Chapter 2

Literature Review

2.1 INTRODUCTION

The current research work is focused on development of vapor power generation cycles suitable for hot climatic conditions. The research activities involved in the thermodynamic cycles have been perceived. In solving a power cycle, the choice of working fluid is imperative. The thermodynamic properties of the preferred working fluid must be established. The literature gaps have been identified after the through review of reported works in the area of binary vapor power cycles. A binary mixture consists of one higher boiling point fluid and one lower boiling point fluid. Ammonia has got low boiling point in ammonia-water mixture, which permits utilization of the waste heat source and helps to boil at low temperature. The zeotropic nature of ammonia-water mixture will make it possible boil and condense at a range of temperatures. This permits a closer match between heat source and working fluid mixture. In azeotropic nature, the mixture behaves as a pure substance, boils or condenses at constant temperature. The similar molecular weight of ammonia as that of water, make it possible to utilize the standard steam turbine components.

The literature survey has been carried out in the following areas.

1. Thermodynamic properties of NH$_3$-H$_2$O mixture
2. Kalina cycle system (KCS)
3. Exergy analysis of KCS
4. Innovations in KCS
5. Combined power and cooling systems

2.2 THERMODYNAMIC PROPERTIES OF AQUA AMMONIA

Ziegler and Trepp (1984) portrayed a new correlation of ammonia-water mixture. The properties have been developed up to a pressure of 50 bar and temperature of 500 K. Renon et al. (1986) suggested cubic equation of state as a good description of vapor-liquid equilibria for the ammonia-water system. In studying vapor-liquid equilibrium for binary mixtures, four intensive variables to be
overlooked are temperature, pressure, single liquid mole fraction and single vapor mole fraction (Reid et al., 1987). Ruiter (1990) presented a simplified thermodynamic model for excess enthalpy of mixtures. Patek and Klimfar (1995) developed simple procedure avoiding numerous iterations for calculating thermodynamic properties of mixture suitable up to 20 bar pressure. According to Orbey and Sandler (1995) combination of activity coefficient models with equations of state both at infinite pressure and at zero pressure have been presented. Abovsky (1996) derived the ammonia-water properties from 200 K to 640 K and up to pressure of 230 bar. Najjar (1997) evaluated the thermodynamic properties of ammonia-water mixture in the superheated region using two constant equation of state. The thermodynamic properties of ammonia-water mixture have been calculated based on the cross over equation (Kiselev and Rainwater, 1997). Nowarski and Friend (1998) proposed an extended corresponding states method in evaluating the ammonia-water mixture thermodynamic surface. Thorin et al. (1998) compared four different correlations in assessing the thermodynamics properties of ammonia-water mixture. Tsai and Chen (1998) assessed Peng-Robin equation of state to polar and non polar fluids. Tillner Roth and Friend (1998) introduced a fundamental equation of state for the Helmholtz free energy of the ammonia-water mixture. The thermodynamic space between the solid-liquid vapor boundary and the critical locus in the liquid and vapor phases for pressures up to 400 bar is presented.

