CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Development of new thermodynamic systems and their analysis is important in research as it contributes to new knowledge and helps in finding means for efficient utilization of energy sources. This is possible only through identification of research gap in a specific research area and for that purpose, review and evaluation of previous research studies is extremely important. In this context, it can be mentioned that a number of thermodynamic analyses on VARS is available in the literature. These are mainly related to performance analysis of VARS with various working fluid pairs either with computer based simulation techniques or with the help of experiments. In most of these thermodynamic analyses, focus is made on evaluating the effect of operating conditions on performance of individual components and the overall VARS. Moreover, each analysis is different from the other in some aspect or the other, either in terms of the configuration or the method of analysis. Say for example, there are studies which report on VARS performance using energy analysis where, mainly the COP is evaluated and sometimes, the effects of the component temperatures on COP are investigated through parametric study. But, a VARS can also be analyzed with the help of exergy because exergy is the most appropriate method for comparing VARS performance with different sources of heat for the generator, because depending upon the temperature of the heat source, the quality of energy input will be different and under such situation, the exergetic efficiency will give a better insight into the system operation rather than the COP. The analysis can also be different from the VARS configuration point of view, depending on whether the investigated system is a single effect or multi effect type. Another important aspect of VARS analysis is the source of heat which could be hot water, high pressure steam, waste heat stream or non–conventional solar and geothermal energy sources. There are some studies which consider both the topping power/heat engine cycle and bottoming VARS in calculating the various thermodynamic performance parameters.

Similarly, there are studies which are related to thermodynamic analysis of ST based VPC or some location specific existing steam power plants operating on various fuels such as coal, heavy fuel oil and natural gas etc. Some are related only to energy analysis while in some other studies, energy and exergy analyses are performed together. In some studies, parametric analysis is done to investigate the effect of operating parameters on power, efficiency and irreversible losses of the plant.

In this chapter, focus is made on review of the absorption cooling system and vapor power cycle (VPC) based power systems separately and also on the review of CPC systems with different heat sources. The previous works related to thermodynamic analysis of absorption cooling systems, VPC based power systems and CPC systems are reviewed in detail in this chapter.

2.2 Heat driven vapor absorption refrigeration system

Increased concern for global warming and environment has stimulated active research interest in the development of VARS as an alternative to the VCRS. VARS is a heat driven cooling system that uses a refrigerant absorbent pair as its working fluid. It can avoid the use of CFCs which are major source of greenhouse gasses with large ODP. Thus, VARS helps reducing the emissions of greenhouse gasses such as CO_2 [1].However, its COP is low compared to VCRS although higher COP can be achieved through usage of double and multi effect VARS. Trygg and Amiri [2] made a comparison between vapor compression and absorption chillers for energy utility in district cooling and Swedish municipality industries. They found absorption cooling a cost effective energy system without any negative impact of its lower COP (due to increased electricity production) which also reduce global emissions of CO_2 significantly.

2.2.1 Working fluid pairs of refrigerant and absorbent/mixture of absorbent

NH_3–$H_2O$and H_2O–LiBr solution pairs are the most widely used working fluid pairs in VARS. Aqua ammonia VARS requires more heat recovery means and components such as analyzer, rectifier etc. that adds to the system complexity. Moreover, corrosion occurs in the system when copper is used and there is danger of fire with ammonia in concentration of 25% (by volume) in air. On the other hand, H_2O–LiBr bromide VARS is predominantly used for air conditioning application and it performs better than aqua ammonia system.

Many other pair of solutions have also been investigated as possible alternatives to NH_3–H_2O and H_2O–LiBr which include Acetone–zinc bromide[3], water–

monomethylamine [4], water–potassium formate [5], water– [lithium bromide+potassiumformate] [6], ammonia–lithium nitrate [7], ammonia–sodium thiocyanate [7], methanol–lithium bromide [8], methanol–lithium chloride [9], R134a–dimethyl acetamide [10], water–[lithium bromide + lithium chloride + Zinc chloride] combination [11]; Water–[lithium bromide + potassium formate + sodium formate + potassium acetate and sodium lactate] [12] etc. H_2O–LiBr and NH_3–H_2O pairs are still considered the best for use in VARS [13].

Ajib and Karno [3] measured and analyzed the thermo–physical properties such as vapor pressure, density, viscosity, specific heat capacity, specific electrical resistance and specific enthalpy of acetone–zinc bromide solution for using as working fluid in absorption refrigeration machine. Based on experimental data, equations and state diagrams for the solution were presented correlating pressure and temperature and enthalpy and temperature separately. Pressure–enthalpy correlation and diagram were also obtained for pure acetone as refrigerant. They indicated that the acetone–zinc bromide solution could be a suitable working solution for absorption refrigeration machine at low temperature.

In an experimental study, Riffat et al. [5] compared the absorption and desorption characteristics of a water–potassium formate (H_2O–CHO_2K) and H_2O–LiBr mixtures where they observed higher desorption rates in case of H_2O–CHO_2K binary mixture. Higher desorption rate helps in lowering the generator heat requirement and improving efficiency of absorption cycle. It was also reported that the production cost of H_2O–CHO_2K was less and H_2O–CHO_2K is less corrosive and more acceptable ecologically than H_2O–LiBr.

Ferreira [7] presented thermodynamic and physical property data equations for ammonia–lithium nitrate (NH_3−$LiNO_3$) and ammonia–sodium thiocyanate (NH_3−NaSCN) solutions for use in computer program. The equations were developed with the objectives of using them in performing thermodynamic and economic cycle calculations for absorption refrigeration systems with NH_3−$LiNO_3$ and NH_3−NaSCN solutions as working fluids.

Safarov [8] reported properties (pressure, density and temperature) of methanol–lithium bromide (CH_3OH−LiBr) while carrying out experiments in a constant volume piezometer over a wide range of temperature (298.15 K to 398.15 K) and pressure (1 atm. to 60 MPa) at 0.08421, 0.13617, 0.19692, 0.23133 and 0.26891 mole fractions. An equation of state was derived for$CH_3OH-LiBr$ solution from the experimental results providing a theoretical analysis of the equation. Use of $CH_3OH-LiBr$ enables one to replace aqueous solutions at temperatures below the freezing point of water. Moreover, the viscosity of $CH_3OH-LiBr$ was lower than H_2O–LiBr solution. The advantage with $CH_3OH$is that it has high vaporization temperature and low density, low heat capacity and low freezing temperature.

Safarov [9] further reported vapor pressure of $CH_3OH-LiBr$ and $CH_3OH-LiCl$ solutions at various temperatures in the range from 298.15–323.15K and evaluated the osmotic and activity coefficients and the activity of the solvent. He carried out experiments for $CH_3OH-LiBr$ solutions in the molality range from 0.22 to 11.515 mol/kg and for $CH_3OH-LiCl$ solutions in the molality range from 0.34–6.176 mol/kg.

It was thus seen that, often empirical property relations are developed by researchers based on experimental results. This is mainly done to develop equations for calculating thermodynamic and physical properties of different binary mixtures with reasonable accuracy. A usual practice in research is that many such empirical equations are used in modelling VARS with these binary mixtures as working fluids.

2.2.2 VARS performance analysis with various solution pairs

Karamangil et al. [1] examined the performance of a VARS using H_2O–LiBr, NH_3–H_2O, NH_3–$LiNO_3$ solution pairs separately. They investigated the effects of operating temperatures, the effectiveness of solution, refrigerant and solution–refrigerant heat exchangers (SHE, RHE, SRHE) on performance using a developed software package. The system with the H_2O–LiBr mixture showed higher COP values compared to the systems using ammonia based mixtures. However, range of the generator temperatures was reported to be narrow for H_2O–LiBr based system due to crystallization of the LiBr solution. NH_3–$LiNO_3$ solution was found to be more suitable at low generator temperatures.

