratio 'D', it was observed that at certain lower range of D values, it was the parallel system that performs better than the reverse parallel one while at some higher range of D values; the reverse parallel system outperforms the parallel one. Further, it was seen that the lower limit of D in the parallel and reverse parallel systems is actually dependent on the VARS components' temperatures.

10. From energetic performance comparison between the H₂O–LiCl and H₂O–LiBr operated double effect series, parallel and reverse parallel configurations; it was found that the H₂O–LiCl systems provide better performance at identical operating conditions. This was however an observation which is true under identical operating conditions and relatively at lower T_{LPG} and T_{HPG} only.

11. The extent up to which T_{LPG} can be increased in the double effect H₂O–LiCl systems is limited due to the restriction imposed by the 50% maximum solution concentration limit. In the H₂O–LiBr systems however, the system operation is possible for a wider range of T_{LPG} .

12. Among H₂O–LiCl operated double effect series, parallel and reverse parallel configurations, in all the four test cases, the parallel configuration provides superior performance not only in terms of higher COP and but also with higher exergy efficiency and lower system irreversibility, This is an observation particularly at higher values of the selected T_{LPG} and T_{HPG} range. At certain lower range of selected T_{LPG} and T_{HPG} values, it was seen that the double effect series flow VARS configuration provides higher COP, higher exergy efficiency and also lower system irreversibility than those of the parallel configuration.

13. Comparing the exergetic performances of the H₂O–LiCl and H₂O–LiBr operated double effect VARS configurations, it was found that not only from COP point of view but exergetically also, the H₂O–LiCl operated double effect systems perform better than their H₂O–LiBr counterparts under identical operating conditions, particularly at low T_{LPG} and T_{HPG} . Compared to the H₂O–LiBr systems, the exergy efficiency is high and the total system irreversibility is low in the H₂O–LiCl operated double effect VARS configurations in all the four test cases. Thus, both the energy and exergy analysis confirms superior performance of the double effect H₂O–LiCl VARS configurations over double effect H₂O–LiBr systems under identical conditions at relatively low T_{LPG} and T_{HPG} .

14. Specifically in case of the double effect parallel system, the optimal distribution ratios obtained for the four test cases, with respect to the H₂O–LiCl operated system, are in the range from 46.67–56.36% which are relatively high

compared to the range of values from 40.79–47.32 found in case of the H₂O–LiBr system. Further, in the H₂O–LiCl operated double effect parallel system, the optimal distribution ratio increases proportionately with increase in condenser and absorber temperatures. In the H₂O–LiBr system however, no such trend was seen.

15. Out of the four various cases of fixed components' temperatures considered, better system performance from the double effect H₂O–LiCl VARS configurations was obtained during Case 1 at $T_C = T_A = 33^\circ\text{C}$ and $T_E = 8^\circ\text{C}$. From the GA based optimization of the double effect series flow H₂O–LiCl VARS configuration, the optimum T_{LPG} and T_{HPG} were found to be 71.24°C and 104.75°C respectively corresponding to Case 1. From parametric analysis also, almost the same optimum T_{LPG} and T_{HPG} were obtained during Case 1 for the H₂O–LiCl operated double effect series configuration which were 71°C and 105°C respectively. These optimum T_{LPG} and T_{HPG} values for the H₂O–LiBr operated double effect series flow configuration were however 74.71°C and 111.67°C respectively. At the optimized conditions, for almost the same COP of the two systems, the corresponding exergy efficiency was however slightly more and the total system irreversibility was relatively less for the H₂O–LiCl operated double effect series flow configuration compared to that of the H₂O–LiBr operated system. These optimal T_{LPG} and T_{HPG} values for the other cases were however different.

16. The optimal T_{HPG} and T_{LPG} combination corresponding to maximum COP and maximum exergy efficiency (or minimum irreversibility) in the H₂O–LiCl based double effect series configuration was almost a single optimal solution which however in the H₂O–LiBr series flow system were found to be little different. In the parallel configuration however, during Case1, the optimal combinations of D , T_{LPG} and T_{HPG} corresponding to the maximum COP and the maximum exergy efficiency were little different for both the H₂O–LiCl and H₂O–LiBr systems.

