

CHAPTER-2
LITERATURE REVIEW

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2.1 Introduction

Thermodynamic modelling and performance analysis of energy systems has been an important field of research in the field of thermal engineering. Often, performance of thermal energy systems are evaluated with the help of first law based energy and second law based exergy analysis. As far as the application of laws of thermodynamics is concerned, a lot of studies have been carried out in the past to evaluate energetic and exergetic performance of thermal systems. In many cases, optimization techniques are also applied to optimize thermal systems to obtain optimum performance and better efficiency. Sometime, inverse analysis is also done to estimate important unknown operating parameters of thermal systems.

Vapor absorption refrigeration systems (VARs) belong to an important class of thermal systems. There is growing interest on the development of VARs in the recent decade due to its certain benefits over conventional vapor compression refrigeration systems (VCRs). Absorption refrigeration systems help saving costly primary energy and provide an excellent opportunity for using waste heat stream or non-conventional solar/geothermal energy as heat source. It is environment friendly as it does not affect the ozone layer depletion and the green house gas emissions caused by chlorofluorocarbons (CFCs) used in VCRs. However, its lower coefficient of performance (COP) is a concern which however can be increased by using multi effect VARs.

VARs of different configurations have been analyzed thermodynamically in many studies to evaluate their performance with the help of computer based simulation techniques as well as experiments. Review and evaluation of previous research studies is an important part of research. Therefore, in this chapter, it is attempted to provide a detail review of previous studies performed on half, single and multi (double and triple) effect VARs. Most of the previous theoretical and experimental studies done on single and multi effect VARs are considered for discussion to identify the research gap in this specific field of research.

2. 2 Property models of some specific refrigerant absorbent pairs

As stated earlier in Chapter 1, the most widely used refrigerant and absorbent pairs in VARS are the ammonia–water ($\text{NH}_3\text{--H}_2\text{O}$) and water–lithium bromide ($\text{H}_2\text{O--LiBr}$). $\text{NH}_3\text{--H}_2\text{O}$ is preferred for use in low temperature industrial process cooling while $\text{H}_2\text{O--LiBr}$ is mainly used in chilling/air conditioning applications. Investigations are being done in search for newer refrigerant–absorbent pairs and also to analyze VARS performance with working fluid pairs other than $\text{NH}_3\text{--H}_2\text{O}$ and $\text{H}_2\text{O--LiBr}$ [1–8].

The properties of $\text{H}_2\text{O--LiBr}$ solution are available in ASHRAE Handbook, Fundamentals [9] and many other references [10, 11, 12, 13]. Binary mixture of $\text{H}_2\text{O--LiBr}$ has certain advantages in terms of safety, volatility ratio, affinity, stability, and latent heat [9]. However improper selection of pressure and temperature may lead to crystallisation. Maintaining vacuum in the system is an important issue with $\text{H}_2\text{O--LiBr}$. One more disadvantage with $\text{H}_2\text{O--LiBr}$ is its high viscosity due to which it demands high pumping power. However these shortcomings could be overcome with the use of additives like alcohols with relatively high molecular mass [9].

Lansing [10] in 1976 published a report on properties of $\text{H}_2\text{O--LiBr}$ solution showing dynamic behaviour of $\text{H}_2\text{O--LiBr}$ system with the help of a computer simulation program. He derived a new set of mathematical expression to define the three–dimensional surface of $\text{H}_2\text{O--LiBr}$ solution’s concentration, refrigerant and solution temperature in the range of 0.50 to 0.65% (wt) concentration of LiBr in the solution. In the selected range of concentration of LiBr in the solution, Lansing [10] calculated most of the properties of $\text{H}_2\text{O--LiBr}$ solution such as enthalpy, entropy, heat capacity, pressure etc. in describing the modelling of the $\text{H}_2\text{O--LiBr}$ system completely for dynamic performance analysis.

Chua et al. [11] investigated some properties of $\text{H}_2\text{O--LiBr}$ solution keeping the operating temperatures range from 0 to 190°C and the concentrations ranging from 0 to 75 wt%. Basically, they presented co–relations to determine properties like specific enthalpy, entropy, and heat capacity of $\text{H}_2\text{O--LiBr}$ solution.

Kaita [12] also reported on thermodynamic properties of $\text{H}_2\text{O--LiBr}$ solution at high temperatures and pressures. They developed equations from the measured data available in the literature, to estimate the vapor pressure, enthalpy and entropy of $\text{H}_2\text{O--}$

LiBr solution which were valid in the concentration range of 40–65 wt% and temperature range of 40–210°C.

The empirical property equations proposed by Patek and Klomfar [13] are the most recent. These correlations are defined as explicit functions of operating temperature and solution composition at different thermodynamic condition. The property equations given for pressure, density, heat capacity (at constant pressure), enthalpy, and entropy of H₂O–LiBr solution are valid in the temperatures ranges from 273 to 500 K and for solution concentration from 0 to 75% (wt) of LiBr in the solution.

Patek and Klomfar [14] has also provided functional forms for properties of NH₃–H₂O solution from vapour–liquid equilibrium phase. The property equations were developed from critically calculated experimental data of NH₃–H₂O solution essentially to cover in the range of operating condition for absorption cycles. Xua and Goswami [15] also derived equations for pure ammonia and water properties using Gibbs free energy equations. Mejbri and Bellagi [16] also presented thermodynamic properties of the NH₃–H₂O solution from three different approaches using an empirical Gibbs free enthalpy model, the Patel–Teja cubic equation of state and the PC–SAFT equation of state. Zeigler and Trepp [17] also used the approach of Gibbs’s free energy for the property modeling of the ammonia water mixture.

2.3 Alternate refrigerant absorbent pairs for VARS

In a VARS, property of the refrigerant absorbent pairs plays a major role and greatly affects the performance [18]. The most important requirement for a suitable refrigerant absorbent pair is that the absorbent must be miscible with the refrigerant in the liquid phase in the operating temperatures range. Moreover, the refrigerant absorbent pair should be chemically stable, non–toxic, and non–explosive. As stated earlier in Chapter 1, water is a good natural refrigerant and majority of the VARSs uses water as refrigerant [19].

Many alternate refrigerant absorbent pairs have been investigated as possible substitutes to NH₃–H₂O and H₂O–LiBr. Long back in 1984, Ferreira [20], from published experimental results, derived property equations for NH₃–LiNO₃ and NH₃–NaSCN as possible alternative to NH₃–H₂O for use in VARS. He advocated for use of the newer refrigerant absorbent pairs in VARS using waste heat or solar thermal energy

as heat source, which however may not be possible for $\text{NH}_3\text{-H}_2\text{O}$ based system at heat sink temperature above $30\text{ }^\circ\text{C}$. Further, he claimed 10% higher COP for $\text{NH}_3\text{-LiNO}_3$ and $\text{NH}_3\text{-NaSCN}$ as compared to that of the $\text{NH}_3\text{-H}_2\text{O}$ operated system under similar operating conditions.

Riffat et al. [2] investigated the use of water–potassium formate ($\text{H}_2\text{O-CHO}_2\text{K}$) as a possible substitute for $\text{H}_2\text{O-LiBr}$ in VARS application where they compared the absorption and desorption characteristics of the two solution pairs. It was found that the rate of absorption was 5% low for $\text{H}_2\text{O-CHO}_2\text{K}$ as compared to $\text{H}_2\text{O-LiBr}$. Contrary to this, the desorption rate was more in case of $\text{H}_2\text{O-CHO}_2\text{K}$ and a higher desorption rate is desirable as it helps in lowering the generator heat requirement and improving the VARS COP. Further, they reported that the production cost of $\text{H}_2\text{O-CHO}_2\text{K}$ is less and $\text{H}_2\text{O-CHO}_2\text{K}$ is also less corrosive and more environment friendly than $\text{H}_2\text{O-LiBr}$.