Xu and Goswami (1999) used the Gibbs free energy method for mixture properties and the bubble and dew point temperature equations for phase equilibrium. Sharma et al. (1999) assessed vapor liquid equilibrium data for mixtures by neural network. Edison and Sengers (1999) have presented an equation for calculating thermodynamic properties of ammonia in the critical region up to 500 K. Weber (1999) has proposed virial coefficients for ammonia-water mixture up to 900 K. Holcomb and Outcalt (1999) developed an equation of state for ammonia-water mixture suitable for geothermal power cycles. The equations have been developed to suit at high ammonia concentrations with pressures and temperatures 77 bar and 379 K. In calculating thermodynamic properties of fluid mixtures, a generalized model for various fluid mixtures has developed (Lemmon and Tillner-Roth, 1999). Thorin (2001) assessed the size of heat exchangers with thermo physical properties using different correlations. Excess enthalpy of ammonia-water mixture in gaseous phase
have been obtained using virial cross coefficients. The values have been evaluated up to 493.15 K (Wormald and Wurzberger, 2001). Inoue et al. (2002) has carried out an experimental study on ammonia-water mixture and addressed the difficulty in predicting the heat transfer coefficients. Barhoumi et al. (2004) projected modelling of the thermodynamic properties of ammonia-water mixture up to 500 K and 100 bar. Thermophysical properties of ammonia – water mixture with various correlations up to low temperature applications have been presented (Conde-Petit, 2006). Mejbri and Bellagi (2006) assessed the thermodynamic properties of ammonia-water mixture using empirical approach, semi-empirical model and perturbed chain statistical associating fluid theory equation of state. Alamdari (2007) proposed equations in determining the vapor-liquid equilibrium properties of ammonia-water mixture up to 140 °C and 100 bar. In the near and supercritical regions the pressure, volume and temperature properties for ammonia-water mixture have been calculated up to 280 bar pressure and 634 K temperature. Farrokh Niae et al. (2008) suggested a new accurate cubic three parameter equation of state for calculating pressure, volume, temperature and vapor liquid equilibrium equations for high polar fluids. The properties of ammonia-water have been evaluated at critical point using simple polynomial correlation (Akasaka, 2009). Polikhronidi et al. (2009) measured the PVT properties of ammonia-water mixture in the supercritical regions up to a temperature of 361 °C and 280 bar pressure.

Enthalpy, entropy, internal energy, exergy, fugacity etc. are useful thermodynamic properties to examine the energy and exergy performance. Ammonia in a mixture boils at low temperature as its boiling point is very low. Ammonia – water mixture as zeotropic has the tendency to boil and condense at a range of temperatures retaining a closer match between heat source and working fluid. The thermodynamic formulae for properties of ammonia-water mixture developed by Ziegler and Trepp (1984), Xu and Goswami (1999) are used in the present work to solve KCSs. For second law evaluation, exergy values of mixture have been developed. The methodology to develop the properties and its values are given in appendix A.
2.3 KALINA CYCLE SYSTEM

The Kalina cycle system is a power generation cycle which converts thermal energy to mechanical power utilising two different components as working fluid. The thermodynamic irreversibility in the system is reduced by varying the ammonia-water mixture ratio in every component of the system. This favors an increased overall thermal efficiency. Kalina (1984) a Russian Engineer, has invented the Kalina cycle. It has been proposed that Kalina cycle is a suitable technology to recover waste heat from power plants, solar collecting systems and similar. KCS utilizing waste heat recovery are in operation at Sumitomo metal steel works and Fuji oil refinery in Tokyo Bay. Geothermal plants exist in Husavik Iceland and Unterhaching Germany. The Kalina cycle trademark and patents are owned by Global Geothermal Ltd, the parent of recurrent engineering Inc. Mirolli et al. (2002) has proposed thermodynamic evaluation for series heater Kalina plant located at Husavik, Iceland. Mlcak et al. (2002) reported the operation of a 2 MW Kalina cycle at Iceland. It has been identified that Kalina cycle and organic Rankine cycle (ORC) are the suitable power generation technologies for decentralized power generation. Both have their individual merits and demerits. Recently researchers are focusing on Kalina cycle attributable to flexibility in operation and environmentally friendly nature. The Kalina cycle recovers energy from low-grade waste heat. Mlcak (2001) presented the design features of Kalina plant and start – up experience.