Based on the above findings, it is recommended that the single and double effect H₂O–LiCl VARS configurations can be used relatively at lower generator temperature in order to obtain better system performance (higher COP and exergy efficiency and lower system irreversibility) over H₂O–LiBr systems. The selection of appropriate generator temperature in case of the single effect and LPG and HPG temperatures (T_{LPG} and T_{HPG})

in case of the double effect systems is crucial in this regard. For the single effect H₂O–LiCl VARS, low generator temperature up to a minimum 63°C is possible provided the condenser temperature is also selected accordingly with a difference of 38°C. Accordingly, an appropriate heat source with relatively low temperature can be used for driving a single effect H₂O–LiCl VARS. Similarly for the H₂O–LiCl operated double effect VARS configurations, heat sources with temperatures in the range 130–135°C such as steam, solar energy (solar water heaters, solar ponds etc.), geothermal and other waste heat sources (hot liquid and water from industrial processes, engine cooling water) could be selected. For heat sources with temperatures above 140°C, however, double effect H₂O–LiBr VARS configurations would be suitable because at higher T_{LPG} and T_{HPG} , double effect H₂O–LiBr VARS configurations would perform better than their H₂O–LiCl counterparts. From the simulation and optimization of single and double effect VARS configurations, finally the following specific input parameters are recommended for condenser temperature (T_C), absorber temperature (T_A) and evaporator temperature (T_E) of 35°C, 35°C and 5°C respectively. The other recommended input parameters are shown in the consolidated Table 7.1.

At the above recommended components' temperatures, the single effect H₂O–LiCl system would give a higher COP (0.837), higher exergy efficiency (22.83%) and lower total system irreversibility (45.44 kW) compared to those (0.781, 22.56% and 52.89 kW) of the single effect H₂O–LiBr system. At the recommended input temperatures, the H₂O–LiCl operated double effect series configuration, although would have a slightly lower COP of 1.234 compared to 1.352 of the H₂O–LiBr counterpart, but the exergy efficiency would be more (21.94%) and total system irreversibility (49.30 kW) would be less compared to 20.98% and 52.62 kW of the H₂O–LiBr counterpart. Similarly, in the double effect parallel configuration also, at the recommended temperatures, the COP of the H₂O–LiCl operated system would be slightly less (1.3) compared to 1.377 of the H₂O–LiBr. But the exergy efficiency would be more (23.02%) and the total system irreversibility would be less (46.13 kW) compared to the exergy efficiency (21.79%) and total irreversibility (49.44 kW) of the H₂O–LiBr based double effect parallel system. In the reverse parallel configuration, however, at the recommended input conditions, the H₂O–LiCl based system would not only have lower

COP (1.194) but also lower exergy efficiency (21.29%) and higher irreversibility (50.46 kW) compared to those (1.325, 21.66% and 48.17 kW) of the H₂O–LiBr system.

Table 7.1: Input parameters for the single and double effect VARS (series, parallel and reverse parallel) configurations at $T_C=35^\circ\text{C}$, $T_A=35^\circ\text{C}$ and $T_E=5^\circ\text{C}$

Parameters	Single effect VARS	
	Water–LiCl	Water–LiBr
Generator Temperature (T_G)	72°C	85°C
Double effect VARS (Series configuration)		
	Water–LiCl	Water–LiBr
LPG Temperature (T_{LPG})	73.54°C	86.42°C
HPG Temperature (T_{HPG})	112.36°C	132.09°C
Double effect VARS (Parallel configuration)		
	Water–LiCl	Water–LiBr
Distribution ratio (D)	56.36%	41.13%
LPG Temperature (T_{LPG})	73.52°C	77.02°C
HPG Temperature (T_{HPG})	112.91°C	129.03°C
Double effect VARS (Reverse Parallel configuration)		
	Water–LiCl	Water–LiBr
Distribution ratio (D)	62%	38%
LPG Temperature (T_{LPG})	70°C	72°C
HPG Temperature (T_{HPG})	112°C	124°C

7.2 Scope of future work

The following are the proposed future research and experimental works that can be carried out with H₂O–LiCl based single, double and other multi-effect VARS configurations.

1. Since single effect H₂O–LiCl VARS performs better at low generator temperature, therefore, coupling of single effect H₂O–LiCl VARS might be possible with solar flat plate collector integrated with storage tank. Experimental analysis of solar hybrid single effect VARS with H₂O–LiCl as working solution might give encouraging results, which may be carried out as future research study in this field. Further it is also possible to carry out theoretical study with such a solar hybrid VARS.

2. In case of double effect H₂O–LiCl VARS configurations, due to complexity in the flow design and higher investment costs, such systems are not suitable as standalone systems. Coupling of H₂O–LiCl based double effect VARS configurations with solar thermal collectors or other heat recovery systems may be explored for proposing new energy systems involving VARS and performance analysis of new such systems with the help of thermodynamic principles.
3. Increasing stages or effects is directly proportional to system cost and complexity in case of VARS. Therefore, economic analysis may be carried to find out more details regarding associated cost and thereby to justify the added cost and higher performance of multi-effect systems over single effect VARS.
4. Thermo economic/Exergoeconomic optimization, involving total cost rate and the cost rate of exergy destruction as objective functions, may be another possible future work in this area to find out more details regarding optimal performance of single and multi-effect absorption cooling systems with H₂O–LiCl as solution pair.