Safarov [21] carried out experiments in a constant volume piezometer over a wide range of temperature and pressure at various mole fractions to derive an equation of state for $\text{CH}_3\text{OH-LiBr}$ solution. He reported on the certain properties of $\text{CH}_3\text{OH-LiBr}$ solution while recommending its use at temperatures below the freezing point of water. The viscosity of $\text{CH}_3\text{OH-LiBr}$ was found to be lower than that of $\text{H}_2\text{O-LiBr}$. Further, CH_3OH has higher vaporization temperature, lower density and lower heat capacity than those of $\text{H}_2\text{O-LiBr}$.

Later Safarov [5] extended his experimental study to evaluate properties of $\text{CH}_3\text{OH-LiCl}$ solution and compare with $\text{CH}_3\text{OH-LiBr}$ solution. He developed Antoine type equation to correlate experimental vapour pressure data of LiCl and LiBr solutions in methanol. Additionally, the osmotic and activity coefficients and the activity of the solvent were also evaluated by carrying out experiments at different molality range for $\text{CH}_3\text{OH-LiBr}$ and $\text{CH}_3\text{OH-LiCl}$.

Ajib and Karno [8] explored the possibility of using acetone–zinc bromide solution in an absorption refrigeration machine of 10 kW capacities. For this purpose, first the thermo–physical properties such as vapor pressure, density, viscosity, specific heat capacity, specific electrical resistance and specific enthalpy were determined from experiments. Next, based on experimental data, equations and state diagrams were developed for the acetone–zinc bromide solution, correlating the temperature separately

with the pressure and the enthalpy. Pressure–enthalpy correlation and diagram were also developed for pure acetone. They recommended that the acetone–zinc bromide solution could be a suitable working solution pair for VARS application specifically for utilizing heat source at low temperature.

2.4 Water–lithium chloride (H₂O–LiCl): a potential working solution pair for VARS

Water–lithium chloride (H₂O–LiCl) is another solution pair with enormous potential for use in VARS in air conditioning application. It is relatively cheaper and has certain other benefits over other conventional refrigerant absorbent pairs. Properties of H₂O–LiCl solution have been determined in a number of studies and accordingly, mathematical correlations are developed through curve fitting of experimental results.

Chaudhari and Patil [22] measured vapour pressure of aqueous solutions of lithium chloride at various temperature and solution concentration by differential static method and then calculated enthalpies of solution by Haltenberger method using experimental vapour pressure and heat capacity data. They also constructed the Duhring chart and enthalpy–concentration chart for aqueous lithium chloride solution. Crystallization of anhydrous salt from the salt solution is a serious problem associated with VARS operation. Solution concentration and temperature directly affect this phenomenon; hence the solid–liquid equilibrium boundary (solubility curve) which gives the limit of operating temperatures is very important in VARS study and must be known as it forms the basis for computation of important thermodynamic properties of the system. Solubility boundary of LiCl–H₂O system has been extensively studied.

Monnin et al. [23] evaluated the solubility data of lithium chloride salts (anhydrous LiCl, LiCl–H₂O, LiCl–2H₂O, LiCl–3H₂O, and LiCl–5H₂O) and from their solubility in pure water, they calculated various thermodynamic properties using Pitzer’s ion interaction model and the mean spherical approximation model of aqueous LiCl solutions. They accumulated the prior data for various hydrates of aqueous LiCl in pure water and investigated the solubility curve for aqueous LiCl solution. They used more than 450 experimental data for the solubility measurement of LiCl hydrates in aqueous solution with respect to temperature.

Conde [24] presented empirical correlations for calculation of solubility boundary, vapour pressure, density, surface tension, dynamic viscosity, thermal conductivity, specific thermal capacity and differential enthalpy of dilution for different hydrates of aqueous LiCl solutions. Curve fitting with previous experimental data was done to reproduce new sets of equation with good precision within the validation range and limits of concentration of LiCl.

Sencan and Kalogirou [25] determined vapour pressure of H₂O–LiCl and LiBr + LiNO₃+LiI+LiCl–H₂O solution pairs using artificial neural network (ANN). Experimental vapour pressure results were obtained for the two solution pairs at various concentration and temperature which were later used to train and test the ANN. They observed only 0.84% difference between the predicted and actual vapour pressure. They advocated for LiCl–H₂O and LiBr+LiNO₃+LiI+LiCl–H₂O as prospective and alternate refrigerant–absorbent pair for cooled absorption refrigeration systems.

Zeng and Zhou [26] measured vapour pressure for obtaining solubility curve for LiCl in aqueous solution. They calculated and compared the earlier solubility data to present their own solubility curve using Brunauer–Emmett–Teller (BET) absorption model with the preferred water activity coefficient data at solution concentration, less than 20 mol/kg and within the temperature range of 273.15 K to 428.65 K.

Patek and Klomfar [27] also presented empirical relations for the solid boundary of LiCl–H₂O as a function of temperature and molar concentration. They used equation of special structure, states of the transition points as parameter in the solubility curve for direct parallel non linear and linear optimization of temperature–composition and composition–temperature equations.

Patek and Klomfar [28] again formulated equations, collecting a huge number of experimental data, for calculation of various thermodynamic properties (density, isobaric heat capacity, enthalpy, entropy, enthalpy of dilution, osmotic coefficient etc.) of LiCl–H₂O system which are valid from the crystallization line up to 400 K and for solution concentration from 0 to 50 wt% of LiCl in the solution. They presented vapour–liquid equilibrium solubility line using Gibbs energy equations for vapour and solution phases separately.

2.5 First law based energy analysis of VARS with various solution pairs

Lot of studies was done earlier to evaluate VARS performance from energetic point of view with various solution pairs including H_2O – LiBr and NH_3 – H_2O .

Saravanan and Maiya [1] with the help of computer based simulation technique, carried out energy analysis of a single effect VARS with four binary mixtures [H_2O – LiBr , H_2O – NaOH , H_2O – LiI and H_2O – LiCl], five ternary mixtures [H_2O –(LiBr + LiI), (salt mole ratio 4:1); H_2O –(LiCl + LiNO_3), (2.8:1); H_2O –(LiBr + LiNO_3), (4:1); H_2O –(LiBr + ZnBr_2), (2:1) and H_2O –(LiBr + LiSCN), (1:1)] and seven quaternary mixtures [H_2O –(LiBr + LiCl + ZnCl_2), (3:1:4); H_2O –(LiBr + ZnCl_2 + CaBr_2), (1:1:0.13); H_2O –(LiBr + ZnBr_2 + LiCl), (1:1.8:0.26); H_2O –(LiBr + LiI + $\text{C}_2\text{H}_6\text{O}_2$), (3:1:1); H_2O –(NaOH + KOH + CsOH), (4.3:3.6:2.4); H_2O –(LiNO_3 + KNO_3 + NaNO_3), (5.3:2.8:1.9) and H_2O –(LiCl + CaCl_2 + $\text{Zn}(\text{NO}_3)_2$), (4.2:2.7:1)]. In order to provide a comparative assessment, they showed the performance variations of VARS COP, cut-off temperature, circulation ratio and efficiency ratio with the changing component operating temperatures and the heat exchanger effectiveness for all these aqueous solutions as a part of parametric study.

Pilatowsky et al. [3] performed energy analysis to evaluate the COP of a single effect VARS using mono-methylamine-water (CH_3NH_2 – H_2O) as solution pair. They examined two single effect VARS designs, a basic design and a refined one. Use of a sensible heat recovery exchanger was the main difference between the two designs and of course they found higher COP for the refined system employed with the sensible heat recovery exchanger than the basic VARS. CH_3NH_2 – H_2O was considered as a possible substitute for NH_3 – H_2O where CH_3NH_2 is the refrigerant and H_2O is the absorbent. The advantage with CH_3NH_2 – H_2O is that it could be operated at low generator temperature in the range of 60–80°C and hence, they recommended for utilizing solar energy to operate VARS with CH_3NH_2 – H_2O as solution pair.

Lucas et al. [4] used a mixture of LiBr and potassium formate (CHO_2K) in a proportion of 2:1 (by mass) as absorbent instead of LiBr alone. From experimental results, they developed empirical relation for property calculation of the proposed mixture in water. Next, with this new ternary mixture, they evaluated the performance of a single effect VARS where they obtained higher COP at generator temperature as low

as 55°C. Further they observed lower heat of dilution for this new absorbent mixture which attributed to reduced thermal loads in the VARS generator and absorber. Lucas et al. [29] further investigated the effect of addition of a surfactant (n-Octanol) on absorption capacity of LiBr and CHO₂K mixture in water.

