Mapping of optimum operating condition for LiBr–water refrigeration cycles

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Abstract. In this work, optimum operating condition maps are generated covering wide ranges of refrigeration and sink temperatures for single- and double-effect LiBr–water vapour absorption refrigeration cycle. These optimum condition maps will be useful to choose optimum operating conditions while designing LiBr–water cycle for desired applications. Methodology for generating such maps is discussed in detail, which can also be used for other absorption refrigeration cycles with various working fluids. Three configurations of LiBr–water absorption refrigeration cycles, single effect, double-effect series flow and double-effect parallel flow, are analysed with the most accurate thermodynamic property correlation available in the literature. Sensitivity of cycle performance to various operating variables such as generator, absorber and condenser temperatures is determined. Second law analysis shows that when a higher temperature heat source is available, double-effect cycles are more effective over single effect as they have higher coefficient of performance.

Keywords. Absorption refrigeration; LiBr–water; single effect; double effect; COP; optimum.

1. Introduction

Cooling systems based on the absorption refrigeration principles have become increasingly popular among researchers in the recent years because of environmental concerns and improved energy utilization. Vapour absorption refrigeration (VAR) cycle differs from Vapour compression refrigeration (VCR) cycle in the way by which compression of the refrigerant is achieved. VCR cycle uses the highest quality form of energy, i.e., electricity, whereas VARs use low quality form of energy, i.e., heat, to obtain the liquid refrigerant at the desired pressure and temperature. Compared with VCR cycles, VARs have low COP value, but still VARs are attractive because of their ability to use waste heat or low grade heat, including solar or geothermal, as energy sources to get refrigeration. Also VARs make use of the substances that are not ozone depleting and do not cause global warming. Thus, VARs are a useful means for converting waste heat into useful refrigeration without causing any environmental damage.

The most commonly used absorbent/absorbate pairs for absorption refrigeration cycles are $\text{NH}_3\text{--H}_2\text{O}$ and $\text{LiBr--H}_2\text{O}$. When the required refrigeration temperature is 0°C or less, $\text{NH}_3\text{--H}_2\text{O}$ refrigeration cycles are mostly used while in the case of $\text{LiBr--H}_2\text{O}$ cycles the minimum refrigeration

temperature is usually limited by water freezing point. These are mostly preferred when moderate refrigeration temperature is required such as air-conditioning applications. Single-effect $\text{LiBr--H}_2\text{O}$ refrigeration cycles operate in the temperature range of $75\text{--}95^\circ\text{C}$ with water as coolant in the absorber and condenser and have COP around 0.8, which is higher than that of $\text{NH}_3\text{--H}_2\text{O}$ refrigeration cycle. Also $\text{LiBr--H}_2\text{O}$ cycles are simple in design and operation and safer as compared with $\text{NH}_3\text{--H}_2\text{O}$ cycles.

2. Previous work

Significant work has been done to understand performance of absorption cycles with respect to various operating parameters. Wijesundera [1] developed expressions for determining performance limits of absorption cycle considering the external heat transfer irreversibilities. Effect of ambient temperature on the performance of single-effect $\text{LiBr--H}_2\text{O}$ cycle was investigated by Mostafavi and Agnew [2]. Xu *et al* [3] and Xu and Dai [4] performed the thermodynamic analysis of double-effect parallel and series flow $\text{LiBr--H}_2\text{O}$ absorption refrigeration cycle. They investigated the effect of heat recovery ratio, solution circulation ratio (SCR) and distribution ratio of solution on the performance of the cycle. Sun [5] reported detailed thermodynamic design data and optimum design maps for the

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in the generator is sent through the solution heat exchanger (SHE), where it preheats the weak LiBr solution (8) (low LiBr weight fraction) coming from the absorber. The strong LiBr solution (11) is then throttled to the absorber pressure and then sent to the absorber, where it absorbs the refrigerant vapour (6) from the evaporator. The absorber operates at the pressure (P_{abs}), which is close to that of the evaporator.