Henry and Mlcak (1996) reported the basic principles and arrangement of Kalina cycle. Jonsson (2003) in his research work has made analysis over power cycles and concluded that ammonia-water cycle has got high performance over steam power plants. Ammonia can be used in thermal power installations in a mixture with water without any problems. It is cheap and readily available, has no corrosive effect on iron and its alloys, and is soluble in water in any concentration (Brodyanskii, 2006). Marcuccilli and Zouaghi (2007) suggested radial inflow turbines are superlative for binary cycles to get maximum isentropic efficiencies. Lolos and Rogdakis (2009a) correlated the equations for performance of solar Kalina power cycle for low temperature heat recovery and suggested 130 °C as a maximum cycle temperature. A low temperature Kalina cycle has been analyzed by Lolos and Rogdakis (2009b). Condenser pressure and source temperature have been focused at low sink temperature.
Asou et al. (2007) compared Kalina cycle and conventional ocean thermal energy conversion (OTEC) system with ammonia-water mixture as working fluid. Bliem (1988) reported about the power increment of 190% with a decrease in the turbine back pressure from 110 bar to 32 bar, corresponding increase in pressure ratio from 1.8 to 6.2. Dejfors et al. (1998) suggested that higher maximum pressure can improve the binary mixture cycle. Hatem (2007) has presented an experimental study on ammonia vapor in ammonia water solution. With the increase in heat generation the efficiencies of turbine increases with increased system efficiency (James Hartley, 2001). Bai (2004) developed models for the components involved in Kalina cycle using binary mixture as working fluid. Prisyazhniuk (2008) provided the possibilities of reducing the fuel consumption and discharge into the environment in a thermal power plant.

As the solar energy is considered as the future energy, the interest in the applications of solar energy is increased worldwide. Due to its costs, the solar energy applications have been restricted with its success. Some new and emerging developments in solar energy have the potential to change this situation (Goswami et al., 2004). Hu et al. (2010) concluded that solar energy is an environmental friendly source of energy for power generation with high efficiency. They highlighted the advantages of integration of solar energy with fossil fuelled power generation systems. Mills et al. (2004) designed a 250 MW solar thermal power plant with compact linear fresnel reflector array system and suggested the low temperature operation as cost effective. Valan Arasu and Sornakumar (2007) fabricated a solar parabolic trough collector and developed the correlation equations for efficiency.

In the US department of Energy’s Technology Engineering Center, California a Kalina demonstration plant has been started operating in 1992. Initially to generate 3 MWe of power, the plant used waste heat at a temperature of approximately 540 °C with the maximum pressure and temperature of 110 bar and 516 °C (Leibowitz and Mirolli, 1997). Marston (1990) carried out a parametric analysis for a Kalina power cycle with gas turbine exhaust’s heat recovery and iteration has been carried out to the cycle loop with the initial assumption of separator inlet concentration. With this iteration, the separator inlet concentration becomes dependent and calculated after getting the consistency of the iteration. He suggested a condensation at slightly
above atmospheric pressure with low concentration of ammonia and heat input at higher concentration. El-Sayed and Tribus (1985) assessed the performance of Kalina cycle with the Rankine cycle. But the configurations developed by them were much complicated because several heat exchangers had more than two streams. Marston and Hyre (1995) modified the El-Sayed and Tribus configuration with a simple two stream heat exchangers. Condensation is achieved slightly above atmospheric pressure with low concentration of ammonia.

The potential use of non-conventional fluids in Rankine cycle and the Kalina cycle, to improve the performance with respect to conventional single and dual flash steam power plants has been proved (Desideri and Bidini, 1997). They modified the main parameters, such as turbine inlet condition and type of fluid. Rogdakis and Antonopolos (1991) showed that for fixed upper (superheating) and lower (condensation) temperatures, the Kalina cycle shows 20% higher efficiency than Rankine cycle. Rogdakis (1996) optimized the cycle and developed correlations describing the optimum operation of the cycle. Dejfors and Svedberg (2010) showed that the vapor absorption cycle has a higher net power output and consequently a lower total exergy loss compared to other Rankine cycles. Murugan and Subbarao (2008) performed the energy and exergy analysis for the proposed Rankine-Kalina combined cycle. They integrated the steam Rankine cycle with low temperature Kalina cycle and showed 1.4% more efficiency compared to the condensing Rankine cycle.