In a similar study, Donate et al. [6] theoretically, with the help of a computer based simulation program, evaluated the performance of a single effect VARS using mixtures of LiBr with HCO₂Na, HCO₂K, CH₃CO₂Na and CH(OH)CO₂Na as absorbents in water. Prior to performance evaluation, the properties such as density, viscosity, enthalpy of dilution, solubility and vapour pressure of the mixtures were measured. The thermodynamic performance analysis revealed better system performance with the mixtures (COP 0.93 to 0.94) compared to COP of 0.75 with LiBr alone. The idea behind using such mixtures of LiBr with the organic salts of sodium and potassium was to overcome some of the limitations of LiBr as absorbent alone.

Muthu et al. [7] carried out experiments in a single effect VARS to evaluate its performance with R134a–N, N–dimethyl acetamide (DMAC) as refrigerant absorbent pair. Hot water was used as heat source for operating the VARS and the thermal performance was measured at various components operating temperature. They observed that the system took two hours of time to attain steady state while operating the system with a heat input of 4 kW and maintaining the source and sink temperatures respectively at 80°C and 30°C. Further, they obtained low COP in the range of 0.25–0.45 under the tested operating temperatures. However, they found that R134a–DMAC could be suitable candidate for VARS operation with low temperature heat sources.

Joudi and Lafta [30] applied mass and energy balance to the individual components of a H₂O–LiBr based single effect VARS driven by hot water. Like in other studies, they evaluated the effect of operating conditions on VARS performance. However, this study was different from other previous studies in the sense that it was based on a new heat and mass transfer based absorber model contrary to previous models based on only heat transfer.

Kaynakli and Kilic [31] evaluated the effects of components' temperatures and heat exchangers' effectiveness on components' thermal loads and COP of a single effect H₂O–LiBr VARS. They observed higher COP during system operation at higher

generator and evaporator temperatures. VARS COP was also found to increase at lower condenser and absorber temperatures. Among the SHE, RHE and SRHE, it was the SHE effectiveness that was more sensitive to system performance compared to the other two.

Karamangil et al. [32] investigated thermodynamic performance a single effect VARS using $\text{H}_2\text{O-LiBr}$, $\text{NH}_3\text{-H}_2\text{O}$, $\text{NH}_3\text{-LiNO}_3$ as working fluids. In their system, they considered one solution heat exchanger (SHE), one refrigerant heat exchanger (RHE), and one solution-refrigerant heat exchanger (SRHE). Through a parametric study, with the help of software package, the effects of components' temperatures and heat exchangers' effectiveness on VARS performance were evaluated. While comparing the three solution pairs, they found higher COP with $\text{H}_2\text{O-LiBr}$ compared to that with $\text{NH}_3\text{-H}_2\text{O}$. However, due to crystallization of the LiBr solution, the system operation was possible only for a narrow range the generator temperatures. Further they found that $\text{NH}_3\text{-LiNO}_3$ provides better performance at low generator temperature.

2.6 Solar powered VARS

Some published articles on solar powered absorption cooling systems are discussed below.

Florides et al. [33] presented dynamic simulation of a solar heat driven single effect $\text{H}_2\text{O-LiBr}$ VARS where they used TRNSYS platform for modeling the VARS. The meteorological data of Nicosia, Cyprus were used for the transient simulation analysis. They compared three types of solar thermal energy collector as primary energy source for the VARS. Among the flat plate, evacuated tube and compound parabolic collectors, the last one was reported to be the most efficient collector with minimum area requirement for integration with the single effect VARS.

Florides et al. [34], with the help of computer program, examined (i) the COP of a single effect $\text{H}_2\text{O-LiBr}$ VARS in relation to the changing generator temperature, (ii) system efficiency in relation to the SHE area, (iii) the solution strength effectiveness in relation to the absorber solution outlet temperature and (iv) the difference between the absorber LiBr inlet and outlet percentage ratio etc. The theoretical results obtained from computer simulation were compared with experimental results derived from a small unit 1 kW capacity. They also presented some heat exchanger design related information along with cost analysis of a domestic size absorber cooler. This study was mainly

carried out to prepare a household design of a single effect H₂O–LiBr based VARS for using solar thermal energy and in this regard, they also presented a cost analysis involved installation and operation of the given system.

Liu and Wang [35] proposed a novel solar/gas driven double effect H₂O–LiBr VARS. The water was first heated in a solar collector and then stored in a thermal storage tank. This hot from the storage tank was later used as a heat source to supplement the amount of heat required for vapour generation in the low–pressure generator (LPG) of the double effect VARS. The high–pressure generator (HPG) leaving water vapor was also a source of heat for the LPG. In the HPG, natural gas was burnt to provide the required heat.

Assilzadeh et al. [36] carried out a similar simulation study using weather data of Kuala Lumpur, Malaysia in the TRNSYS software. They used a commercial single effect H₂O–LiBr VARS integrated with an evacuated tube collector, storage tank unit, auxiliary heater and a cooling tower set up. They determined the collector slope angle for maximum absorption of solar thermal radiation, pump flow rate, auxiliary boiler thermostat setting, storage tank volume and collector area to optimize the VARS performance. It was found that an optimal size of the storage tank provides flexibility for continuous cooling load operation as well as better performance of the VARS. Further, an economic analysis was also performed with respect to minimum collector area requirement.

Mittal et al. [37] carried out theoretical analysis of a solar–powered, single–effect H₂O–LiBr VARS to simulate system performance with the help of weather data of Bahal, Bhiwani, Haryana, India. A flat plate solar collector was used and they studied the effect of hot water inlet temperature on COP and the surface area of the absorption cooling component.

Pongtornkulpanich et al. [38] designed and installed a solar heat driven 10 ton single effect H₂O–LiBr VARS at the School of Renewable Energy Technology, Phitsanulok, Thailand. From the analysis, they could show that a 72 m² evacuated tube solar collector could replace a yearly average of 81% of thermal energy requirement, while the remaining 19% was supplied by a LPG–fired backup heating unit. Further, they demonstrated that the solar based absorption cooling system economics are dominated

mainly by the initial cost of the solar collector array and the absorption chiller and these are significantly higher than the conventional compression refrigeration system.

In a similar study, Mazloumi et al. [39] simulated a solar single effect H₂O–LiBr VARS to supply approximately 5 ton of cooling load during peak summer season (July) for a typical house at Ahwaz city of Iran. They used a horizontal N–S parabolic trough collector for heating water which was stored in an insulated thermal storage tank. For supplying the given cooling load, the minimum solar collector area required was determined to be 57.6 m². Further they showed that the water flow rate in the collector had no role to play on the minimum collector area required but it significantly affected the optimum capacity of the storage tank.

Xu et al. [40] analyzed another solar powered H₂O–LiBr VARS using typical meteorological data of Shanghai, China. In this system, the heat of solar radiation was converted first into chemical potential of the working fluid and then it was stored in the system. The stored energy was again converted to heat to drive the VARS when AC was required. In this work, they used variable mass energy transformation and storage (VMETS) technology in order to maintain the consistency between the solar radiation and the air conditioning (AC) load. The system simulation was done to investigate the system dynamics by developing a dynamic model. The results indicated two COPs (0.7525 or 0.7555) for two different cases of air cooled and water cooled condenser. The solar collector area for the case of air cooled condenser was found more (66 m²) compared to 62 m² in case of water cooled condenser.

Monne et al. [41] used TRNSYS software to simulate performance of a solar powered VARS using two years (2007 and 2008) weather data of Zaragoza, Spain. For the validation purpose, they used experimental results of a 4.5 kW single effect H₂O–LiBr absorption chiller combined with a flat plate collector and a dry cooling tower. From the simulation as well as experimental results, they found that the system COP is strongly influenced by the cooling water temperature and the generator driving temperature. They also proposed for an alternate geothermal heat sink and with new heat sink, they observed 42% improvement in the COP.