Pilatowskyet al. [4] theoretically analyzed a single–stage VARS using mono–methylamine–water (CH_3NH_2–H_2O) solution while evaluating its COP at low generator temperatures in the range of 60–80°Cfor application in food product preservation and rural air conditioning using solar absorption cycles. In CH_3NH_2–H_2O VARS, $CH_3NH_2$is the refrigerant and $H_2O$is the absorbent, therefore cooling below 0°C is possible, however, rectification of vapor produced in the generator is a usual problem.

Lucas et al. [6] mixed LiBr and CHO_2Kin a proportion of 2:1 (by mass) to use it as absorbent in place of LiBr to simulate the performance of a single stage absorption refrigeration cycle theoretically from empirical data and compare with the performance of H_2O–LiBr system. The lower heat of dilution was reported to be the advantage of the new absorbent mixture as it reduced the thermal loads in the generator and absorber. Higher efficiency of the absorption cycle was possible with this new absorbent mixture at generator temperature as low as 55°C. In another study, Lucas et al. [14] studied the effect of addition of a surfactant (n–octanol) in the solutions as a means to improve the absorption capacity of LiBr and CHO_2K mixture.

Muthu etal. [10] presented experimental study in a VARS of 1 kW capacity using R134a–N, N–dimethyl acetamide(DMAC) as working fluid. The system was designed and tested for various operating conditions using hot water as heat source. In this work, performance of the fabricated system was evaluated with respect to various operating parameters such as heat source, condenser, absorber and evaporator temperatures. The results indicated that the system attained steady state in two hours with a heat input of 4 kW at sink and source temperatures of 30°C and 80°C respectively. COP was obtained in the range of 0.25–0.45 under the tested conditions. The study also revealed the feasibility of using R134a–DMAC as working fluid in the absorption machine using low potential heat sources for various applications.

Saravanan and Maiya [11] carried out thermodynamic analysis of water based 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+$C_2H_6O_2$),(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+$CaCl_2$+$Zn(NO_3)_2$), (4.2:2.7:1)] with the help of computer simulation. Variations of performance parameters (cut–off temperature, circulation ratio, COP and efficiency ratio) of these aqueous solutions were compared with operating temperatures (generator, evaporator, condenser and absorber temperatures) and heat exchanger effectiveness as parameters.

Donate et al. [12] evaluated mixtures of lithium bromide and organic salts of sodium and potassium (formate, acetate and lactate) as alternative absorbents for absorption refrigeration machines. The main objective was to overcome the limitations of lithium bromide and improve the characteristics and the efficiency of the refrigeration cycle. In order to select the mixture that presents better properties for its employment in absorption refrigeration cycles, a thermodynamic analysis was done. Density, viscosity, enthalpies of dilution, solubility and vapour pressure data of the proposed mixtures were measured. A simulation program was developed to evaluate temperatures, heats exchanged in the different sections and the efficiency of the absorption cycle.

Kaynakli and Kilic [15] made a thermodynamic analysis of the H_2O–LiBr absorption refrigeration cycle evaluating the influences of generator, evaporator, condenser and absorber temperatures and effectiveness of heat exchanger on the thermal loads of various components and coefficients of performance. VARS performance improves with increasing generator and evaporator temperatures, while it reduces with increasing condenser and absorber temperatures. SHE affects the system performance more than the RHE and SRHE.

Joudi and Lafta [16] developed a computer model based on mass and energy balance for studying the effect of operating conditions on performance of individual components and the overall VARS that uses H_2O–LiBr as working pair and hot water as the source of heat for water vapor generation. They developed a new model specifically for the absorber considering simultaneous heat and mass transfer instead of only heat transfer.

2.2.3 Second law (exergy) analysis of VARS

Exergy analysis is often carried out for evaluating performance of complex thermodynamic systems. Some complications of energy resource utilization which is not possible to evaluate though first law based energy analysis can be done through exergy analysis. Exergy analysis of single effect, double effect and triple effect VARS has been performed in many studies. These are categorically discussed in sections 2.2.3.1 and 2.2.3.2.

2.2.3.1 Exergy analysis of single effect VARS

Talbi and Agnew [17] carried out an exergy analysis on a single–effect H_2O–LiBr VARS to determine the exergy losses in each system component. They found that the absorber was the most crucial component with a maximum contribution of 59.06% of total exergy loss followed by the generator with a contribution of 27.02%. They also highlighted on possible means of reducing exergy losses in these two vital system components in their analysis.

Lee and Sherif [18] analyzed a single effect H_2O–LiBr system on the basis of first and second law of thermodynamics while determining the system COP and exergetic efficiency under different operating conditions of heat source, cooling water, chilled water, and supply hot water temperatures. The system was considered for both building cooling and heating purpose with production of (i) chilled water in the evaporator for cooling and (ii) hot water by simultaneous heating of water in the absorber and condenser respectively. From the parametric analysis of the system designed for cooling, it was found that the system COP and exergetic efficiency are high at low cooling water temperature. Higher COP was also obtained at high chilled water temperature but the exergetic efficiency was low. Further, it was observed that COP initially increases with increasing heat source temperature up to a certain threshold value and beyond the limit, it again starts decreasing. This negative effect was more noticeable for the exergetic efficiency. Using the same system for heating purpose, they found COP and the exergetic efficiency both increasing with heat source temperature but simultaneously the risk of crystallization also increases. Further they observed that at low ambient temperature, the system is not suitable for heating due to low performance and freezing problem, hence, recommended use of the heat source stream for direct space heating without operating the absorption system.

Sencan et al. [19] also made a similar analysis on a single effect H_2O–LiBr system. They also found both cooling and heating COP slightly increasing with heat source temperature. Similarly, the exergetic efficiency was found decreasing with heat source temperature in both cooling and heating applications. It was also observed that the condenser and evaporator heat loads and exergy losses are less than those of the generator and absorber.

Kilic and Kaynakli [20] analyzed the energetic and exergetic performance of a single–stage H_2O–LiBr absorption refrigeration system. They observed better system performance at higher generator and evaporator temperatures, while the system performance deteriorates at higher condenser and absorber temperatures. In their analysis they found the generator producing the highest exergy loss.

2.2.3.2 Exergy analysis of double/triple effect VARS

Xu and Dai [21] carried out thermodynamic analysis to study the effect of design parameters including heat–recovery ratio, circulation ratio and distribution ratio on performance of a parallel flow type H_2O–LiBr based double–effect absorption chiller. They found higher COP with high distribution ratio and high heat–recovery ratios in the high and low temperature heat exchanger. COP however decreased with solution circulation ratio.

Arun et al.[22] analyzed the performance of a double effect parallel flow H_2O–LiBr ARS on the basis of LPG equilibrium temperature while comparing the COP and its sensitivity to operating conditions with those of a double effect series flow system. It was found that throughout the operating conditions, the maximum attainable COP was more for the parallel flow system. Further it was observed that the COP of the parallel flow system was more sensitive to evaporator temperature compared to condenser and absorber temperatures variation. The impact of external heat input to the LPG was also found more in the parallel flow system than the series flow system.

Jiang et al. [23] compared COP and the cyclic characteristics of a small double effect ARS with a three–pressure absorption–ejector hybrid refrigeration system (AEHRS) through presentation of thermo–economic models of the two systems. The thermo–economic performance of the two systems in two running modes (600 and 1000 h per year) was calculated using waste heat and natural gas fuel as heat source. The COP of the three–pressure AEHRS was found in the range of 0.9–1.0 and this was slightly lower than that of the double effect VARS. It was found that the annual total cost of the two systems is dependent on the primary investment, depreciation and the annual interest rate and it was less for the three–pressure AEHRS compared to that of the double–effect VARS.

Adewusi and Zubair [24] analyzed the performance of one single–stage and one two–stage NH_3–H_2O absorption refrigeration system on the basis of second law of thermodynamics to evaluate entropy generation of various system components. They found higher COP for the two stage system, however, the total entropy generation was more. Usually, when a higher COP is achieved at some operating conditions, it is also expected that the system's total entropy generation should also be less. So, this contradiction was explained with respect to the performance results of both the single and two–stage systems. Further investigation was done to evaluate the effect of heat exchanger effectiveness and components' operating temperatures on performance of both the systems.