Panea et al. (2010) recommended the Kalina cycle over Rankine cycle in producing power at low temperature geothermal source. With the incorporation of heat recovery improvement in efficiency is achieved. Compared to the isothermal boiling/condensing processes in a Rankine cycle, the wavering temperature during the heat transfer processes reduces the thermodynamic irreversibility of heat exchange process (Ibrahim and Klein, 1996). Kalina cycle has got large improvement in thermal efficiency, large reduction in cost, no combustion system, equivalent or lower capital costs, no major modifications to equipment used in conventional power plants, greater flexibility in operation and no vacuum maintenance requirements. With the combined Rankine and Kalina cycle systems better matching could be achieved (Mittelman and Epstein, 2010). A comparison
between Rankine and Kalina cycles on energy and exergy point has been made (Zhang et al., 2012). Kalina cycle has got better thermodynamic performances than the Rankine and ORC with respect to both energy and exergy efficiencies. Roy et al. (2010) estimated thermodynamic analysis of two Rankine cycles with and without regenerators. The exergetic efficiency is inversely proportional to output, whereas the heat exchanger’s surface is directly proportional to output. Stecco and Desideri (2004) compared the heat recovery vapor generator (HRVG) with water and ammonia-water as binary mixture. With mixture in boiler the heat recovered is 25% more than with single component. As per Spinks (1991) calculations, using typical geothermal wells in New Zealand, Rankine cycle produces 10 MW net output. Styliaras (1996) optimized the ammonia-water mixture Rankine cycle with the addition of absorber-generator and claims an efficiency of 14% as maximum at an upper temperature of 100 °C. Shi and Che (2009) investigated a combined ammonia-water mixture Rankine cycle and liquefied natural gas (LNG) power generation cycle. The combined system produces energy and exergy efficiency of 33.28% and 48.87% at high pressure and temperature of 30 bar and 150 °C.

Valdimarsson and Eliasson (2003) showed the cost benefit of Kalina cycle over ORC and found from their contour diagrams, that the best power and best-cost points are different. Hettiarachchi et al. (2007) analyzed the performance of the Kalina cycle system for low-temperature geothermal heat sources and compared with an ORC performance. They investigated the effect of the ammonia fraction and turbine inlet pressure on the cycle performance. Bombarda et al. (2010) compared the thermodynamic performances of Kalina cycle and ORC cycle, using hexamethyldisiloxane as working fluid with the heat source constituted by the exhaust gases (35 kg/s for both engines, at 346 °C). They showed a net electric power of 1615 kW and 1603 kW respectively for Kalina and ORC cycle. Dipippo (2004) also compared ORC with Kalina cycle and highlighted the importance of Kalina system for the geothermal power plants. Solar energy has been selected as a source of heat in the current investigation of Kalina power system. Wang et al. (2009) used single flash steam cycle, dual-pressure steam cycle, ORC and Kalina cycle for cogeneration in cement plant in order to recover waste heat from the preheater exhaust and clinker cooler exhaust gases. They showed that compared with other systems, Kalina cycle could achieve the best performance in cement plant. Galanis et
al. (2009) reviewed some prototypes of power plants with unconventional fluids (refrigerants, CO₂, binary mixtures) and summarized some of the relevant scientific and technical work. ORC, supercritical Rankine cycle and Kalina power cycle are the suitable thermal technologies for low-grade heat recovery (Wang et al., 2010). Cayer et al. (2009) developed the carbon dioxide transcritical cycles for the lower temperature heat recovery. Baik et al. (2011) compared carbon dioxide and R125 transcritical cycles for a low grade heat source and proved that R125 transcritical cycle produces 14% more power than the carbon dioxide transcritical cycle. Franco and Villani (2009) developed an ORC with a geothermal heat source suitable for medium temperature. Aneke et al. (2011) reported the sizing details of heat exchangers in the ORC and suggested that sizing is reduced with dual source compared with single source.