Cascales et al. [42] developed a number of dynamic simulation models in TRNSYS platform to obtain appropriate design configuration of a solar driven H₂O–LiBr

VARS for classroom cooling in an educational institute in Puerto Lumbreras, Murcia, Spain. One such model considered manufacturer data while the others were artificial neural network (ANN) models based on adaptive resonance theory. The experimental data of two years of performance were collected; some of these were used for ANN training and some others for model validation.

Li et al. [43] analyzed the performance of a solar driven air cooled double effect H₂O–LiBr VARS using monthly average meteorological data (hourly solar irradiance and ambient temperature) of subtropical Guangzhou at various collector temperatures. They recommended for a 110–130°C range of solar collector inlet temperature for improved system performance with lower crystallization risk. It may be mentioned here that the crystallization risk is more with the air-cooled systems compared to water cooled ones, although they are attractive otherwise due to absence of the cooling tower (CT) and other associated installation [44].

Marc et al. [45] presented dynamic modeling of a solar powered single-effect H₂O–LiBr absorption chiller taking into account both the transient and steady state phases. First they presented the dynamic modeling of the H₂O–LiBr absorption chiller and then the model results were validated with experimental results. They also optimized the COP of the chiller at different levels of refrigerating capacities.

Ochoa et al. [46] developed a mathematical model to determine the overall heat transfer coefficients of the heat exchangers of chillers. The model solved a non-linear system of equations using finite difference method to simulate and predict the behavior of internal and external parameters such as temperature, concentrations and pressures when these are subjected to disruptions in the power supply and thermal load. They obtained correct model results as they could reproduce the temperatures and the COP with those provided by the commercial manufacturer.

Chen et al. [47] developed a solar powered air-cooled single effect absorption chiller of 6 kW cooling capacity. The chiller was fabricated and tested for real application without allowing crystallization to take place. They also analyzed the influence of different operating conditions on the chiller performance. The developed chiller could meet 65% of the total building cooling load with an average COP of about

0.61. It was also mentioned the system converted 28% of the solar radiation into cooling capacity.

2.7 VARS driven by engine exhaust and other waste heat sources

A VARS can be driven by any waste heat stream like engine exhaust or waste heat streams of gas turbine (GT) and steam turbine (ST) based thermal power plants. Such cogeneration systems integrated with VARS have been analyzed in many previous studies and some of them are briefly discussed in the following sections.

2.7.1 Engine exhaust heat driven VARS

Mostafavi and Agnew [48] also made use of diesel engine exhaust heat to operate a single effect VARS and evaluated the performance of the diesel engine together with the VARS by calculating the VARS cooling capacity for air conditioning purposes.

Havelsky [49] considered utilization of diesel engine exhaust heat and hot engine cooling water separately for running a single effect VARS in two different combined cogeneration systems. The study focused on evaluating and comparing the efficiency of the two cogeneration systems with normal systems where heat, cold and power are produced separately.

Talbi and Agnew [50] analyzed theoretically the performance of four different configurations (Pre-inter cooler engine, Inter-cooled combination engine, pre-cooled engine and Non-cooled engine) of a combined turbocharged diesel engine and an absorption refrigeration unit. With the help of performance analysis software, they investigated the all the four configurations by evaluating performance of both the engine and the cooling plant.

Manzela et al. [51] carried out experiments in a single effect $\text{NH}_3\text{-H}_2\text{O}$ VARS using engine exhaust heat as energy source. They evaluated the effect of VARS integration on engine performance and exhaust emissions. It was found that when the VARS is installed in the engine exhaust, the hydrocarbon emissions increase while the carbon monoxide emission reduces. Carbon dioxide emission is not affected by VARS integration.

Ouadha and El-Gotni [52] also explored the possibility of using waste heat of marine diesel engine to drive a single effect $\text{NH}_3\text{-H}_2\text{O}$ VARS. A thermodynamic model

was developed and system performance was investigated at various temperatures of the VARS components. They observed better performance of the VARS at high generator and evaporator temperatures and low condenser and absorber temperatures.

Rego et al. [53] examined the dynamic performance of a single effect $\text{NH}_3\text{-H}_2\text{O}$ VARS driven by engine exhaust. For this purpose, a microcontroller and a stepper-motor were used to regulate a valve for controlling the flow of hot exhaust gas from the engine and the heat input based on generator temperature of the cooling system. They recommended that the operating range of the engine exhaust driven VARS can be expanded through dynamic controlling of hot gas flow rate and heat input.

Du et al. [54] performed experiments in $\text{NH}_3\text{-H}_2\text{O}$ based VARS for waste heat utilization of diesel engine exhaust. They adopted the design of side cooling rectification and side heating generation to achieve proper heat matching for better heat recovery and improved system performance. The experimental results showed a reliable system operation even with a sharp variation of the engine exhaust condition.

Yuan et al. [55] has recently presented on both theoretical and experimental investigations of $\text{NH}_3\text{-H}_2\text{O}$ based VARS and freezing pre-desalination based marine engine exhaust gas heat recovery system. In this study, they have introduced an energy storage sub-cycle to overcome underutilization of energy and balance the excessive cooling output of the VARS. The energy storage sub-cycle basically uses seawater as phase-change material for energy storage which is also pre-desalinated in this sub-cycle.

Hanriot et al. [56] investigated experimentally the performance of a $\text{NH}_3\text{-H}_2\text{O}$ VARS powered by waste heat from the exhaust of an automotive engine. The exhaust system was connected to the generator of a commercial system that was originally designed to operate by an LPG burner. They designed a close looped exhaust gas flow control system for maintaining a fixed generator temperature and performed a series of test at different generator temperatures (180, 200, 240, and 270°C) by monitoring the engine torque, speed, and temperature at different points of the system. Satisfactory performance was obtained at a generator temperature of 200°C.

2.7.2 GT and ST based VARS

Mone et al. [57] examined utilizing GT exhaust stream in H₂O–LiBr based single, double and triple effect absorption chillers. It was found that the cooling capacity of the chillers was more dependent on the exhaust gas flow rate rather than exhaust temperature. The highest cooling capacity was obtained from the triple effect system with minimum heat rejection.

Colonna and Gabrielli [58] considered a plant configuration comprising of a GT coupled with a NH₃–H₂O absorption refrigeration plant and a heat recovery steam generator (HRSG).

Hwang [59] analyzed the performance of a vapor absorption chiller driven by waste heat from a micro–GT. The chilled water produced in the chiller was used for subcooling condensed liquid refrigerant of a vapor compression refrigeration system (VCRS) and precooling condenser entering air of the VCRS. The VCRS compressor was driven by power obtained from the micro–GT.

Bruno et al. [60] investigated the performance of a combined micro–GT and gas driven double effect H₂O–LiBr absorption chiller with and without addition of extra fresh air for post combustion. Bruno et al. [61] again in another study, analyzed a number of cogeneration systems involving biogas fuelled micro GT and commercially available single and double effect H₂O–LiBr and NH₃–H₂O VARSs.

Huicochea et al. [62] analyzed the performance of a combined micro GT and double–effect H₂O–LiBr VARS theoretically using experimental exhaust heat data of the micro GT.

Martins et al. [63] also considered a combined GT and NH₃–H₂O based VARS to evaluate its performance at various compressor pressure ratios, GT expansion ratios and operational pressures of the VARS.

Often VARSs are used in combination with GT plants to cool compressor inlet air in order to increase density of incoming air. This results in increase in the turbine output and efficiency. Ameri and Hejazi [64] investigated a steam driven double effect H₂O–LiBr absorption chiller and HRSG integrated GT plant. They observed 11.3% power increase in the GT plant with inlet air cooling produced by the GT exhaust driven

absorption chiller. There are similar other studies which report on GT exhaust driven VARS used for the purpose of inlet air cooling of GT plants [65–67].

Gogoi and Talukdar [68] analyzed a combined ST based power cycle and single effect H₂O–LiBr VARS where a detailed parametric analysis was done to investigate the effects of boiler pressure, fuel flow rate, VARS cooling load and component temperatures on performance of the topping power cycle and bottoming VARS. They also provided performance comparison of the combined plant with the ST plant (without VARS) to quantify performance change due to VARS integration.