Manohar et al. [25] developed an artificial neural network (ANN) model based on feed forward back propagation learning algorithm to predict performance of a steam driven double effect series flow type H_2O–LiBr absorption chiller. First the network was trained with experimental data of one year and then testing was done to predict the chiller performance based on the chilled water inlet and outlet temperatures, cooling water inlet and outlet temperatures and steam pressure. The results showed that the ANN model was quite successful in predicting the chiller performance quite accurately within ±1.2% of the actual values.

Gomri and Hakimi [26] presented exergy analysis of a double effect H_2O–LiBr absorption refrigeration system. They developed a new set of formulations of thermodynamic properties of H_2O–LiBr solution and calculated the COP, the exergy losses and the number of exergy of each system component. Number of exergy is a parameter defined as the ratio between exergy destroyed and exergy supplied. The absorber and the high pressure generator (HPG) were found to be major contributor to the total exergy destruction of the double effect refrigeration system. Further it was found that system performance increased with increasing low pressure generator (LPG) temperature, while it decreased with increasing high pressure generator (HPG) temperature.

Figueredo et al. [27] developed a thermodynamic model to analyze the behavior of a double–stage H_2O–LiBr absorption chiller of 200 kW cooling capacity driven by heat source at 170°C from natural gas. The system was also analyzed as a single stage chiller driven by heat source at 90°C from solar energy and in combined mode at both the temperatures simultaneously. In winter, the system operates in double–lift mode for heating.

Gomri [28] presented the exergy analysis of the triple–effect H_2O–LiBr absorption refrigerating system evaluating COP, exergetic efficiency, exergy losses and the number of exergy of each component of the system. Triple–effect chillers perform better than the double–effect chillers, however they require higher operating temperatures which can sometimes limit the choices of materials and refrigerant/absorbent pairs. He further observed that the effect of LPG temperature was more prominent than the temperature of the medium pressure generator (MPG) at fixed HPG temperature. Moreover, it was not possible to operate the system at all LPG temperatures, there was a range which was totally dependent upon the selection of the MPG temperature.

Shin et al. [29] developed a model to simulate the dynamic performance of a double effect H_2O–LiBr absorption chiller and validated the model results with the test data of a commercial medium chiller. Dynamic behavior of the system components was modeled using first–order nonlinear differential equations based on heat and mass balances and solving them numerically together with calculation of thermodynamic properties of H_2O–LiBr solution. At a given constant heat input, they found that the chiller dynamics is mainly controlled by the cooling water and the chilled water inlet temperatures. With step change in the load at fixed cooling water and the chilled water inlet temperatures, they observed a 15 minute response time for the chilled water exit temperature which they attributed to the thermal capacities of the chiller. Further as a means of improvement in performance control and anti–crystallization, they recommended for use of dilution cycle which is activated when the chilled water exit temperature falls below 4°C by turning off the fuel gas valve and normal operation of the other pumps and valves.

Kaushik and Arora [30] performed energy and exergy analysis to compare performance of a single and a double effect (series flow type) H_2O–LiBr ARS through parametric variation of component temperatures, pressure drop between evaporator and absorber, and effectiveness of heat exchangers. The COP of the double effect system was found in the range of 1–1.28 compared to 0.6–0.75 of the single effect system. In both the single and double effect systems, absorber produced the highest irreversibility. It was shown that the single and double effect systems have an optimum generator temperature at which the COP and exergetic efficiency are maximum. COP and exergetic efficiency of the two systems were found higher at low absorber temperature. With increase in evaporator temperature, COP showed an increasing trend while the exergetic efficiency reduced.

Gomri [31] made a comparative study between single and double effect absorption refrigeration systems with identical cooling load. Simulation results were used to study the influence of the various operating parameters on COP, components' thermal loads, exergetic efficiency and the total change in exergy of the two systems. The COP of double effect system was found approximately twice the COP of the single effect system but the exergetic efficiency of double effect system was only slightly higher than that of the single effect system. It was also found that for each condenser and evaporator temperature, there is an optimum generator temperature at which the COP and exergetic efficiency of the single and double effect systems are maximum and total change in exergy is minimum.

In another study, Gomri [32] compared performances of single, double and triple effect absorption cooling cycles operating under the same cooling load of 300 kW. Simulation was done to study the influence of various operating parameters on COP and exergetic efficiency. It was concluded that the COPs of the double and triple effect systems are almost two and three times more than that of the single effect system. The exergetic efficiency of the double and triple effect systems were also slightly higher. It was again found that there exists an optimum generator temperature corresponding to each condenser and evaporator temperature, at which the systems produce maximum COP and exergy efficiency.

Gebreslassie et al.[33] conducted exergy analysis for single, double, triple and half effect H_2O–LiBr absorption refrigeration cycles while evaluating the COP, exergetic efficiency and the exergy destruction rates of each cycle with changing heat source temperature. The COP was the highest for the triple effect cycle while the exergetic efficiency was not much different among the other configurations. The effect of heat source temperature on exergy destruction rates was found similar for the same type of components in all the cycles, while the values were quantitatively different for the cycles with different configuration. They observed higher exergy destruction in the absorbers and generators, especially at higher heat source temperature.

Yin et al. [34] developed the design of a double effect steam driven H_2O–LiBr chiller model to predict steady state performance of the chiller through refinement of model results using measured test data of a 16 kW water–LiBr double–effect absorption chiller under various conditions. They further opined that the model based design of an individual absorption chiller can be later be expanded to overall building cooling, heating and power (BCHP) systems. They also emphasized on possibility of developing an integrated design and control strategy for maximizing the overall efficiency and minimizing capital and maintenance costs of the BCHP systems.

Farshi et al. [35] developed a computational model to study the effects of operating parameters on crystallization phenomena in three classes of double effect H_2O–LiBr ARSs (series, parallel and reverse parallel) with identical refrigeration capacities. It was found that the crystallization possibility increases in the series flow configuration, with increasing temperature in the HPG, evaporator and low temperature heat exchanger. Crystallization possibility was also found to be more at low condenser and absorber temperatures. It was shown that compared to series flow system, the crystallization possibility is low in the parallel and the reverse parallel configurations with wide range of operating conditions without crystallization risks.

Farshi et al. [36], in another study, again compared three classes of double–effect H_2O–LiBr ARSs evaluating the influence of various operating parameters on first and second law performance characteristics of the systems. The advantages and disadvantages of different configurations of double–effect H_2O–LiBr ARSs were found out in terms of the performance variation corresponding to changes in (i) effectiveness of the solution heat exchangers, (ii) pressure drops between the evaporator and the absorber and (iii) pressure drops between the LPG and the condenser, and (iv) external heat supplied to the LPG.

Farshi et al. [37] carried out an exergo–economic analysis to differentiate three classes of water–LiBr double effect ARSs (series, parallel and reverse parallel) while investigating the influence of various operating parameters on product cost flow rates and total investment costs. They concluded that the total investment costs and the product cost flow rates of the system configurations and their selection mainly depends upon the operating conditions. The total investment costs were found low for all the three systems at high HPG and evaporator temperature. Low total investment cost was also obtained at low condenser temperature and low effectiveness of the solution heat exchanger. In all the three systems, the evaporator and the absorber were found to be the most expensive components.

Li and Liu [38] investigated the effect of generator heat load ratio (ratio of energy input between the high pressure and the low pressure generator) on COP and crystallization of series, pre–parallel, rear parallel and reverse parallel flow configuration of an air cooled water–LiBr double effect absorption chiller. They found that COP increases with decrease in heat load ratio while also the risk of crystallization increases.