3.1 Modelling and simulation

Following assumptions were made for the modelling of the cycle:

1. Liquid refrigerant leaves condenser in saturated state.
2. Refrigerant vapour leaving evaporator is in saturated state.
3. LiBr–H₂O solution leaving absorber and generator is saturated at their corresponding temperature and pressure.
4. Throttling is a constant-enthalpy process.
5. Heat losses to surrounding and pressure drop in pipe lines are negligible.

The accuracy of the simulation model in predicting the behaviour of any thermodynamic cycle depends on the accuracy with which the thermodynamic properties of the working fluid are calculated at different points of the cycle. The present work uses internationally accepted and the most accurate IAPWS-IF-97 equations [15] to calculate water and steam properties. The properties of LiBr–H₂O solution are calculated using the correlation developed by Patek and Klomfar [16], which are valid over wide ranges of compositions and temperatures. Computer codes were developed for the working fluid property calculation as well as for the simulation of the single-effect LiBr–H₂O absorption refrigeration cycle in the programming software SCILAB.

The independent variables to model the single-effect absorption cycles are generator temperature (T_{gen}), evaporator temperature (T_{evap}), absorber temperature (T_{abs}), condenser temperature (T_{cond}) and refrigerant flow to the evaporator ($m_{refrigerant}$). The pressure of the condenser (P_{cond}), and hence the generator pressure (P_{gen}), is determined by the condenser temperature (T_{cond}), which in turn depends on the cooling water temperature. The evaporator pressure (P_{evap}) is taken as the saturation pressure corresponding to evaporator temperature (T_{evap}). The composition of solution in the generator (x_{gen}) is calculated such that the vapour pressure of the solution leaving the generator is equal to the generator pressure (P_{gen}). In a similar way, composition in the absorber (x_{abs}) is calculated based on temperature of the solution leaving the absorber and the pressure in the absorber. All the flow rates in the cycle are evaluated using overall material and component balance equations. Once the flow rates are found, all the heat loads are calculated using energy balance equations.

Coefficient of performance (COP) of the cycle is calculated as follows:

$$COP = \frac{Q_{evap}}{Q_{gen}} \quad (1)$$

The maximum possible theoretical COP for a cycle is the Carnot COP (COP_c), which is given by Kaynakli and Kilic [14]

$$COP_c = \left(\frac{T_{gen} - T_{abs}}{T_{cond} - T_{evap}} \right) \left(\frac{T_{evap}}{T_{gen}} \right) \quad (2)$$

The second law efficiency (η) for a cycle is defined as

$$\eta = \frac{COP}{COP_c} \quad (3)$$

One more parameter that is defined to evaluate performance of the cycle is SCR, which is the ratio of mass flow rate of strong LiBr solution from the generator to the mass flow rate of the refrigerant going to the evaporator [14]:

$$SCR = \frac{m_{gen}}{m_{refrigerant}} \quad (4)$$

3.2 Sensitivity analysis

Sensitivity analysis was carried out to determine the effect of operating parameters on the performance of the cycle and to find the optimum operating conditions for the desired refrigeration temperature.

Figure 2a shows sensitivity of COP to the generator temperature for different evaporator temperatures. The COP goes through a maximum for all evaporator temperatures with increase in the generator temperature. Figure 2b shows variation in COP with the condenser temperature. With increase in the condenser temperature, the composition of the strong solution from the generator approaches towards the weak solution composition from the absorber. This reduces both the evaporator duty and the reboiler duty. It was observed that the rate at which both duties decreases was almost the same; hence, the COP appears to be almost constant between 25 and 40°C. Beyond condenser temperature of 40°C, the solution circulation rate increases exponentially, and hence increases the generator duty significantly. Therefore, a sharp decrease in COP was observed after 40°C condenser temperature. Figure 3a shows that COP increases with a decrease in the absorber temperatures. A sharp decrease in the COP can be observed at some higher absorber temperatures. Further increase in absorber temperature makes the cycle infeasible.

Figure 3b shows sensitivity of the second law efficiency to the generator temperature for different evaporator temperatures. For lower evaporator temperature, efficiency is higher than that for higher evaporator temperature. For evaporator temperature of 5 and 10°C, the efficiency goes

Figure 2. Sensitivity of COP with generator and condenser temperature. (a) Effect of generator temperature on COP. (b) Effect of condenser temperature on COP.