2.8 Exergy analysis of VARS

Exergy analysis is carried out for evaluating the second law based performance of a thermal system and irreversible losses occurring in different components of the system. Single effect, double effect and triple effect VARS have been analyzed based on second law of thermodynamics in many research studies. Some of these are discussed in the following sections.

2.8.1 Exergy analysis of single effect VARS

Talbi and Agnew [69] while performing exergy analysis on a single–effect H₂O–LiBr VARS found that the absorber contributed maximum 59.06% to the total irreversible loss with the generator to follow with a contribution of 27.02%. In this article, they also discussed about ways and means for reducing irreversible losses in these two important VARS components.

Lee and Sherif [70] performed exergy analysis of a single effect H₂O–LiBr system at different heat source, cooling water, chilled water, and supply hot water temperatures. The system was designed for production of chilled water in the evaporator for cooling and hot water in the absorber and condenser for heating. They observed higher COP and exergetic efficiency at low cooling water temperature when the system was operated in the cooling mode. It was also observed that COP increases initially with the heat source temperature but beyond certain limit, it again decreases and this was more noticeable in case of the exergy efficiency. In the heating mode also, COP and exergy efficiency increase with heat source temperature but simultaneously the risk of crystallization also increases. At low ambient temperature, however, they recommended

for use of direct space heating without the use of the VARS due to low system performance and freezing problem associated with water.

In a study, Sencan et al. [25] also observed similar behavior of cooling and heating COP slightly increasing and exergy efficiency decreasing with heat source temperature in a single effect H₂O–LiBr VARS. Further, they observed higher thermal loads and irreversible losses in the generator and absorber compared to those in the condenser and evaporator.

Kilic and Kaynakli [71] carried out exergy based performance analysis of a single effect H₂O–LiBr VARS and found the generator contributing the highest to the total irreversible losses. They also observed that the system's exergetic performance improves at higher generator and evaporator temperatures while the reverse happens at higher condenser and absorber temperatures.

Abu–Ein et al. [72] performed energy and exergy analyses of a solar heat driven NH₃–H₂O VARS of 10 kW capacities where they evaluated the COP, exergetic COP (ECOP) and the exergy losses of each system component at various operating conditions. The generator temperatures corresponding to the minimum and maximum COP and ECOP were found to be 110°C and 200°C respectively. Among the VARS components, the generator contributed maximum (40%) to the total system irreversibility. In the absorber, the maximum irreversibility occurred at a generator temperature of 130°C at all evaporator temperatures.

Khaliq [73] analyzed the exergetic performance of a trigeneration system consisting of a GT, an HRSG and a H₂O–LiBr VARS. He evaluated the energy and exergy efficiencies along with irreversibility of each system component with changing compressor pressure ratio, turbine inlet temperature, and VARS evaporator temperature. It was found that the components' irreversibility decreases with pressure ratio and while it increases with increase in the turbine inlet temperature. Among the VARS components, the generator produced the highest irreversibility followed by the absorber, condenser and the evaporator.

Gogoi and Talukdar [74] carried out exergy analysis of a combined ST based power and single effect H₂O–LiBr VARS for evaluating its exergetic performance by evaluating exergetic efficiency and component irreversibility of the power cycle and

VARs components under the influence of operating parameters such as boiler fuel flow rate, boiler pressure, VARs cooling capacity and components' temperature.

Mohtaram et al. [75] investigated a combined Rankine power and $\text{NH}_3\text{-H}_2\text{O}$ VARs to produce power and refrigeration from the same heat source. Parametric analysis was done to evaluate the effects of environmental temperatures, heat source, refrigeration, inlet pressure and temperature and the density of the $\text{NH}_3\text{-H}_2\text{O}$ dilution on exergy efficiency, cooling output and net power of the system. Additionally they performed optimization of the combined cycle thorough application of genetic algorithm to maximize the plant efficiencies.

2.8.2 Exergy analysis of double effect VARs

Xu and Dai [76] investigating the thermodynamic performance of a parallel flow type double-effect $\text{H}_2\text{O-LiBr}$ VARs observed that the COP decreases with increase in the solution circulation ratio while it increases at high distribution ratio and high heat-recovery ratios of the high and the low-temperature heat exchanger.

Arun et al. [77] compared the thermal performances of the parallel and series flow configurations of double effect $\text{H}_2\text{O-LiBr}$ VARs on the basis of LPG equilibrium temperature. They found comparatively higher COP with the parallel system over the entire range operating conditions that was considered. It was also found that the COP of the double effect parallel configuration is more sensitive to change in evaporator temperature compared to the condenser and the absorber temperatures. They also observed higher impact of LPG heat input on performance of the parallel flow configuration over the series flow one.

Adewusi and Zubair [78] analyzed the exergetic performances of a single and a two-stage $\text{NH}_3\text{-H}_2\text{O}$ VARs where they investigated the effects of heat exchanger effectiveness and components' operating temperatures on performance of both the single and two-stage systems. They found that the COP of the two stage system was more but accordingly, the total entropy generation was also found to be high.

Manohar et al. [79] applied an artificial neural network (ANN) based model to predict the performance of a steam driven double effect series flow type $\text{H}_2\text{O-LiBr}$ VARs. First, experimental data were used to train the ANN and later, with the ANN

model, VARS performance was tested at different steam pressure, inlet and outlet temperatures of the chilled and cooling water.

Gomri and Hakimi [80] performed exergy analysis in a series flow type double effect H₂O–LiBr VARS to calculate its COP, the exergy losses in each system component. They identified the HPG and the absorber as the major sources of exergy destruction. Further they observed that performance of the double effect VARS improves at higher LPG temperature while it deteriorates at higher HPG temperature.

Figueredo et al. [81] analyzed the thermodynamic behavior of a natural gas driven double stage H₂O–LiBr VARS of 200 kW cooling capacity with heat source at 170°C. A solar heat source at 90°C was also utilized by them for driving a single stage chiller in the combined mode at both the temperatures simultaneously. During winter, the system was operated in the double–lift mode for heating purpose.

Shin et al. [82] simulating the dynamic performance of a double effect H₂O–LiBr VARS found that the chiller dynamics is mainly controlled by the inlet temperatures of the cooling and the chilled water at a given heat input. The system dynamics was simulated by considering step change in the cooling load at fixed cooling and the chilled water inlet temperatures. As a means to further improve the system control and to avoid crystallization, they recommended for activation of a dilution cycle through turning off the fuel gas valve and normal operation of the other pumps, in case the chilled water exit temperature falls below 4°C.

Kaushik and Arora [83] made exergetic performance comparison between a single and a series flow type double effect H₂O–LiBr VARS. As obviously, the COP of the double effect system was found to be higher than that of the single effect system. They also mentioned about an optimum generator temperature at which the COP and exergy efficiency of the single and double effect systems are maximized. The performances of the two systems were found to improve at low absorber and high evaporator temperature with an exception in case of the exergy efficiency at higher evaporator temperature. Among all the components, it was the absorber that produced the highest irreversibility in both the systems.

Gomri [84] also compared the performances of a single effect and a double effect series flow H₂O–LiBr VARS at equal cooling load. He found that the COP of double

effect system was almost the double of the single effect system, but the exergy efficiency was not very high compared to that of the single effect one. He also found that corresponding to each condenser, absorber and evaporator temperature, there exists an optimum generator temperature at which the COP and exergy efficiency of the two systems are maximum and total change in exergy is the minimum.

Yin et al. [85] developed a thermodynamic model to predict steady state performance of a steam driven double effect H₂O–LiBr VARS using test data of a 16 kW H₂O–LiBr double effect absorption chiller under different test conditions. In this study, they explored the possibility of expanding the model based design of the absorption chiller to an overall building cooling, heating and power (BCHP) systems. Further, they emphasized on development of a proper design and control strategy for the proposed BCHP systems in order to maximize its efficiency and minimize the capital and the maintenance costs.