Chacartegui et al. (2009) developed ORC for combined bottoming cycles. These developments can be shared with other power generators, like solar thermal facilities. It is also possible to integrate these systems as bottoming cycles for combined cycle power plants. Srinivas et al. (2008) studied the heat recovery from gas turbine exhaust with Kalina bottoming cycle and also highlighted the benefit over the steam bottoming cycle. Mirolli (2001) concluded that the distillation condensation subsystem technology is a key component for the high efficiency of a Kalina cycle plant for waste heat recovery power plant applications. Heppenstall (1998) identified Kalina as a bottoming cycle and showed better performance compared to steam bottoming cycle. Minea (2007) stated that the Kalina cycle may produce power in the future especially with industrial waste heat and biomass. The low-grade waste heat cannot be used for steam production in a conventional steam cycle. The alternative way to generate electricity at low temperature is Kalina power system. Ogriseck (2009) integrated the Kalina cycle process in a combined heat and power plant and maximized the electricity with recovery of heat and without demand of additional fuels. Bloomquist (2003) proposed Kalina cycle and considered as the technology for the integration of geothermal power projects. The overall fuel use efficiency is improved by integrating power production and agribusiness using Kalina cycle (Bloomquist, 2005). Guzovic et al. (2010) suggested that Kalina cycle as binary power plants can be considered as a medium temperature power plant producing electricity from geothermal source at Republic of Croatia. A simple procedure has
been carried out to assess the performance of power and cooling system (Srinivas and Vignesh, 2012; Srinivas et al., 2011). Koroneos and Rovas (2007) concluded that the electricity produced by vapor dominated system is economically and environmentally in a better position than from coal or diesel. Korobitsyn (1998) proposed advanced thermal conversion methods for cogeneration and combined power cycles.

The low temperature Kalina power plant works with the source temperature up to 150 °C. Kalina cycle with high temperature heat recovery works from 250 – 600 °C of source. Kalina and Hillsborough (2006) proposed a power system suitable for moderate heat source such as geothermal waste heat. But this configuration has not yet been solved and reported in the literature.

2.4 EXERGY ANALYSIS OF KALINA CYCLE SYSTEMS

Exergy is the maximum useful work obtained during an interaction of a system with equilibrium state. The total exergy can be calculated as the summation of physical and chemical exergies. In other terms, it is a measure of the potential of the system or flow to cause change. By energy analysis alone a power generation system cannot be assessed. It is important to propose exergy efficiency for the chosen systems. With the exergy analysis the losses in the entire components of the power system can be evaluated and compared.

Dorj (2005) presented a thermo-economic solution for Kalina power plant with a focus on energy and exergy with a result of 14% cycle efficiency. Kohler and Saadat (2004) modelled binary systems and suggested the importance of second law efficiency for performance evaluation. Arslan (2010) has investigated electricity generation from geothermal field and determined the optimum operating conditions for the chosen plant design based on the exergetic and life-cycle cost concepts. In the current work, Kalina power cycle configuration suitable for medium temperature heat source (190 – 225 °C) has been configured and evaluated to assess the merit compared to the other available configurations. In Kalina cycle, the ratio of exergy loss with the net generated power was less compared with the Rankine cycle (Srinophakun et al., 2001). Singh and Kaushik (2012) coupled low temperature Kalina cycle system with steam power plant. Ammonia mass fraction in the mixture
and turbine inlet pressure has been considered as key parameters. They concluded that maximum exergy destruction occurs at evaporator.