2.2.4 Thermo–economic analysis and optimization of VARS

The works of Misra et al. [39–41] is about thermo–economic optimization of single and double effect H_2O–LiBr system and also the aqua–ammonia VARS. In Ref. [39], the thermo–economic theory was applied to a single effect H_2O–LiBr VARS for minimizing its overall operation and amortization cost. In article [40], the thermo–economic concept was used for optimization of a double–effect H_2O–LiBrVARS for minimizing its overall product cost. Next the thermo–economic concept was applied for optimization of an aqua–ammonia VARS for minimizing its overall product cost [41]. In these works, a simplified cost minimization methodology was used for the purpose of minimizing the overall system operating and product cost through formulation of exergo–economic cost balance equations. Effects of design variables on costs were thermo–economically evaluated for choosing the optimum values of the design variables for obtaining the cost effective system. Finally, an approximate optimum design configuration was obtained by means of sequential unit by unit local optimization of the system. Sensitivity analysis was also carried out to show that the changes in optimal values of the decision variables were negligible with changes in the fuel cost. The generator heat source, in all the three works, was considered as high–pressure steam.

Gebreslassie et al. [42] performed a non–linear programming based optimization study for minimization of the absorption chiller area and its operational impact on the environment based on global warming potential. The solution involves the selection of the best design from a set of design alternatives for the absorption cycles based on constraints and benefits of the given application.

2.3 Review on VCRS analysis with conventional and alternate refrigerants

Lot of researches has been done on VCRS using conventional and alternate refrigerants. The objective is to obtain better cooling performance with minimum contribution to ozone depletion and global warming. A good number of studies on VCRS performance analysis are available in the literature.

Dalkilic and Wongwises [43] made a theoretical performance study on a traditional VCRS with refrigerant mixtures of R134a, R152a, R32, R290, R1270, R600, and R600a in various proportions and compared their results with R12, R22, and R134a. They recommended blends of R290/R600a (40/60 by wt. %) and R290/R1270 (20/80 by wt. %) as alternatives for R12 and R22 respectively.

Padilla et al. [44] conducted experiments on a domestic refrigerator using R12 and R−413a refrigerants for comparative dynamic analysis of performance. The overall energy and exergy performance of the system working with R413A was found better than that of R12.

Sagia and Paignigiannis [45] carried out exergy analysis of a single stage VCR cycle with refrigerant mixtures R−404A, R−410A, R−410B and R−507 as working fluids providing detailed information on the variation of cycle's exergy efficiency with evaporating and condensing temperatures.

Sencan et al. [46] presented energy and exergy analysis to a VCR system for determining effects of sub−cooling and superheating with R134a, R407c and R410a as refrigerants.

Arora and Kaushik [47] presented a detailed exergy analysis of a VCR cycle for computing COP, exergy destruction, exergetic efficiency and efficiency defects for R502, R404A and R507A with evaporator and condenser temperatures in the range of −50 °C to 0 °C and 40 °C to 55°C respectively.

Wua et al. [48] has recently made an analysis studying the feasibility of replacing R134a with R161 in a small automobile air−conditioning unit. They first developed a theoretical model to predict the performance and later performed experiments in a single stage VCR unit with R134a and R161 as refrigerants to validate the theoretical results.

The results showed that the COP of the unit was more with R161 in the range of evaporator temperatures from −5°C to 10°C.

Many such investigations have been done to analyze performance of VCRS with existing and alternate refrigerants not only from the first law (energy) point of view but also on the basis of second law (exergy) of thermodynamics. Few more studies on VCRS are cited below. Qureshi et al. [49] studied experimentally the effects of employing a mechanical sub cooling cycle with a residential 1.5 ton simple VCRS with R22 refrigerant in the main cycle and R12 in the subcooling cycle. The results indicated improvement in evaporator cooling load (CL) and the cycle’s second law efficiency with the use of mechanical sub−cooling (5°C−8°C).

Llopis et al. [50] made performance comparison of R404A and R507A in the evaporating temperature range between −36°C and −20°C at a condenser temperature of 40°C in a double−stage VCR cycle with and without a subcooler. The plant efficiency was higher for R404A than R507A without subcooler, especially at high evaporating temperatures. However with the subcooler incorporated, the COP values with R404A and R507A were almost similar.

Bayrakci and Ozgur [51] presented on energetic and exergetic performance of a VCRS using pure HC refrigerants (R290, R600, R600a and R1270), R22 and R134a. COP, exergy efficiency and total irreversibility of the VCRS were evaluated as a function of evaporator temperatures (from −25°C to 0°C) at three different condenser temperatures viz. 30°C, 40°C and 50°C. COP and exergetic efficiency was found higher with R1270 and R600 than R600a and R290.

Kilicarslan [52] conducted experiments and also presented theoretical analysis of two single stage VCRSs separately and also analyzed a two stage cascade system connecting the two single stage systems. A single refrigerant R134a was used in the topping and bottoming cycle of the cascaded system.

Chesi at el. [53] used solar powered ejection machine to increase efficiency of a traditional vapor compression machine by subtracting heat from the condenser. A transient analysis was performed with climatic data taken from four different locations worldwide for evaluating the system benefits and highlighting issues related to system design and operation.

Gazda and Kozioł [54] proposed a hybrid refrigeration system (air blast−cryogenic freezing) comprising of air blast freezing system (based on single VCRS) and a cryogenic refrigeration system for supplying liquid nitrogen. Experiments were performed to evaluate the COP and primary energy ratio (PER) of the hybrid system. The difference between COP and PER is that PER takes into account the total energy consumption including energy consumed in the auxiliary equipment of the system. The COP of the hybrid system was 22% higher than the air blast system and while it was 3.6 times lower than the cryogenic system COP. As opposed to this, hybrid system PER was 1.8 times higher than that of the cryogenic system and 6 times lower than the PER of air blast system.

Comodi et al. [55] designed a vapor compression chiller operated with R507 refrigerant specifically for air cooling at inlet to the compressor of a 100 kW micro gas turbine. Gas turbine power output is very sensitive to inlet air temperature and their results indicated 8% electric power and 1.5% efficiency gain with reduction in inlet air temperature down to 15°C.

Ge et al. [56] integrated a tested 80 kW recuperated microturbine trigeneration system into a base energy system used in a supermarket of UK. The space conditioning in the base system uses a gas boiler for space heating and a CO_2 cascaded VCRS for space cooling. In the trigeneration system, the gas boiler and compression chiller of the base system are substituted with a waste heat boiler and absorption chiller respectively. High temperature micro turbine exhaust is first utilized in the waste heat boiler to provide hot water for space heating and then to drive the absorption chiller to produce chilled water for space cooling.

2.4 Review on combined absorption–compression refrigeration systems

New design concepts of combined absorption–compression refrigeration systems are also developed. One such combined system (CS) is proposed in Ref. [57] which is obtained by coupling a single stage VCRS and a single effect VARS in the cascade condenser where refrigerant (R22) vapor of the VCRS condenses and rejects heat to evaporate water of the H_2O−LiBr VARS. They also made comparative analysis based on first and second laws between the hybrid and the independent VCRS for the same CL of 66.67 kW and found significant improvement in performance with the hybrid system.

Han et al. [58] in his combined absorption–compression refrigeration system utilized waste heat of flue gas to generate high−temperature vapor from one stream of absorber leaving strong NH_3–H_2O solution which in the CS is split into two streams. The vapor is then used for power generation in a turbine that drives the compressor of the VCRS. Low temperature flue gas heat is further utilized in a low temperature heat exchanger to generate NH_3 vapor from the other stream of absorber leaving strong solution. The NH_3 vapor from the evaporator is also split into two streams; one stream goes into the absorber while the other stream is compressed in the VCRS compressor which then mixes with vapor stream coming from a rectifier and then condensed in the condenser. The rectifier receives exhaust vapor from the turbine, strong NH_3–H_2O solution from the low temperature heat exchanger and generates pure ammonia vapor and weak solution.

Zhao et al. [59] in an optimization study considered two such NH_3–H_2O combined absorption/compression refrigeration cycles with one and two solution circuits. The combined cycle with one solution circuit consists of gas engine exhaust driven absorption chiller, a condenser, an evaporator and a compressor which is also driven by the engine. In the combined cycle with two solution circuits, the condenser and evaporator of the one solution circuit combined cycle are replaced with a second absorber and a second generator. The study showed better performance in case of the combined cycle with two solution circuits.