Farshi et al. [86] investigated the crystallization characteristics of the series, parallel and reverse parallel configurations of double effect H₂O–LiBr VARS at identical cooling loads. In the series flow system, they found more risk with crystallization at higher HPG, evaporator and low temperature heat exchanger temperatures. The risk to crystallization was also more at low condenser and absorber temperatures. Further they found higher crystallization possibility with the series flow system than with the parallel and the reverse parallel configurations.

Next, Farshi et al. [87] compared the energetic and exergetic performances of the series, parallel and reverse parallel configurations of the double effect H₂O–LiBr VARS. The differences in performance of the three systems were evaluated with respect to change in parameters such as SHE effectiveness, heat supplied to the LPG from external source and pressure drops between (i) the evaporator and the absorber and (ii) the LPG and the condenser.

Farshi et al. [88] further evaluated the effects of operating parameters on product cost flow rates and total investment costs of the three different double effect H₂O–LiBr VARS configurations through an exergo–economic analysis. They found strong dependence of operating conditions on costs of the three system configurations and their selection. The total investment costs of the systems were found to reduce at high HPG

temperature, high evaporator temperature, low condenser temperature and low SHE effectiveness. Among the components, the costs of the evaporator and the absorber were found to be the highest in all the three VARS configurations.

Li and Liu [89] evaluated the effect of generator heat load ratio, the ratio of HPG to LPG heat input, on COP and crystallization characteristics of series, pre-parallel, rear parallel and reverse parallel flow configurations of an air cooled double effect H₂O–LiBr VARS. They found that COP increases when the heat load ratio reduces, however, simultaneously, the risk to crystallization also increases.

Talukdar and Gogoi [90] proposed a combined ST based power cycle and a boiler flue gas driven double effect series flow type H₂O–LiBr VARS. Exergy analysis was carried to show the performance variation of the topping power cycle and the bottoming VARS with changing HPG temperature from 120°C to 150°C. Further, the performance of this combined system was compared with a similar system integrated with a single effect H₂O–LiBr VARS.

2.8.3 Exergy analysis of triple effect VARS

Gomri [91] performed exergy analysis of a triple effect H₂O–LiBr VARS to evaluate COP and exergy efficiency of the VARS and exergy losses of each system component. He observed that at fixed HPG temperature, it was the LPG temperature which influences system performance more than the medium pressure generator (MPG) temperature. Further he found that for a given MPG temperature, there is a limit beyond which LPG temperature cannot be increased further as it leads to crystallization of the salt solution.

Gomri [92] again considered a triple effect H₂O–LiBr VARS to provide comparative assessment of its performance with a single and a double effect (series flow type) system at an identical cooling load of 300 kW. Evaluating the influence of operating parameters on COP and exergetic efficiency, he found three and two times more COPs in the triple and double effect systems in comparison to the single effect system. The exergy efficiency of the double and triple effect systems were also found to be slightly higher than that of the single effect one. Gomri [92] also identified an optimum generator temperature for each set of fixed condenser and evaporator temperatures in realizing maximum performance from the three systems.

Gebreslassie et al. [93] also evaluated the exergetic performance of a triple effect H₂O–LiBr VARS by calculating the COP, exergy efficiency and the exergy destruction rate at various heat source temperatures. They also compared the performance of the triple effect system with those of half, single and double effect systems. Although the highest COP was found with the triple effect system, but the exergy efficiency of the system were not much different from each other. In all the four systems, they noticed higher rates of exergy destruction in the absorbers and generators and these exergy destruction rates increased with increase in the heat source temperature.

Kaita [94] carried out performance simulation analysis on parallel–flow, series–flow and reverse–flow configurations of triple–effect H₂O–LiBr VARS and presented a comparison among the cycles based on COP, maximum allowable operating pressure and temperature. The simulation results showed highest COP for the parallel flow system while in the reverse–flow cycle, the maximum pressure and temperature were found lower than those of other cycles. However they pointed out that in case of the reverse–flow cycle, if some solution leaving the low and medium temperature generator bypasses the medium and high temperature generators and returns to the solution to the absorber, the system performance is significantly improved.

2.9 VARS performance analysis using H₂O–LiCl as working solution pair

Although a number of property related researches have been done and mathematical correlations (based on experimental results) are developed for determining properties of aqueous of H₂O–LiCl solution, but researches on performance study of VARS using H₂O–LiCl as working solution pair are limited. A few articles on H₂O–LiCl based VARS performance analysis are however available which are discussed below.

Grover et al. [95] made theoretical study of a single stage H₂O–LiCl VARS where they used a set of temperature dependent equations for calculating solution concentration and enthalpy to determine COP and flow ratio (FR) at various combinations of component temperatures. FR is a performance parameter defined as the ratio of the mass flow rate of the salt solution entering the generator to the mass flow rate of refrigerant. Further, the COP and FR results of H₂O–LiCl system were compared with published results of H₂O–LiBr system. It was shown that FR is low and COP is more in

the H₂O–LiCl system than those of the H₂O–LiBr system under identical operating conditions.

Won and Lee [96] investigated the energetic performance (COP and FR) of a double–effect H₂O–LiCl VARS through computer simulation at various operating temperatures. A performance comparison between H₂O–LiCl and H₂O–LiBr systems was also provided in terms of energetic performance parameters where they observed higher COP and lower FR in respect of the H₂O–LiCl VARS.

Saravanan and Maiya [1] also provided thermodynamic analysis of a water based VARS with four binary mixtures including that of H₂O–LiCl. The equations proposed by Grover et al. [95] were used for calculating thermodynamic properties of H₂O–LiCl solution and H₂O–LiCl was found superior in terms of cut–off temperature (minimum generator temperature at which the system can operate) and FR.

She et al. [97] proposed a novel low grade heat–driven VARS using H₂O–LiCl in the high–pressure cycle and H₂O–LiBr in the low–pressure cycle. In this work, three different heat source utilization modes viz. two parallel modes (PM–1 and PM–2) and one serial mode (SM) are considered to provide performance comparison among them and also with a traditional double–stage H₂O–LiBr VARS. The effect of heat source temperature, intermediate pressure and the component temperatures on system performance was also analysed in this paper.

The research works [1, 95–97] are however totally based on energy analysis which alone is not sufficient to evaluate features of energy resource utilization as it provides only the quantitative measurement and completely ignores the qualitative aspect of it.

Bellos et al. [98] later on made energetic and exergetic performance comparison of H₂O–LiCl and H₂O–LiBr working pairs in a single effect solar absorption cooling system by integrating the absorption refrigeration systems with a solar flat plate collector and a storage tank. The two solution pairs were examined by varying the heat source temperature at three reference temperatures of 25°C, 30°C and 35°C with an objective of maximizing the exergy efficiency through minimization of the solar collector area. The exergy efficiency was found to be higher in case of H₂O–LiCl with 8% lower collector

area with H₂O–LiCl fulfilling the demand of the same given cooling load. The optimum heat source temperature was also found less for H₂O–LiCl.

The above articles are however related to performance analysis of single effect H₂O–LiCl VARS. In so far as double effects H₂O–LiCl absorption refrigeration systems are concerned, there is no study that reports on thermodynamic performance analysis of double effect H₂O–LiCl absorption refrigeration systems.

She et al. [97] analyzed the performance of a novel two stage VARS using H₂O–LiCl and H₂O–LiBr solution pairs. The two stage VARS consists of three cycles: the water cycle, the low pressure cycle and the high pressure cycle. The water cycle consists of the condenser, the evaporator and the refrigerant expansion valve. The low and high pressure cycles consist of one generator, one absorber, one solution heat exchanger (SHE), one solution pump (SP) and one solution expansion valve in each cycle. They used H₂O–LiCl pair in the high pressure cycle while H₂O–LiBr pair was used in the low pressure cycle. The superheated water vapour generated in the low pressure generator (LPG) goes to the high pressure absorber (HPA) where it is absorbed by the dilute H₂O–LiCl solution. They considered three different heat source utilization modes viz. two parallel modes (PM–1 and PM–2) and one serial mode (SM) to provide performance comparison among them and also with a traditional double–stage H₂O–LiBr VARS. The effect of heat source and the component temperatures on system performance was also investigated. This two stage system proposed by She et al. [97] is however entirely different from any of the three flow configurations (series, parallel and reverse parallel) of double effect VARS mentioned above.