Figure 3. Sensitivity of COP and second law efficiency. (a) Effect of absorber temperature on COP. (b) Effect of generator temperature on efficiency.

through a maximum with increase in the generator temperature. For evaporator temperature of 15°C, the efficiency decreases with increase in the generator temperature. The decreasing trend of the second law efficiency for all evaporator temperatures is due to the fact that the Carnot COP (COP_c) increases with increase in generator temperature.

Figure 4 shows variation in the SCR value with the generator temperature. For all evaporator temperatures, initially at low generator temperature, the SCR is very high. At low generator temperature, composition difference between the generator and absorber is very less. This leads to higher solution flow between the absorber and the generator for required refrigeration duty. It is not

recommended to operate in this region because the higher SCR will not only require higher pumping power but also larger equipment size. After a sharp decrease, the SCR continues to decrease with increase in generator temperature, albeit mildly.

3.3 Optimum operating conditions map for single-effect LiBr–water cycle

Thorough sensitivity analysis was done and the operating conditions for the maximum COP values are found in a similar way as described in section 3.2 for more absorber, condenser, generator and evaporator temperatures. Using

Figure 4. Effect of generator temperature on solution circulation ratio.

these optimum condition data, a map giving maximum COP value for given heat sink, heat source and evaporation temperatures was generated as shown in figure 5.

This map can be used for determining the optimum operating condition for required refrigeration temperature. T_a represents the sink temperature, which is the absorber and condenser temperature for the cycle. Sink temperature can be decided based on cooling utility available. If the desired refrigeration and sink temperatures are fixed, optimum generator temperature can be read from the map. If the generator temperature is fixed based on available heat source, the optimum refrigeration temperature can be determined from the map for a given sink temperature.

Both air-cooled absorber and condenser operate at high temperatures. In such a situation, the chart given in figure 6 can be used to determine optimum operating conditions.

4. Double-effect series flow LiBr–H₂O absorption refrigeration cycle

A double-effect LiBr–H₂O absorption refrigeration cycle with series flow of the generator liquid is as shown in figure 7. It has two generators: a high temperature generator (HTG) and a low temperature generator (LTG). Heat is supplied to the HTG to produce steam (2). This steam serves as a heat source for the LTG. The strong LiBr solution (3) produced in the HTG is sent to the LTG through the SHE (SHX-1). It preheats the weak LiBr solution (15) coming from the SHX-2. The steam (2) produced in the HTG is condensed in the LTG to produce additional steam (6). The steam (6) generated in the LTG is

then condensed in the condenser to get the liquid refrigerant (10).

The strong LiBr solution (7) from the LTG is sent to the absorber through the SHX-2. It preheats the weak LiBr solution (14) coming from the absorber. The liquid refrigerant (10) is then throttled to the evaporator pressure. The refrigerant (11) evaporates in the evaporator by taking heat from the medium in the evaporator to be cooled. The refrigerant vapour (12) from the evaporator is sent to the absorber, where it is absorbed in the strong solution (17). The heat of mixing in the absorber and the latent heat of condensation in the condenser are removed using suitable cooling utility such as cooling water.

4.1 Modelling and simulation

Modelling of the double-effect LiBr–H₂O absorption refrigeration cycle with series flow is performed on the basis of the same assumptions as those in the case of single-effect cycle in section 3.1. In addition to those, the following assumptions were made:

1. Difference of 5°C was assumed in the LTG, between the heat source and the working fluid for heat transfer. The heat source temperature for the LTG is the condensation temperature of steam from the HTG at (8).
2. The strong LiBr solution leaving the HTG is cooled in SHX-1 to the LTG temperature. HTG not only operates at higher temperature but also at higher pressure, as compared with LTG. If the strong solution from HTG is cooled below LTG temperature in SHX-1, part of the heat given by vapour 2 to LTG will get utilized to bring

Figure 5. Optimum conditions map for single-effect LiBr–H₂O cycle for lower absorber and condenser temperature.