Thus we come across several studies in the literature based on VCRS alone and also in the combined mode with VARS.

2.5 Review on comparative analysis of VCRS and VARS

Among all the refrigeration systems used in refrigeration and HVAC industry, VCR and VAR systems are the two principle types that are used in various cooling applications. VCRS uses high grade energy while VARS uses low grade thermal energy as driving force for refrigeration.

Trygg and Amiri [2] while comparing vapor compression and absorption chillers, found absorption cooling more cost effective for district cooling and Swedish municipality industries in spite of the low COP of the absorption chiller.

Elsafty and Daini [60] made a cost analysis to compare a vapor compression air−conditioning system with a solar powered H_2O−LiBr vapor absorption system (single and double−effect). The analysis was carried out on the basis of present worth value (PWV) and equivalent annual cost (EAC) methods. The PWV and EAC were found minimum in case of the double−effect vapor absorption system.

2.6 Thermodynamic analysis of VPC based steam power plants

Many research articles based on exergy analysis of thermal power plants have been published in the literature. Kaushik et al.[61] have discussed a good number of previous investigations done on exergy analysis of power plants covering both the ST based and the combined cycle power plants.

Oktay [62] presented exergy analysis of a power plant in Turkey using a fluidized bed boiler. Exergy efficiencies, irreversibility of plant components were determined and performance comparison was provided between the fluidized bed and conventional power plant.

Regulagadda et al. [63] conducted energy and exergy based parametric study in order to determine optimized parameters for a 32 MW power plant installed in Chennai, India. Parameters such as steam mass flow rate, BP, condenser pressure, steam temperature, reference temperature etc. were varied to investigate their effect on power and efficiency of the plant.

Habib and Zubair [64] examined the second law performance of a reheat–regenerative power plant. The reduction in the irreversible losses with the addition of backward, cascade–type feedwater heaters and/or a reheat option were compared with a conventional energy–balance approach. The results indicated that most of the irreversible losses occur in the boiler and these losses are significantly reduced after incorporation of feedwater heating. Feedwater heating resulted in 18% reduction in the exergy destruction rate of the cycle with corresponding improvement in efficiency by 12%. Further, total irreversibility reduced to 24% and efficiency increased to 14% by use of reheating.

Erdem et al. [65] presented comparative analysis of performance of coal (lignite) fired thermal power plants in Turkey from energetic and exergetic viewpoint. Thermodynamic simulation results were compared with the design values of the power plants in order to make comprehensive evaluations and identify the main sources of thermodynamic inefficiencies of each plant.

Sengupta et al. [66] carried out exergy analysis of a 210 MW coal–based thermal power plant at different operating conditions by splitting up the entire plant into three zones (1) only the turbo–generator with its inlets and outlets, (2) turbo–generator, condenser, feed pumps and the regenerative heaters, (3) the entire cycle with boiler, turbo–generator, condenser, feed pumps, regenerative heaters and the plant auxiliaries for determining irreversibility contribution of different sections. The exergy efficiency was calculated using the operating data from the plant at different conditions, viz. at different loads, different condenser pressures, with and without regenerative heaters and with different settings of the turbine governing.

Li and Liu [67] obtained exergy loss distribution of a 300 MW coal–fired power plant using the fuel and product concept of thermodynamics. Boiler was the component that contributed the largest exergy loss of 80%. This was mainly attributed to irreversible phenomenon of combustion, heat transfer and dissipation in the boiler. They also reported the plant performance under rated condition, 75%, 50% and 30% loads. The load reduction was achieved by using the method of sliding pressure regulation.

Ganapathy et al. [68] determined the energy and exergy losses in the individual components of a lignite fired thermal power plant using the mass, energy and exergy balance equations. The comparison between energy and exergy losses of the individual plant components showed that the maximum 39% energy losses occurred in the condenser, whereas the maximum 42.73% exergy losses occurred in the combustor.

Zhang et al. [69] made exergo–economic analysis of a 300 MW pulverized coal fired power plant located in China providing detailed analysis for cost formation of the power plant as well as the effects of different operating conditions on the performance of each individual component. To perform the thermo–economic analysis of the plant, a simulator was developed from thermodynamic modelling of the plant. With the thermodynamic properties of the most significant mass and energy flow streams being obtained from the plant; this simulator could reproduce the cycle behavior for different operating conditions with relative errors less than 2%. The models of the simulator were refined using data from designed performance tests of the plant.

Kopac and Hilalci [70] applied energy and exergy analysis to a reheat regenerative type power plant in Turkey to determine energy loss and irreversibility in each system component at different ambient temperatures within the range of 5–35°C.The percentage efficiency defects of each components (or the ratios of the irreversibility rates to the fuel exergy rate) and the rational efficiency, the exergy efficiencies of the boiler, the turbine, the pump, the heaters and the condenser were determined for different ambient temperatures. It was found that the efficiency defect of boiler had strong effects on the total efficiency defect and the rational efficiency of the plant. The ambient temperature had high effect on the changes of the boiler irreversibility (or efficiency defect of boiler) but it had low effect on outer components of the plant.

Aljundi [71] presented energy and exergy analysis of Al–Hussein power plant in Jordan analyzing the system components separately to identify and quantify the sites having largest energy and exergy losses. The plant performance was estimated by a component–wise modelling and a detailed break–up of energy and exergy losses was presented. The maximum energy loss occurred in the condenser while the total exergy destruction was the maximum in the boiler system.

Ameri et al. [72] performed exergo–economic analysis for the Hamedan steam power plant in Iran. The exergy loss of each component was determined and the effects of the load variation and ambient temperature were evaluated. The exergy efficiencies of the boiler, turbine, pump, heaters and the condenser were estimated at different ambient temperatures. The results showed that 70.5% and 15.5% of total energy were lost in the condenser and the boiler respectively. In the second part of the work, the exergoeconomic analysis was done in order to calculate the cost of exergy destruction. The exergy analysis revealed that 81% of the total exergy destruction occurred in the boiler compared to only 5% exergy loss in the condenser. From the exergoeconomic analysis, it was found that the costs of exergy destruction were higher in the boiler and the turbine compared to the other plant components. An optimization study was also performed additionally taking the total cost of exergy destruction and purchase as objective function and it was shown that cost reduction is possible through proper adjustment of the steam extraction rate and pressure of the water heaters.

Dincer and Muslim [73] performed energy and exergy analyses of a steam power plant based on reheat Rankine cycle where the energy and exergy efficiencies of the plant were evaluated for different system parameters such as boiler temperature, BP, mass fraction of steam feeding the regenerator and work output.

Rosen and Dincer [74] performed an exergoeconomic analysis of power plants operating on a range of fuels such as coal, oil, uranium. They developed relationship between capital costs and thermodynamic losses of four different coal fired, oil–fired and nuclear electrical generating stations.

As such, there are plenty of works available in the literature which report on thermodynamic analysis of thermal power plants. In some, the analysis is done completely on theoretical basis while some others are related to thermodynamic analysis of few location specific power plants. Similarly, some of the studies[62,63,65–70]mentioned above are based on exergy analysis of coal fired thermal power plants while in articles [71] and [75], the analysis is done for heavy fuel oil and natural gas fired thermal power plants respectively. The performance of a power plant relies heavily on fuel quality and its calorific value. Other operating parameters such as boiler pressure (BP), steam turbine inlet temperature (STIT), number of high and low pressure water heaters, condenser pressure, fuel flow rate (FFR) and air flow rate (AFR) also affect power plant performance directly. In some of the above studies, parametric analysis was done mainly to evaluate effect of operating parameters, e.g. in Ref. [66], the power plant performance was evaluated at different loads, condenser pressures, with and without regenerative heaters and with different settings of the turbine governing. Effect of some other operating parameters was analyzed by Regulagadda et al. [63], Zhang et al. [69] and Dincer and Muslim [73]. Energy and exergy based parametric analysis helps in identifying parameters that maximize the system performance and minimize the irreversible losses.