A series flow configuration of a double effect H₂O–LiCl VARS was investigated by Won and Lee [96] long back in 1991, where they evaluated the COP and FR through computer simulation at various operating temperatures. They varied the HPG temperature maximum up to 100°C and made use of the equations proposed by Grover et al. [95] for calculating thermodynamic properties of H₂O–LiCl solution. A performance comparison between H₂O–LiCl and H₂O–LiBr systems was also provided where they found higher COP and lower FR with the H₂O–LiCl system.

Bellos et al. [99] in another study examined the performance of a double effect parallel flow type H₂O–LiCl based absorption chiller powered by solar parabolic trough

collectors. However, in their proposed double effect VARS; they considered two condensers (low and high) as opposed to normal ASHRAE recommended double effect VARS configurations [87], where only a single condenser was used. While comparing the performance with conventional H₂O–LiBr pair, they found 8% higher solar cooling performance with the H₂O–LiCl operated VARS. Parametric analysis was also done by considering three different low condensation temperature levels (30°C, 35°C and 40°C) and four evaporating temperature levels (5°C, 7.5°C 10°C and 12.5°C) while allowing the generator temperature to vary in the allowed range in every case.

2.10 Optimization studies on VARS

In the following research studies, it was attempted to optimize the VARS performance by using some specific optimization methods.

Kizilkan et al. [100] carried out a thermo–economic optimization study, using the structural theory of thermo–economics, in order to determine the optimum operating temperatures and evaluate performance of a single effect water–LiBr VARS where they considered the annual cost of system operation as the single objective function. For a 20 kW system, the optimum heat exchanger areas with corresponding system component temperatures were also determined. They used structural method where exergy losses in a component were correlated with the heat exchanger's area and the cost.

Gebreslassie et al. [101] developed a bi–criteria stochastic non linear programming (NLP) model interfacing with general algebraic modelling system (GAMS) and CONOPT to minimize the total capital cost, running cost, and the overall financial risk associated with operating of a single effect aqua ammonia (NH₃–H₂O) VARS. They used a set of Pareto optimal solutions to meet the objectives. By minimizing the total heat exchange area of the VARS, they also presented the variation for capital cost, expected operating cost, COP and downward financial risk. Through a case study, they explained the robustness of the proposed modelling and optimization of the absorption system. The main objective of this work was to identify the optimum operating and design parameters such that the system design becomes less susceptible to energy cost variation at different thermodynamic states irrespective of the risk of failures.

Gebreslassie et al. [102] further presented a bi-criteria NLP method for a single-effect H₂O–LiBr VARS to minimize the environmental impact caused by the component's higher temperature. They optimized the heat exchanger area of the system components which were invariable to the loss of exergy to the environment. Life cycle assessment (LCA) tool was used to measure the environmental impact of the single-effect H₂O–LiBr system.

Maya et al. [103] also presented a NLP based optimization of a single effect H₂O–LiBr VARS where the annual operating cost was minimized as objective function. The VARS component temperatures and the effectiveness of SHE were the decision variables in their optimization problem. Exergy based thermodynamic modeling, thermo economic model and formulation of inequality constraints were the key behind this study. The optimal solutions were obtained by using the CONOPT solver, which according to the authors, was suitable for the NLP based optimization problem. One important observation which they could make from this study was that the total system irreversibility was significantly high even at the optimized condition which according to them was not favorable from exergy analysis point of view as it represents inefficient use of energy resources.

Parham et al. [104] however optimized the performance of a single effect H₂O – LiCl VARS by using EES software in which a direct search method was applied. The results showed that the COP of the H₂O–LiBr ARS at the optimum conditions was around 1.5–2% higher than that of H₂O–LiCl ARS.

Mazzei et al. [105] also used a NLP based model to determine the optimal operating conditions and the total heat transfer area of the heat exchangers of a single effect H₂O–LiBr VARS. Two objective functions were involved in the optimization where (i) the COP was maximized against fixed total heat transfer area of the heat exchangers and (ii) the total heat transfer area was minimized for a fixed cooling capacity. The presented model was an equation-oriented optimization model with the capacity to obtain optimized results simultaneously with operating condition as well as with sizing of heat transfer area in every system component.

Mussati [106] also, based on a NLP model, optimized the sizes and operating conditions of the process units of a single-effect H₂O–LiBr VARS by minimizing three

single objective functions: the total exergy loss rate, the total heat transfer area and the total annual cost of the system. For cost optimization, he obtained the upper and lower bounds of the decision parameters respectively from the optimal solutions corresponding to minimization of the total exergy loss rate and minimization of heat transfer area.

Cimsit et al. [107] used a non-linear simplex direct search method for optimizing a R134a/water-LiBr based compression absorption cascade refrigeration system (CACRS) in which the compression system refrigerant that condenses in the cascade condenser is the heat source for refrigerant evaporation in the VARS. In this study, thermo economic optimization was done to find the optimum operating temperatures at VARS and VCRS components, SHE effectiveness and isentropic efficiency of the compressor. The following works are somewhat related to optimization of double effect H₂O-LiBr VARS.

Azhar and Altamush [108] optimized the components' operating temperatures of single, double (series flow) and triple effect H₂O-LiBr VARSs to maximize COP and minimize consumption of liquefied petroleum and compressed natural gas. Since, HPG and LPG temperatures have a direct impact on system performance, therefore, the optimization of the double effect VARS was done in two steps. First, the maximum COPs were determined by varying the HPG temperature for some selected temperature values in the high pressure condenser (HPC). After identifying the corresponding values of optimum HPG temperatures, next the HPC temperatures were varied to find the optimum HPC temperature and the maximum COPs at various evaporator temperatures. The maximum COP values and corresponding optimized HPG temperatures obtained from the first step were re-plotted to determine the optimum generator (HPG and LPG) temperatures in the second step of optimization corresponding to the maximum of the maximum COPs. It was considered that the HPC and LPG temperatures were close to each other. Similarly, for the triple effect system, the optimization was carried out in three steps. Mainly they followed an iterative method of optimization to determine the optimum generator temperature for the single effect system. In the double effect system, two condensers (low and high pressure) were used and the optimum LPG, HPC and HPG temperatures were determined for various cases of fixed evaporator, absorber and low pressure condenser temperatures.

Mussati et al. [109] used an NLP based approach to minimize the total annual cost of a double effect series flow type H₂O–LiBr VARS and proposed a new configuration by eliminating the low temperature solution heat exchanger (LTSHE) from the double effect series flow VARS. This way, for the optimized new configuration, they could reduce the total annual cost, the capital and the operating expenditures by around 9.5%, 11.1% and 4.9%, respectively.

Shirazi et al. [110] presented multi-objective optimization of solar powered single, double and triple effect water–LiBr absorption chillers driven by evacuated tube collectors (ETCs), evacuated flat plate collectors (EFPCs), and concentrating parabolic trough collectors (PTCs). First the systems simulation models were developed using TRNSYS which were then coupled with MATLAB to use its genetic algorithm (GA) based optimization toolbox. During the optimization, the solar collector specific area, storage tank specific volume, collector slope, solar pump nominal flow rate, and collector set-point temperature during summer and wintertime were selected as design variables for simultaneous minimization of the primary energy consumption and the levelized total annual cost. As such, this optimization study was mainly related to optimization of solar collector geometry and not the ARS operating parameters.

2.11 Summary of the Review

From the literature review, it was seen that lot of thermodynamic studies have been performed on different VARS configurations starting from half effect to triple effect system with conventional and alternate working solutions. Thermodynamic analysis is usually carried out from two aspects either by using the first law based energy analysis or the second law based exergy analysis. As far as VARS is concerned, energy analysis mainly deals with evaluation of VARS COP and thermal loads in the VARS components. Often parametric analysis is done to evaluate the effects of components' temperatures and other operating parameters on VARS performance with the help of energy analysis. Energy analysis, although it helps but often it is considered insufficient when it comes to evaluation of irreversible losses that occur in different system components. Energy analysis does not provide the designer the best insight into the system's operation. Therefore, exergy analysis based on second law is needed if someone desires to evaluate the source of inefficiency and irreversible losses occurring in various system components. Any attempt to reduce system irreversibility would result

in better performance through efficient utilization of energy resources. Therefore, to reduce irreversibility, it is necessary to quantify them through exergy analysis as it offers the system designers a plenty of scope for improvement of system operations [111].