Figure 6. Optimum conditions map for single-effect LiBr–H₂O cycle for higher absorber and condenser temperature.

the strong solution 5 to its saturation temperature. This will reduce the vapour flow 8 from LTG and will affect the COP of the cycle. Hence, outlet temperature of solution from SHX was assumed to be the same as that of LTG.

The independent variables for modelling of double-effect series flow absorption cycles are operating temperature of HTG (T_{gen}), condenser temperature (T_{cond}), evaporator temperature (T_{evap}), absorber temperature (T_{abs}) and molar flow of solution to HTG.

Figure 7. Double-effect series flow LiBr–H₂O absorption refrigeration cycle.

4.2 Sensitivity analysis

Performance sensitivity of the double-effect series flow LiBr–H₂O refrigeration cycle was analysed for various operating temperatures.

Figure 8a shows effect of the high temperature generator (HTG) temperature on the COP value for evaporator temperature of 5, 10 and 15°C. For all evaporator temperatures, the COP goes through a maximum. The effect of the condenser temperature on COP for the HTG temperature of 152°C is as shown in figure 8b. The COP increases with a decrease in the condenser temperature. The effect of the absorber temperature on the COP for the same HTG temperature is shown in figure 9a. The COP decreases with an increase in the absorber temperature. Variation in the second law efficiency with the HTG temperature is shown in figure 9b. The efficiency shows decreasing trend with an increase in the HTG temperature. The SCR for the cycle is calculated as the ratio of mass flow rates of the total refrigerant generated in both the effects to the strong solution leaving from the second effect. A decreasing trend for the SCR is observed with an increase in the HTG temperature as shown in figure 10. At low HTG temperature, the SCR is very high, indicating very high solution flow in the system. The HTG temperature range in which there is sharp decrease in the SCR is not recommended for the cycle operation.

The double-effect LiBr–water refrigeration cycle has large COP value, greater than one, for the given refrigeration temperature. This is because of the fact that heat given to the generator (HTG) is utilized twice to produce refrigerant (steam). In the second generator (LTG), the latent heat of refrigerant from HTG is used to produce

additional refrigerant. The double-effect cycle operates at much higher temperature than the single-effect cycle for the same refrigeration temperature. Hence, the double-effect LiBr–water refrigeration cycle should be preferred when higher temperature heat source is available.

4.3 Optimum operating condition map for double effect series flow LiBr–water cycle

Exhaustive sensitivity analysis was performed for the double-effect series flow LiBr–water cycle. Optimum conditions for given evaporator temperature were obtained base on the sensitivity analysis results as discussed in section 4.2. A map giving operating condition for maximum COP at required evaporator temperature is as shown in figure 11. Using this map, optimum heat source temperature can be chosen for given evaporator, absorber and condenser temperature.

5. Double-effect parallel flow LiBr–H₂O absorption refrigeration cycle

Double-effect LiBr–H₂O absorption refrigeration cycle with parallel flow of generator liquid is as shown in figure 12.

The basic unit operations for double-effect parallel flow cycle are the same as those of the series flow cycle. The difference is in the solution flow circuit between the two generators. After the refrigerant vapours (12) are absorbed in the strong LiBr solution (19) in the absorber, the weak LiBr

Figure 8. Sensitivity of COP with generator and condenser temperature. (a) Effect of HTG temperature on COP. (b) Effect of condenser temperature on COP.

Figure 9. Sensitivity of COP value and second law efficiency. (a) Effect of absorber temperature on COP. (b) Effect of HTG temperature on efficiency.

solution (13) formed is pumped to the SHX-2 SHE. After exchanging heat in SHX-2, the weak LiBr liquid (15) splits into two streams, (16) and (17). Stream (16) goes to the HTG through SHX-1, while stream (17) directly goes to the LTG. Similar to the series flow cycle, heat is supplied to the HTG. The strong LiBr solution formed in both the generators is mixed to form the stream (7) before it passes through SHX-2. The rest of the operation is same as that of the series flow cycle.

5.1 Modelling and simulation

Modelling of the double effect LiBr–H₂O absorption refrigeration cycle with parallel flow is done on the basis of the same assumptions as those in the case of series flow cycle

in section 4.1. For parallel flow cycle, there is an additional independent variable that needs to be considered, which is the split ratio of weak LiBr solution from absorber to HTG and LTG. The split can be considered as an operating parameter as the flow to LTG can be manipulated independently.