2.7 Thermodynamic analysis of CPC system

2.7.1 Thermodynamic analysis on binary mixture based CPC system

Xu et al. [76] proposed a novel combined power and cooling system combining a Rankine cycle and an absorption refrigeration cycle. Ammonia–water binary mixture was used as working fluid in the system where superheated NH_3 vapor expands in a turbine to produce power. During expansion in the turbine, the temperature of the NH_3 vapor reduces to value lower than the ambient and thus it facilitates cooling in a heat exchanger. Further, it used an absorption condensation process instead of the conventional condensation process. They recommended that the proposed cycle can be used as a bottoming cycle utilizing waste heat of a conventional power cycle or an independent cycle using low temperature sources such as geothermal and solar energy.

Hasan et al.[77] analyzed the combined power and refrigeration cycle proposed by Goswami et al. [77] with the help of first and second laws of thermodynamics. The thermodynamic performance of the cycle was optimized for maximum second law efficiency using a commercially available optimization program. A maximum second law efficiency of 65.8% was obtained at a heat source temperature of 420 K. An exergy analysis was performed to study losses in different components of the cycle. It was found that the largest contribution to irreversibility came from the absorber, while the rectifier and the solution heat exchanger also contributed significantly to total irreversibility. Little exergy destruction took place in the boiler as well which is somewhat more at low heat source temperatures, but drops as the source temperature increases.

Tamm et al. [78] made intensive investigation of the same CPC cycle proposed by Goswami et al. [76] both theoretically and experimentally. Through an initial parametric study, first they showed the possibility of optimizing the system against first or second law efficiency, as well as power or cooling output. However, for solar heat source, they realized that the second law efficiency is the most appropriate objective function as the spent heat source fluid is recycled through the solar collectors. Further they demonstrated that the cycle could be optimized using generalized reduced gradient method. It was found from simulation that optimization of the cycle for second law efficiency produces no refrigeration at high heat source temperatures, which however is possible with low heat source temperature. Later, an experimental study was performed to demonstrate the feasibility of the cycle and compare the experimental results with the theoretical simulation. Results showed that the vapor generation and absorption condensation processes work fine experimentally. It was also found that the non–isentropic expansion process in the turbine is the most significant source of irreversibility in the cycle.

Wang et al. [79] also proposed a similar kind of combined power and absorption refrigeration cycle using a binary ammonia–water mixture as working fluid. A parametric analysis was conducted to evaluate the effects of heat source temperature, environment temperature, refrigeration temperature, turbine inlet pressure, turbine inlet temperature, and basic solution ammonia concentration on net power output, refrigeration output and exergy efficiency of the combined cycle. Further, a genetic algorithm based optimization technique was applied for maximizing exergy efficiency.

Few more studies on combined power and refrigeration cycle using binary mixture of ammonia and water are also found in articles [80–83]. Zheng et al. [82] proposed an absorption power and cooling cycle and a thermodynamic analysis of the cycle was performed using log p–T, log p–h and T–s diagrams. The cycle was analyzed by means of a simulation on the basis of two performance criteria viz. the overall thermal–efficiency and the exergy efficiency. The overall thermal efficiency and the exergy efficiency of the cycle were found to be 24.2%and 37.3% respectively.

Liu and Zhang [80] proposed a novel ammonia–water cycle for cogeneration of power and refrigeration. In order to meet the different concentration requirements in the heat addition and the condensation process, a splitting/absorption unit was introduced and integrated with an ammonia–water Rankine cycle and an ammonia refrigeration cycle. This system was proposed to be driven by industrial waste heat or a gas turbine flue gas. The cycle performance was evaluated in terms of exergy efficiency and it was found that there were certain split fractions which maximized the exergy efficiency for a given basic working fluid concentration. Compared with the conventional separate generation system of power and refrigeration, this cogeneration system had an 18.2% reduction in energy consumption.

Zhang and Lior [81] proposed a new ammonia–water system for cogeneration of refrigeration and power which operates in a parallel combined cycle mode with the ammonia–water Rankine cycle and the ammonia refrigeration cycle interconnected by absorption, separation, and heat transfer processes. They performed a parametric study to investigate the influence of the basic working solution concentration, the cooling water temperature, and the Rankine cycle turbine inlet parameters on the cycle performance in terms of both energy and exergy efficiencies. Further a comparative analysis was done to show that the energy consumption in cogeneration cycle is greatly reduced when compared to the conventional separate generation of power and refrigeration for the power and cooling outputs.

As described in chapter 1, Liang et al. [84] proposed a combined Rankine–absorption refrigeration cycle to recover waste heat from engine coolant for water preheating and waste heat from engine exhaust gas for producing superheated steam. The source of heat for the ammonia–water based absorption cycle was the steam from the turbine outlet and the absorption system was used for cooling onboard ships.

Sadrameli and Goswami [83] observed that cooling in an ammonia–water based CPC cycle comes at some expense of work production. Therefore, to resolve this tradeoff between the conflicting objectives of cooling and work, they optimized the operating conditions of the cycle by defining a specific coefficient of performance. The simulation of the cycle was carried out using ASPEN Plus simulator and the optimum operating conditions were found by using the equation oriented mode of the simulator.

2.7.2 Thermodynamic analysis on waste heat driven CPC system

Thermodynamic analysis of waste heat driven CPC systems has been performed in a number of studies. Some previous studies on CPC systems are categorized based on the waste heat source and discussed in the following sections.

2.7.2.1 Review on thermodynamic analysis of ICE exhaust driven ARS

Havelsky [85] analyzed two combined cogeneration systems using separately the exhaust heat of ICE combustion products and engine cooling water as driving heat source of VARS where a heat pump was also integrated. In the first configuration, ICE combustion product was used as heat source for the VARS while the heat flow from ICE cooling and the condenser heat output of the heat pump were used for water heating. Cooling of the ARS absorber and condenser was achieved through series connection of water line from heat pump evaporator and heat exchanger for water heating. In the second configuration, exhaust heat from ICE cylinder cooling was the driving source for the ARS, while the exhaust heat of ICE combustion products was used for water heating. The method of ARS absorber and condenser cooling was the same as in the first configuration. The study provided comparison of energetic efficiency of the combined cogeneration systems with conventional separate production of heat, cold and power through which it was shown that energy saving is possible with the designed combined cogeneration systems.

Mostafavi and Agnew [86] analyzed a combined diesel engine and VARS to evaluate network, efficiency, and the temperature of diesel engine exhaust gases as a function of pressure and temperature ratio of the diesel engine cycle. The magnitudes of the available thermal energy and the diesel engine exhaust energy were calculated. The variations of efficiency, availability of cooling capacity for air conditioning purposes and network of the diesel engine as a function of cycle pressure ratio were also determined for different configurations.

Talbi and Agnew [87] theoretically made performance analysis of four different configurations of a combined turbocharged diesel engine and absorption refrigeration unit viz. (i) Pre–inter cooler engine, (ii) Inter–cooled combination engine, (iii) pre–cooled engine and (iv) Non–cooled engine. The simulation was performed using engine performance analysis software called SPICE. The influence of the different cycle configurations and performance parameters on performance of the engine and the cooling plant was examined. It was demonstrated that a pre– and inter–cooled turbocharged engine show considerable benefits in terms of specific fuel consumption, efficiency and output for the diesel cycle performance.

Manzela et al. [88] made experimental study of an NH_3–H_2O ARS using the exhaust of an internal combustion engine (ICE) as energy source. The energy availability of exhaust gas and the effects of the ARS on engine performance, exhaust emissions, and power economy were evaluated. The engine was tested in a bench test dynamometer with 25%, 50%, 75% and wide–opening positions of the throttle valve with the ARS attached to the exhaust pipe. The ARS reached a steady state temperature between 4 and 13 °C after 3 hour engine operation depending on engine throttle valve opening. With the refrigeration system installed in the engine exhaust they found higher hydrocarbon emissions. However, the carbon monoxide emissions reduced and the carbon dioxide concentration remained unaltered.