Since VARS performance is directly linked with the heat source and the components' operating temperatures, therefore, an exergy based parametric analysis is required to provide more details about the effect of operating parameters on exergetic performances (exergy efficiency and irreversible losses) of VARS compared to what is not possible with the first law based energy analysis. Exergy analysis also helps to detect sources of exergy destructions and propose methods for reduction of exergy destruction.

From the literature review on exergy analysis of single and multi-effect VARS configurations, it was found that a significant amount of exergy destruction occurs in the generator and the absorber of a VARS. In some studies, the absorber was found to be the major contributor to irreversibility while in some other studies; the generator was producing the most of the exergy destruction. Therefore, the exergy destruction associated with the VARS components is purely a subject of what we consider for analysis; the system configuration, the heat source temperature and the other operating conditions.

Further, the performance of a VARS is fully dependent on the working fluid used in the cooling system. Particularly, when it comes to salt solution based VARS, the crystallization is an important phenomenon that must be paid due attention. Moreover, the crystallization characteristics of various salt solutions are different and hence, one system which is suitable for a particular range of operating conditions may not be suitable at other operating conditions of temperatures. The maximum salt concentration in the solution is vital in this regard.

H₂O–LiCl is a potential working fluid pair that can be used in VARS for chilling or air conditioning application. In so far as H₂O–LiCl is concerned, not much articles were found in the literature and as such, research studies on H₂O–LiCl based VARS performance analysis are limited. Few studies on single effect H₂O–LiCl VARS are however available and these studies based on energy analysis have confirmed better system performance in respect of H₂O–LiCl based VARS compared to H₂O–LiBr under identical operating conditions.

Further it was seen that exergy analysis of H₂O–LiBr and NH₃–H₂O VARS has been performed and also available in the literature. But, exergy analysis of single effect H₂O–LiCl VARS was neither available nor it was investigated before to evaluate H₂O–LiCl VARS exergetic performance analyzing the effect of operating temperatures on exergy destruction of each individual components or the overall VARS as a whole prior to our research works presented in this thesis.

Further, from literature survey, it was also found that double effect H₂O–LiBr absorption refrigeration systems have been analyzed in various studies and a good number of research articles on performance analysis of double effect H₂O–LiBr systems are available in the literature. Increased system performance at higher LPG and lower HPG temperature; superior performance of the double effect parallel and reverse parallel flow configurations with lower crystallization possibility, greater sensitivity of the parallel flow system performance to evaporator temperature compared to condenser and absorber temperatures variation; increased crystallization possibility in the series flow configuration at higher HPG and evaporator temperatures; increased crystallization possibility in the series flow configuration at low condenser and absorber temperatures; existence of optimum HPG and LPG temperatures at fixed evaporator, condenser and absorber temperatures are some of the major findings from these previous studies related to double effect H₂O–LiBr absorption refrigeration systems. However, as far as H₂O–LiCl working solution pair is concerned, no research article was found in the literature related to thermodynamic performance evaluation and comparison of H₂O–LiCl based double effect series, parallel and reverses parallel systems, neither from energetic nor from exergetic point of view. In the literature, enough studies related to double effect VARS performance analysis operated with H₂O–LiCl solution pair was not found except a few articles where it was done separately for the series and parallel flow configurations. As such, the double effect series, parallel and reverse parallel VARS configurations were never compared earlier with H₂O–LiCl solution pair and thus, detail analysis is not available. Certainly, the effect of operating parameters on maximum allowable LiCl mass concentration limit (to avoid crystallization) and also on performance of double effect H₂O–LiCl absorption refrigeration systems would be different and this requires a detail investigation.

From literature survey, not many research articles were found related to thermodynamic optimization of double effect VARS. Only in a single article [108], it was attempted to optimize the operating parameters of the H₂O-LiBr operated double effect series flow type VARS configuration, following a totally different approach (two step) and not by using any evolutionary based optimization. Some thermo economic optimization studies are however available and most of these were mainly related to single effect H₂O-LiBr VARS where conventional optimization techniques were used. Conventional gradient based optimization methods such as NLP, simplex search, conjugate gradient method etc. are not suitable for optimizing engineering problems dealing with conflicting objectives. In this regard, evolutionary based search algorithms such as genetic algorithm (GA) are more useful compared to the conventional gradient based search methods.

2.12 Scope of the present work

To address the knowledge gap regarding non availability of results corresponding to (i) exergy analysis of H₂O-LiCl operated single effect VARS configuration, (ii) exergy analysis and optimization of double effect H₂O-LiCl VARS configurations (series, parallel and reverse parallel), the following methodology is adopted in this research study. First, a single effect VARS is considered for exergy analysis with H₂O-LiCl as a working solution. Exergetic efficiency and component irreversibility of the H₂O-LiCl VARS are evaluated with the help of a MATLAB code and presented along with the energy based performance. Since the crystallization characteristics of a particular aqueous salt solution in a VARS are governed by its component operating temperatures, therefore, a VARS designer cannot choose the component operating temperatures arbitrarily. The formulations for thermodynamic properties of H₂O-LiCl solutions are usually valid for the composition range from pure water to 50 wt. %. All combinations of operating temperatures don't fulfill this criterion of maximum solution concentration $\leq 50\%$. Therefore to avoid this problem, a differential evolution (DE) based inverse method is used to estimate the generator, condenser, evaporator and absorber temperatures in this thesis considering the maximum solution concentration below 50% as objective function. Total 34 combinational temperatures are obtained and for each of these combinations the VARS energetic and exergetic performance results are presented. Parametric analysis is performed to show performance variation with component

temperatures. A performance comparison between H₂O–LiCl and H₂O–LiBr systems is also provided under identical conditions.

Next, the series, parallel and reverse parallel flow configurations of double effect H₂O–LiCl absorption refrigeration systems are considered to analyze and compare their performance based on energy analysis. A new set of thermodynamic property relations, which are valid for maximum up to 50% wt. concentration of H₂O–LiCl solutions, is considered. A parametric analysis is carried out to show energetic performance variation of the series, parallel and reverse parallel flow configurations of double effect H₂O–LiCl VARS with LPG and HPG temperatures against fixed evaporator, condenser and absorber temperatures. The effect of distribution ratio on performance the double effect parallel and reverse parallel flow systems is also investigated. Further, the performances of the double effect H₂O–LiCl systems are compared with their counterparts operated with H₂O–LiBr pair under identical operating conditions. Details regarding energetic performance of double H₂O–LiCl VARS configurations and their operational difference with corresponding double effect H₂O–LiBr VARS configurations are also highlighted in this thesis.

In order to find the complete details regarding performance of double effect H₂O–LiCl VARS configurations, additionally, the exergy analysis is also carried out. In the exergy based parametric analysis, the effects of component temperatures on exergetic performance of the series, parallel and reverse parallel flow configurations of double effect H₂O–LiCl VARS are evaluated. Further, the exergetic performances of the H₂O–LiCl based double effect series, parallel and reverse parallel systems are compared with their H₂O–LiBr counterparts under identical operating conditions.

In a next attempt, a GA based multi-objective optimization is performed on the double effect series and parallel configurations in order to find out the optimum performance of the two system configurations and also to provide a comparative assessment between H₂O–LiCl and H₂O–LiBr based systems at the optimized operating conditions. For the multi-objective optimization, the system's COP, exergy efficiency and the total irreversibility are taken as objective functions. In the series configuration, the HPG and LPG temperatures are considered as decision variables while for the parallel configuration, additionally the distribution ratio is also considered as a decision variable. The optimal combinations of HPG and LPG temperatures and distribution ratio

are determined for four different cases of fixed evaporator and condenser (also equal absorber) temperatures and presented along with the optimized performance parameters (COP, exergy efficiency and total irreversibility).

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