Exergy losses represent true losses of the potential that exists to generate the desired products from the inputs. Som and Datta (2008) conducted exergy analysis in combustion system for finding the irreversibility’s. In a combustion process, the primary way of keeping the exergy destruction within a reasonable limit is to reduce the irreversibility in heat conduction. Borgert and Velasquez (2004) obtained additional power by recovering the energy in the combustion gases with Kalina as bottoming cycle. Rosen and Dincer (2001) presented useful insights and direction for analyzing and solving environmental problems of varying complexity using the exergy concept. Mishra et al. (2006) carried out thermodynamic evaluation in an aqua-ammonia vapor-absorption system to minimize the overall production cost. He identified the effects of design variables on cost and suggested values of design variables, which makes the overall system cost-effective. Rosen (2007) proposed that exergy analysis avoids the difficulties associated with energy methods and allows efficiencies to be clearly understood and measures to improve efficiency. He additionally described the environmental implications of exergy.

Wall et al. (1989) defined energy utilization diagram (EUD) as a graphic method to describe the exergy losses in industrial processes. He optimized the Kalina cycle using EUD and illustrated the internal phenomena by showing the distribution of exergy losses for each energy transformation. Nag and Gupta (1997) conducted an exergy analysis for a Kalina cycle at high temperature heat supply. They calculated the exergy losses created with respect to irreversibility in each of the components at a specified dead state. Using Gouy-Stodola equation, the exergy loss in each of the components has been estimated. Nearly 50% of exergy loss takes place in the heat recovery steam generator. Borelli and Oliveira Junior (2008) conducted thermoeconomic analysis for a combined cycle/cogeneration plant and presented electricity cost. Ganapathy et al. (2009) also carried out an exergy analysis for lignite fired thermal power plant. The exergy loss in boiler is 57% and reasoned due to irreversibility inherent in the combustion process, heat loss, and incomplete combustion and exhaust losses. Reddy et al. (2010) carried out a thermodynamic analysis of a coal based thermal power plant and gas based cogeneration power plant.
Hussein et al. (2001) conducted an exergy analysis for a 120 MW thermal power plant in Malaysia. From the results, he concluded that the boiler produces the highest exergy destruction of 54 MW. In the power plant, the high pressure and intermediate pressure turbine produces higher exergy destruction than the low pressure turbine. Rashad and Maihy (2009) presented an energy and exergy analysis of a steam power plant in Egypt. The performance of the plant have been estimated by component-wise and presented detailed break-up energy and exergy losses at different loads. Ehsana (2011) made an exergy analysis in a thermal power plant using ten different types of Turkish lignite. Exergy destruction of each component has been investigated by using conservation of mass and conservation of energy. In the total exergy destruction of the entire plant, boiler has been concluded as the major source with 299.10 MW and 83.29%. Usvika et al. (2009) conducted an exergy analysis for a KCS 34. The exergy flow of Kalina cycle has shown in grassman diagram. The losses in heat exchanging equipments from the cycle are due to pressure drop and heat transfer. Turbine has the highest losses which are due to mechanical and isentropic efficiencies. Rodriguez et al. (2012) reported the sizes of vaporizer, condenser, high temperature recuperator and low temperature recuperator as 455.14 m², 940.18 m², 50.45 m² and 144.65 m² respectively for the capacity of 0.92 MW. The overall product cost is minimized by the thermoeconomic evaluation (Misra et al., 2006).

2.5 INNOVATIONS IN KALINA CYCLE SYSTEMS

The KCS configurations involve the arrangement of heat exchangers and this section is focused in the developments of these arrangements suitable for low, medium and high temperature heat recoveries.