5.2 Sensitivity analysis

Performance sensitivity of the double effect LiBr–H₂O with parallel flow refrigeration cycle for various operating temperatures was analysed.

In parallel flow double-effect cycle, the weak LiBr solution coming from the absorber is split into two streams. One stream enters the HTG and other, LTG. Split ratio (SR)

Figure 10. Effect of HTG temperature on solution circulation ratio.

Figure 11. Optimum conditions map for double effect series flow LiBr–water cycle.

is defined as the fraction of total weak solution flow from the absorber fed to HTG. The performance of the cycle changes with this split ratio. Effect of split ratio on COP of the cycle is as shown in figure 13a. There is a decreasing trend in the COP value for extremely low and high split ratio value. For the split ratio in the range 0.3–0.7, a moderate decrease in COP value is observed. For all evaporator temperature, split ratio of 0.4 seems to be the optimum value. All the analyses hereafter, for this cycle, are done using this split ratio value.

Effect of the HTG temperature on COP of the cycle is as shown in figure 13b. For evaporator temperature of 5 and 10°C, the COP goes through a maximum value with increase in the HTG temperature. For evaporator temperature of 15°C, there is a continuous decreasing trend in the COP. A similar decreasing trend for COP with increase in the condenser and the absorber temperature is observed in figure 14a and b, respectively. Sensitivity analysis for the second law efficiency with the HTG temperature shows a

Figure 12. Double-effect parallel flow LiBr–H₂O absorption refrigeration cycle.

Figure 13. Sensitivity of COP with split ratio and HTG temperature. (a) Effect of split ratio on COP (b) Effect of HTG temperature on COP.

decreasing trend for evaporator temperature of 10 and 15°C. For 5°C evaporator temperature, the efficiency goes through a maximum. Efficiency values are higher for lower evaporation temperatures as can be observed in figure 15a. A decreasing trend for the SCR is observed in figure 15b with increasing HTG temperature. The trend is very similar to that for series flow cycle. The HTG temperature range in which there is a sharp decrease in the SCR is not recommended for the cycle operation because of high solution flow rates.

5.3 Optimum operating condition map for double-effect parallel flow LiBr–water cycle

A map giving optimum operating condition for maximum COP at required evaporator temperature was generated through sensitivity analysis for various refrigeration and sink temperatures as shown in figure 16. Using this map, optimum heat source temperature can be chosen for a parallel flow double-effect LiBr–water cycle for given evaporator, absorber and condenser temperature.

Figure 14. Sensitivity of COP with condenser and absorber temperature. (a) Effect of condenser temperature on COP. (b) Effect of absorber temperature on COP.

Figure 15. Sensitivity of second law efficiency and solution circulation ratio with generator temperature. (a) Effect of generator temperature on efficiency. (b) Effect of generator temperature on SCR.

6. Conclusions

Performance of LiBr–water single-effect, double-effect series flow and double-effect parallel flow absorption refrigeration cycles was analysed for various operating parameters. Optimum operating condition maps were generated for single- and double-effect LiBr–water cycles. These maps are useful for choosing optimum operating conditions for required refrigeration duty considering sink temperature constraints. For single-effect cycle, maps cover its water-cooled as well as air-cooled mode operation. Refrigeration temperatures required for various applications such as generating cooling utility in a process, air-

conditioning, etc. are covered in all optimum condition maps. As the most accurate correlations are used to evaluate thermodynamic property of working fluids, the sensitivity analysis results are highly reliable.

The second law efficiency compares the performance of the cycle to that with an ideal Carnot cycle within the same temperature boundaries. Higher generator temperatures are not recommended for the cycle operation as efficiency values are low. A lower second law efficiency value indicates lower exergetic performance of the cycle, which means that a heat source of high quality is used for a comparatively lower quality work. Second law analysis shows that whenever a heat source is available at a higher temperature,

Figure 16. Optimum conditions map for double-effect parallel flow LiBr–water cycle.

double-effect cycle should be preferred over single effect as it has better COP and efficiency ratio values.