Ouadha and El–Gotni [89] made thermodynamic and feasibility analysis of using waste heat from a marine diesel engine to drive an NH_3–H_2O ARS. The system performance was theoretically investigated using a thermodynamic model developed according to the first law of thermodynamic applied to each system component. The thermodynamic study was carried out through variation of generator, condenser, absorber and evaporator temperatures. High system performance was obtained at high generator and evaporator temperatures and also at low condenser and absorber temperatures. It was also observed that the increase in the solution heat exchanger effectiveness improved the COP of the cooling system with no effect on the circulation ratio.

Rego et al. [90] connecting the exhaust system of an automotive ICE to the generator of an ARS, evaluated the dynamic performance of the ARS as a function of the supplied heat. To measure the dynamic performance, exhaust gas flow was controlled by stepper–motor actuated valves commanded by a microcontroller. Performance parameters such as engine torque, speed, internal temperatures in the ARS were measured in a transient regime. The results indicated better performance during input heat control based on generator temperature of the absorption cycle. It was concluded that the utilization range of the engine exhaust driven ARS can be expanded to high engine speed operating conditions through dynamic controlling supplied heat.

Huangfu et al. [91] introduced a micro–scale tri–generation system consisting of a reciprocating internal combustion LPG and natural gas engine/generator, an adsorption chiller and few heat recovery devices. They conducted an economic analysis determining the economic efficiency and payback period of the system. The system was also analyzed comprehensively from energetic and the exergetic point of view.

2.7.2.2 Review on thermodynamic analysis GT/MGT exhaust driven ARS

Mone et al. [92] investigated the economic feasibility of implementing combined heat and power system by using commercially available GT and single, double and triple effect absorption chillers. It was found that GT exhaust heat availability mainly depends on the exhaust gas mass flow rate, exhaust gas temperature and the GT size. The evaporator cooling capacity of the chillers was more a function of exhaust gas flow rate than the temperature. The possible savings achieved by installing such CHP system was also determined and it was found that the savings are function of the fuel (natural gas) cost and purchased cost of electricity. The triple effect system showed the highest cooling capacity with least amount of rejected heat required.

Colonna and Gabrielli [93] presented a study on trigeneration plants composed by GTs or ICEs that drive an NH_3–H_2O absorption refrigeration plant through a heat recovery exchanger producing either steam and/or pressurized water in the case of the ICEs. The study was focused on comparison of plant configurations for a 10MW trigeneration system for industrial applications. The considered plant configurations comprised (i) a GT coupled to the absorption chiller unit through a HRSG, (ii) three IC engines in parallel producing pressurized water from the cooling water loop and steam from the ICE exhaust, both driving separate absorption cycles at different temperature levels and finally (iii) the same IC engines system in which the whole heat was recovered through a pressurized water cooling heat exchanger driving a single absorption chiller. They also carried out a simplified economic assessment comparing the conventional grid supplied electric energy with an optimized trigeneration plant producing 10 MW electric powers operating for 7000 h/year.

Ameri and Hejazi [75] investigated the effect of inlet air cooling on power output of a gas turbine plant integrated with a HRSG and a steam driven double effect H_2O–LiBr absorption chiller. The absorption chiller system was used to cool the inlet air to make it denser which in turn gives the turbine a higher mass flow rate causing an increase in the turbine output and efficiency. The results showed an overall 11.3% power increase by inlet air cooling achieved through use of GT exhaust driven absorption chiller.

Hwang [94] analyzed the energetic performance of an integrated vapor compression refrigeration system (VCRS) with MGT and vapor absorption chiller driven by waste heat from the microturbine. The chilled water produced by the absorption chiller was utilized for subcooling the liquid refrigerant leaving the condenser and precooling the air entering the condenser of the VCRS. The compressor of the VCRS is driven by the power produced from the microturbine.

Khaliq [95] performed both first and second law analysis of a trigeneration system combining a GT (topping cycle) with a HRSG for process heat and H_2O–LiBr VARS (bottoming cycle) for the cooling purpose. First and second law efficiencies of the combined system and exergy destruction in each system component were evaluated as functions of overall pressure ratio, turbine inlet temperature, process heat pressure and evaporator temperature. He found that the maximum exergy destruction occurred in the combustion chamber and the HRSG. It was also observed that the irreversibility in these components decreases significantly with the increase in pressure ratio and increases significantly with the increase in turbine inlet temperature. Among the VARS components, exergy destruction in the generator was the highest followed by irreversibility contribution of the absorber, condenser and the evaporator at an evaporator temperature of 10°C.

Martins et al. [96] evaluated thermal efficiency and COP of a tri–generation system considering the influence of compressor pressure ratio, GT expansion ratio and operational pressure of the NH_3–H_2O absorption cycle using natural gas as fuel for the combustion chamber of the GT plant. Further, they emphasized on coupled exergy and economic analysis for evaluating feasibility of application of the proposed trigeneration system.

Bruno et al. [97] made performance analysis of combined micro gas turbines and gas driven double effect water–LiBr absorption chillers with post–combustion to investigate the performance of the combined plant with and without addition of extra fresh air for post combustion. Bruno et al. [98] in another study analyzed several types of cogeneration systems involving biogas fuelled micro gas turbine and commercially available single and double effect water–LiBr and ammonia–water absorption chillers.

Huicochea et al. [99] acquired experimental exhaust heat data of a 28 kW micro turbine and analyzed theoretically the thermodynamic performance of a trigeneration system formed by the micro gas turbine and a double–effect water–LiBr absorption chiller.

2.7.2.3 Review on thermodynamic analysis of solar powered ARS

There are also published articles on general and location specific solar powered absorption cooling systems. Some of these are discussed below.

Assilzadeh [100] presented modelling and simulation of an absorption solar cooling system specially designed for Malaysia’s climate using evacuated tube solar collectors and H_2O–LiBr absorption system with the help commercial software TRNSYS. The evacuated tube solar collector system is the topping cycle that provides the heat to produce vapor in the generator of the bottoming VARS.

Mittal et al. [101] presented modelling and theoretical analysis of a solar–powered, single–stage, absorption cooling system using a flat plate collector and H_2O–LiBr solution. A modular computer program was developed for the absorption system to simulate various cycle configurations with the help of weather data of Bahal, Bhiwani, Haryana, India. The effects of hot water inlet temperatures on COP and the surface area of the absorption cooling component were studied.

Abu–Ein et al. [102] provided a detailed energy and exergy analyses of a 10 kW solar energy operated NH_3–H_2O based ARS. The COP, exergetic COP (ECOP) and the exergy losses of each system component were determined at different operating conditions. The minimum and maximum COP and ECOP were found respectively at 110°C and 200°C generator temperatures. Generator contributed about 40% of the total exergy losses in the system. The maximum exergy loss in the absorber was found to occur at a generator temperature of 130°C at all evaporator temperatures.

Florides et al. [103] also presented modelling and simulation of a solar absorption cooling system. The system was modeled using TRNSYS simulation program and the typical yearlong meteorological parameters of Nicosia, Cyprus. They carried out system optimization for selecting the appropriate collector type, the optimum size of storage tank, the optimum collector slope and area, and the optimum thermostat setting of the auxiliary boiler. The system long–term integrated performance showed that substantial amounts of heat are supplied with solar energy both for cooling and hot water production.

Liu and Wang [104] proposed a novel solar/gas driven double effect water–LiBr absorption system where hot water produced from solar energy in the collector was first stored in a storage tank and later used as a source of heat for vapor generation in the low–pressure generator (LPG) together with water vapor leaving the high–pressure generator (HPG). Natural gas was burnt to supply energy for vapor generation in the HPG.