An apparatus has been invented by Kalina (1986), which provides intercooling compensation for the heat used in reheating. Recuperation of available heat has used in the apparatus otherwise that should be remained unused. The arrangement includes condensation subsystem, boiler (preheater, evaporator, and superheater) and turbine. The arrangement developed by Kalina (1988a) is a direct fired power cycle. In this arrangement, the withdrawal has utilized to create a composite stream having high percentage of high-boiling components. Effective recuperative boiling of the working fluid has been achieved due to the composite
stream which condenses over a temperature range. Kalina (1988b) invented a design which involves expanding a gaseous working fluid to a medium pressure to transform energy into usable form. Due to closer match between the working fluid and heat source during pre-heating the cycle provides improved efficiency. Kalina (1991a) implemented a cycle utilizing geothermal fluid as heat source. The multicomponent working fluid has been evaporated with the heat released from a returning stream. In the conversion of low temperature heat to electric power a thermodynamic cycle has been invented (Kalina, 1991b). Kalina (1992) presented an apparatus which converts thermal energy into electric power. The efficiency has been increased by heating at least two multi-component liquid working streams that comprise rich and lean streams.

Kalina (1995a) invented a multistage combustion system for externally fired power plants. The heat released from the combustion chamber will be matched with the thermal characteristics of the working fluid by providing a number of combustion stages. A design for converting heat from geothermal liquid and geothermal steam to electric power has been invented (Kalina, 1995b). An integrated system has been suggested utilizing energy potential of both geothermal steam and geothermal liquid. Kalina and Mirolli (1996) developed a power generation cycle from externally fired power system having two or more combustion zones. A thermodynamic cycle with multiple distillation operations transforms energy into usable form (Kalina, 1996). An apparatus with the aid of regeneration subsystem will achieve an improved efficiency (Kalina and Pelletier, 1997). Kalina and Rhodes (1998) invented a cycle to transmit heat into useful energy using separate closed loops. Kalina et al. (1999) modified the configuration proposed earlier for converting heat into energy. Mirolli (2005) developed Kalina cycle system in waste heat recovery from cement industry and proposed 20% to 40% improvement in performance against the conventional waste heat. Without additional fuel Kalina cycle system produces electricity by utilizing waste heat from the cement plant (Mirolli, 2006).

Peletz and Tanca (2000) implemented refurbishing conventional power plants. In this method, one of the Rankine heaters has been removed and replaced with a heater suitable for a Kalina cycle subsystem. Peletz (2001) proposed a Kalina cycle in converting heat to power. Ranasinghe et al. (2001) proposed a method which heats
the fuel gas to the gas turbine in a combined cycle power plant employing a Kalina cycle. This improves the overall efficiency of the power plant. Ranasinghe et al. (2002) proposed a new thermodynamic cycle with increased efficiency of district water heating in comparison with Rankine cycles. Hansen et al. (2000) proposed a method for power generation system. A multi component working fluid vapor generation system was invented (Hansen et al., 2001a,b). Kalina and Hillsborough (2004a,b,c,d) proposed various thermodynamic configurations for converting energy from a low temperature geothermal stream into useable energy. Kalina and Hillsborough (2005a,b,c) also proposed thermodynamic cycle for converting energy from a low temperature stream into usable energy. The proposed cycle has higher pressure and a lower pressure circuits with working fluid comprising of low boiling and high boiling components. Kalina and Hillsborough (2005d) invented a system which efficiently extracts usable energy from high temperature waste stream. The system includes, two stage turbine energy extraction subsystems, distillation – condensation subsystem and a boiler subsystem in a multi-pressure thermodynamic cycle. Kalina and Hillsborough (2006a) proposed a single flow cascade system with first law and second law efficiencies of 37% and 66% respectively.

A device to boil and vaporize multi-component fluids has been invented in 2006 (Kalina, 2006b). This includes vapor shell, liquid shell, connecting pipes for maintaining nucleate boiling throughout the apparatus length. The apparatus has got very high film heat transfer coefficient. It protects the tubes from burn out. Full vaporization of multi-component fluids can be achieved with this apparatus. An apparatus for converting low and medium temperature to power has been proposed in 2006 (Kalina and Hillsborough, 2006c,d). An improved combustion method also has been invented (Kalina and Hillsborough, 2008).