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Nomenclature

COP	Coefficient of performance
SCR	Solution circulation ratio
HTG	High temperature generator
LTG	Low temperature generator
m	Mass flow rate, kg/s
P	Pressure, kPa
Q	Heat load, kW
RHE	Refrigerant heat exchanger
SHX	Solution heat exchanger
SR	Split ratio
T	Temperature, K
x	LiBr mole fraction in solution

Subscripts

a	Sink
abs	Absorber

C	Carnot
cond	Condenser
evap	Evaporator
gen	Generator
max	Maximum

References

- [1] Wijeyesundera N F 1996 Performance limits of absorption cycles with external heat transfer irreversibilities. *Appl. Therm. Eng.* 16(2): 175–181
- [2] Mostafavi M and Agnew B 1996 The impact of ambient temperature on lithium bromide/water absorption machine performance. *Appl. Therm. Eng.* 16(6): 515–522
- [3] Xu G P, Dai Y Q, Tou K W and Tso C P 1996 Theoretical analysis and optimization of a double-effect series-flow-type absorption chiller. *Appl. Therm. Eng.* 16(12): 975–987
- [4] Xu G P and Dai Y Q 1997 Theoretical analysis and optimization of a double-effect parallel-flow-type absorption chiller. *Appl. Therm. Eng.* 17(2): 157–170
- [5] Sun D W 1997 Thermodynamic design data and optimum design maps for absorption refrigeration systems. *Appl. Therm. Eng.* 17(3): 211–221
- [6] Arun M B, Maiya M P and Murthy S S 2000 Equilibrium low pressure generator temperatures for double-effect series flow absorption refrigeration systems. *Appl. Therm. Eng.* 20: 227–242
- [7] Arun M B, Maiya M P and Murthy S S 2001 Performance comparison of double-effect parallel-flow and series flow

- water–lithium bromide absorption systems. *Appl. Therm. Eng.* 21: 1273–1279 (short communication)
- [8] Misra R D, Sahoo P K and Gupta A 2003 Thermoeconomic optimization of a single effect water/LiBr vapour absorption refrigeration system. *Int. J. Refrig.* 26: 158–169
- [9] Misra R D, Sahoo P K and Gupta A 2005 Thermoeconomic evaluation and optimization of a double-effect H₂O/LiBr vapour-absorption refrigeration system. *Int. J. Refrig.* 28: 331–343
- [10] Liu Y L and Wang R Z 2004 Performance prediction of solar/gas driving double effect LiBr–H₂O absorption system. *Renew. Energy* 29: 1677–1695
- [11] Park C W, Jeong J H and Kang Y T 2004 Energy consumption characteristics of an absorption chiller during the partial operation. *Int. J. Refrig.* 27(8): 948–954
- [12] Assilzadeh F, Kalogirou S A, Ali Y and Sopian K 2005 Simulation and optimization of a LiBr solar absorption cooling system with evacuated tube collectors. *Renew. Energy* 30(8): 1143–1159
- [13] Aphornratana S and Sriveerakul T 2007 Experimental studies of a single-effect absorption refrigerator using aqueous lithium-bromide: effect of operating condition to system performance. *Exp. Therm. Fluid Sci.* 32: 658–669
- [14] Kaynakli O and Kilic M 2007 Theoretical study on the effect of operating conditions on performance of absorption refrigeration system. *Energy Convers. Manage.* 48: 599–607
- [15] Wagner W, Cooper J R, Dittmann A, Kijima J, Kretzschmar H J, Kruse A, Mares R, Oguchi K, Sato H, Stocker I, Sifner O, Takaishi Y, Tanishita I, Trubenbach J and Willkommen T 2000 The IAPWS industrial formulation 1997 for the thermodynamic properties of water and steam. *J. Eng. Gas Turbines Power* 122(1): 150–180, available at <http://www.iapws.org>. URL <http://www.iapws.org>
- [16] Patek J and Klomfar J 2006 A computationally effective formulation of the thermodynamic properties of LiBr–H₂O solutions from 273 to 500 K over full composition range. *Int. J. Refrig.* 29: 566–578