Xu et al. [105] presented a new solar powered H_2O–LiBr based ARS with variable mass energy transformation and storage (VMETS) technology using typical weather data of Shanghai in China. The VMETS technology was used to balance the inconsistency between the solar radiation and the air conditioning (AC) load. The energy collected from the solar radiation was first transformed into the chemical potential of the working fluid and stored in the system. This was later transformed into thermal energy by absorption refrigeration when AC was demanded. A dynamic model was developed for system simulation to investigate the system behavior, including the temperature and concentration of the working fluid, the mass and energy in the storage tanks, the heat loads of heat exchanger devices etc.

Monné et al. [106] developed a model for a solar ARS using TRNSYS and the simulation results were validated with experimental results obtained during two years (2007 and 2008) from a solar cooling system consisting of a flat plate collector, a 4.5 kW single effect H_2O–LiBr absorption chiller and a dry cooler tower. Both the experimental and the simulation results showed strong influence of cooling water temperature and the generator driving temperature on the COP. With the design and installation of an alternative geothermal heat sink, they found an improvement on COP up to 42%.

Cascales et al. [107] developed several models for characterization of a solar assisted H_2O–LiBr ARS designed for a classroom in an educational centre in Puerto Lumbreras, Murcia, Spain. One of the models were based on the manufacturer data catalogue and the others were based on adaptive resonance theory based artificial neural network (ANN). The experimental data obtained during two years of performance were used for ANN training and validation. TRNSYS was used for the dynamic system simulation.

Li et al. [108] developed a parametric model to analyze the performance of a solar air cooled double effect water–LiBr absorption cooling system using monthly average meteorological data (hourly solar irradiance and ambient temperature) of subtropical Guangzhou at various collector temperatures. It was found that the suitable working range of inlet temperature of the solar collector is 110–130°C for improved performance with lower crystallization risk. The possibility of crystallization is more in the air–cooled ARSs compared to water cooled systems, although they are attractive otherwise because of absence of the cooling tower (CT) and other associated installation. CT is an essential component of a steam turbine (ST) based thermal power plant. Hence it is possible to integrate a water cooled double effect H_2O–LiBr ARS with a ST plant.

2.8 Review summary

The literature review in this chapter was done mainly on studies related to VARS, various refrigerant–absorbent pairs used as working fluid in VARS, different VARS configurations and their performance related issues. Obviously some other issues also came up in the review because VARS is a heat driven system. Accordingly, the review was done to explore the possibilities of driving VARS with different waste heat sources including some of the topping power cycles (ICE, GT/MGT, VPC etc.). In such cases the VARS performance sometimes becomes interlinked with the performance of the topping heat providing cycle.

From the literature review on VARS, it was seen that lot of effort has been made into modelling and analysis of different VARS configurations ranging from half effect to triple effect using conventional and newer refrigerant–absorbent pairs. Selecting an appropriate working fluid pair is extremely important because the performance of a VARS is greatly affected by the properties of the working substance. Depending on the nature of the refrigerant in the refrigerant–absorbent mixture, a VARS is used for either low temperature industrial process cooling say in case of NH_3–H_2O based VARS and or for producing cooling at moderate temperature such as air conditioning or chilling application using H_2O–LiBr and other salt solutions as working fluids. NH_3–H_2O and H_2O–LiBr are the most commonly used refrigerant and absorbent pairs in VARS. However, researches are still on to investigate VARS performance with new refrigerant–absorbent pairs to find alternatives for NH_3–H_2O and H_2O–LiBr.

VARS is available in various configurations. The COP of the half and single effect VARS configurations are usually low (below unity), but higher COP (above unity), can be obtained using double and triple effect VARS configuration. As such, the COP of the triple effect VARS configuration would be the highest. However, compared to the triple effect systems, the double effect absorption refrigeration cycles have more commercial use in the refrigeration industry.

Over the years many studies have been performed on absorption cooling systems while some of them deal with energetic performance analysis and some other articles are specific to exergy analysis. In most of the energy analysis, mainly the COP of the VARS is evaluated and sometimes the effects of the component temperatures on COP are investigated through parametric study. However energy analysis alone is not sufficient for evaluating inefficiency of energy systems and often exergy is used as a tool as it provides the framework for evaluating irreversible losses occurring in various system components. Moreover for comparing the performance of a VARS with different generator heat source, exergy is the appropriate method because depending upon the temperature of the heat source, the quality of energy input will be different and in this situation, the exergetic efficiency will give a better insight into the system operation rather than the COP.

Exergy analysis performed on VARS indicated that the generator and the absorber are the two vital components of a VARS where significant exergy destruction occurs; however in some studies it was the absorber that showed maximum irreversibility while in some other studies the generator was the major contributor of irreversibility. As such the exergy destruction occurring in the VARS components varies depending upon the system configuration, heat source and the operating conditions chosen for analysis.

From the literature review, it was also seen that in some of the previous works, the parametric thermodynamic analysis of VARS has been done without considering the source of heat for the VARS generator. This can possibly be done in a situation where the source of heat is assumed to be available for supply of heat to the generator and as such it has nothing to do with the performance of the system providing heat for the VARS. However, when a VARS is considered along with the heat providing system, the performance of the two systems become interdependent; the performance of one will affect the other. In such cases, the analysis is done for both the topping and the bottoming cycles. In some other works however, the authors have shown the generator heat source and simply considered the energy supplied from the source in the analysis.

From the review of VCRS performance analysis, it was seen that energy and exergy analysis of VCRS is quite common which are done mainly to obtain better cooling performance with alternate refrigerants that contribute less to ozone depletion and global warming. Combined absorption-compression refrigeration systems have also been conceptualized and analyzed. Comparative performance analysis is also sometime provided between VARS and VCRS.

From the review on studies related to thermodynamic performance analysis of VPC based steam power plants, binary mixture based and waste heat driven CPC systems, it could be seen that there is no study available in the literature on ST based cogeneration system analysis that integrates a topping ST based power cycle with a bottoming vapor absorption refrigeration cycle.

Further, it was found that the crystallization possibility is more in the air–cooled absorption refrigeration systems compared to water cooled systems, although they are attractive otherwise because of absence of the cooling tower (CT) and other associated installation. CT is an essential component of a ST based thermal power plant. Hence it is possible to integrate a water cooled double effect H_2O–LiBr ARS with a ST plant. The exhaust heat of boiler flue gas of a steam power plant can be used for driving a double effect ARS. In thermal power plants, hot flue gas are sometimes used for preheating of boiler feed water (in economizer) and combustion air (in air preheater). Similarly it can also be used for driving the generator of a VARS. There is no article in the literature that combines a vapour /steam power cycle and boiler flue gas energized double effect H_2O–LiBr ARS.

2.9 Scope of the present work

In the present research work, first a novel combined RRVPC and a single effect H_2O–LiBr VARS configuration is chosen for analysis to evaluate the system performance based on variation of the operating parameters of both the topping RRVPC and bottoming VARS. It is first aimed at modelling all the system components individually and then evaluating the system performance of the proposed CPC system thermodynamically using first law based energy and second law based exergy analysis. Energy and exergy based parametric study evaluating the effect of system operating parameters on performance of the such a combined system is important in the sense that the analyses are done for a novel CPC system and the effect of these parameters on power output from the topping RRVPC of a combined RRVPC and single effect H_2O–LiBr VARS has not been investigated earlier.

Next, another RRVPC based CPC system is taken into consideration with almost similar components in the topping RRVPC but this time with a VCRS as bottoming cycle. Energy and exergy analyses of the VCRS based CPC system are carried out to provide a comparative performance analysis with the previously analyzed VARS based CPC system.

In one more attempt, another novel RRVPC and double effect H_2O–LiBr VARS combined configuration is considered for thermodynamic performance analysis with the help of energy and exergy. Unlike in the previous VARS based CPC configuration where steam extracted from the ST of the topping RRVPC was the heat source for VARS generator, here in this new CPC system configuration, the VARS generator is driven by exhaust heat of the boiler leaving flue gas of the topping RRVPC. The performance of this new CPC cycle configuration is compared with a similar configuration, having a single effect H_2O–LiBr VARS as bottoming cycle.

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