2.6 COMBINED POWER AND COOLING SYSTEMS

Amano et al. (2000) proposed a hybrid power generating and refrigerating cycle with ammonia-water mixture. Ammonia-water mixture turbine cycle (AWMT) and a single-effect ammonia absorption refrigeration cycle (AAR) have been connected to expand the availability of ammonia-absorption cycle. This system has been utilized for low temperature applications. AWMT cycle consists of two Kalina
cycles. AAR is single stage absorption cycle. The performance of hybrid cycle has been compared with AWMT and AAR cycles individually. The heat of rectifications has been decreased in AAR by sharing the working fluid. A combined power and cooling cycle with ammonia-water mixture as working fluid has been proposed (Xu et al., 2000). A parametric analysis has been carried in the chosen cycle. The cooling capacity increases with the rise in pressure and due to the decreased flow rate it descends. The temperatures of boiler, condenser, superheater and absorber have been considered as parameters influencing the performance. Power and cooling cycle can be used as an alternative to fossil fuel technologies (Tamm, 2003). Tamm et al., Tamm and Goswami (2003) and Hasan and Goswami (2003) proposed a combined power / refrigeration cycle using ammonia-water as the mixed working fluids and investigated its performance. Liu and Zhang (2007) proposed a power and refrigeration cycle. With the adoption of cogeneration system 18.2% decrease in energy consumption is achieved over a conventional separate power generation system.

Lu and Goswami (2002) conducted a theoretical analysis for a combined power and refrigeration cycle. Franco and Casarosa (2002) proposed the possibilities to increase the combined cycle plant efficiency and identified the key elements. Lu and Goswami (2003) proposed a combined power and refrigeration cycle which utilizes low temperature heat sources, such as geothermal energy, solar energy using flat plate collectors to produce power and refrigeration in the same cycle. Tamm et al. (2004) showed the feasibility of the vapor generation and absorption condensation processes experimentally. Vijayaraghavan and Goswami (2006) investigated a combined power and cooling technology. For maximum resource utilization efficiency (RUE), the cycle configuration has been optimized. Similar to Kalina cycle, a thermal distillation scheme has been implemented. Vidal et al. (2006) analysed a combined power and refrigeration cycle by the exergy method. This combined cycle utilizes ammonia-water mixture as the working fluid and the simulations has been carried out using ASPEN plus. Zheng et al. (2006) proposed a novel absorption power/cooling combined-cycle (APC) and carried out thermodynamic analysis using p-T, log p-h and T-s diagrams. Sadrameli and Goswami (2007) identified optimum operating conditions for a combined power and cooling thermodynamic cycle. The output has been obtained by expanding ammonia-rich vapor in an expander to sub-ambient temperatures and heating the cool exhaust.
A power and cooling cogeneration using ammonia-water mixture has been analysed (Padilla et al., 2010). It has been noticed that turbine exit quality decreases when the absorber temperature decreases. Pouraghaie et al. (2010) assessed thermodynamic performance optimization of a combined power and cooling cycle. Wang et al. (2008) proposed a combined power and refrigeration cycle, which combines the Rankine cycle and the absorption refrigeration cycle with binary ammonia–water mixture as the working fluid.

From the literature survey, it is clear that the Kalina cycle is suitable for low temperature applications. Kalina cycle also can be extended to combined cooling and power generation.

2.7 SUMMARY

The properties for binary mixture are tedious to develop as it belongs to five different regions. The property values in all the regions are required to solve the thermodynamic model. The correlations suitable for various temperature and pressure ranges have been concentrated in this work. The literature survey provides details about Kalina cycle and about the correlations developed for mixtures as working component. Various new designs for Kalina cycle have been developed earlier. But most of the designs have been developed with low temperature and high temperature heat recoveries. There are no sufficient developments for medium temperature heat recovery. It provides scope for developing a new model suitable for temperature ranging from 170 to 250 °C. In the literature, most of the power cycle has been developed at lower sink temperatures.