ABSTRACT

Paper mills, textile mills, sugar mills, oil refineries, cryogenic systems, steel manufacturing and food processing plants are the typical chemical and process industries that require both power and process heating (or cooling). From efficient energy utilization point of view, it is not advantageous to have two different plants for the power and process plant separately. This is because, fuel consumption and energy losses will be more and it will also lead to unnecessarily increase in the investment and operating cost of the plants. Cogeneration provides a cost effective method in which both power and thermal energy can be produced simultaneously from the same energy source in a single plant. Efficiency of a cogeneration plant is more than that of the individual power and process plants. There are other associated benefits of reduced emission, fuel flexibility, energy reliability and extended operating life of the plant components with cogeneration. A number of cogeneration systems are available. The typical cogeneration systems used in process industries include mainly the steam turbine (ST) based, gas turbine (GT) based, internal combustion engine (ICE) based and fuel cell (FC) based cogeneration systems.

A cogeneration system that produces power and cooling (or refrigeration) simultaneously is called a combined power and cooling (CPC) system. Energy conversion efficiency increases and cooling cost reduces with simultaneous production of power and cooling from the same thermodynamic cycle. There are binary mixture based CPC systems that use mostly ammonia–water (NH_3–H_2O) binary mixture as working fluid. In a NH_3–H_2O based CPC system, power is produced by expanding NH_3 vapour in a turbine. Simultaneous cooling is made possible in this system through expansion of NH_3 vapour to very low temperature without condensation. Combined production of power and cooling is also possible through waste heat recovery from ICE, ST and GT based thermal power plants. Among the various types of refrigeration systems, the absorption refrigeration systems are the ones that can be used in conjunction with the above. ICE exhaust and waste heat steams of ST and GT based thermal power plants are recognized as potential energy sources for absorption refrigeration systems. A vapour absorption refrigeration system (VARS) can also be driven by solar or geothermal energy. The ammonia–water (NH_3–H_2O) and water–lithium bromide (H_2O–LiBr) are the most commonly used working fluid pairs in a VARS. The H_2O–LiBr pair is

mainly suitable for air–conditioning and chilling applications above 4 °C while NH_3–H_2O is used in low temperature process cooling below 0 °C.

In this thesis, two ST based cogeneration systems are proposed and thermodynamic performance studies are carried out. The proposed configurations are basically combined power and cooling (CPC) systems where the topping cycle is a reheat regenerative type vapour power cycle (RRVPC) which is common in both the systems. The topping RRVPC consists of the usual power plant components such as boiler, ST, condenser, cooling tower (CT) etc. It uses a coal fired boiler for steam generation. It also employs one reheater for steam reheating, one open water heater (OWH) and one closed water heater (CWH) for regeneration of boiler feed water. The bottoming cycles are H_2O–LiBr VARSs of single and double effect type respectively. In the first CPC system, the single effect H_2O–LiBr VARS is driven by steam extracted from the ST of the topping RRVPC. In the second CPC system, it uses a double effect series type H_2O–LiBr VARS and the high pressure generator (HPG) of the VARS is driven by exhaust heat of the boiler leaving flue gas of the topping RRVPC.

First, the combined RRVPC and the single effect H_2O–LiBr VARS is chosen for thermodynamic performance evaluation. Thermodynamic models are developed to simulate the system components of the toping and bottoming cycle. A parametric analysis is performed to investigate the effect of boiler pressure, fuel flow rate, VARS evaporator cooling load and operating temperatures on performance of the CPC system. Further a performance comparison of the CPC system is made with the RRVPC (without VARS) to quantify the performance variation due to VARS integration. Comparative performance analysis is also provided for the RRVPC (without VARS) with and without the CWH in the plant. The analysis indicates that the fuel flow rate and boiler pressure affects only the power cycle performance while the evaporator cooling load and VARS components' operating temperature has its combined effect both on the power and the cooling system, the evaporator cooling load is the most crucial among them.

A sensitive analysis is also carried out separately for investigating the influence of VARS operating temperatures, fuel flow rate and boiler pressure on net power and efficiency of the topping RRVPC and VARS coefficient of performance (COP). The sensitivity analysis shows that the power and efficiency of the topping RRVPC change very little with VARS operating temperatures. VARS COP is more sensitive to the change in condenser and absorber temperature compared to change in generator and evaporator temperature.

Next, thermodynamic modeling equations are formulated to perform exergy analysis of the combined RRVPC and the single effect H_2O–LiBr VARS. Exergetic efficiencies of the RRVPC and VARS, energy utilization factor (EUF) of the CPC system and irreversibility in each system component are calculated. The effect of fuel flow rate, boiler pressure, evaporator cooling load and VARS components' temperature on performance, component and total system irreversibility is analyzed. The second law (exergy) based results indicate optimum performance at 150 bar boiler pressure and VARS generator, condenser, evaporator and absorber temperature of 80°C, 37.5°C, 15°C and 35°C respectively. Irreversibility distribution among various power cycle components shows the highest exergy loss with the boiler leaving exhaust flue gas. Boiler and ST are found to be the next major contributors of irreversibility. Among the VARS components, exergy destruction in the generator is the highest followed by irreversibility contribution of the absorber, condenser and the evaporator.

Next, a comparative energy and exergy analyses is provided between two combined systems (CSs), one with the previously analyzed single effect H_2O–LiBr VARS and the other with an R134a based vapour compression refrigeration system (VCRS) as bottoming cycles. The study quantifies the difference in performance of the topping VPC and the bottoming cooling system for the same operating conditions. Net power and efficiencies of the topping power cycle, COP and exergy efficiency of the bottoming refrigeration system (RS), EUF, exergy efficiency of the CS and irreversibility in components of the two systems are compared with respect to variation in cooling load. The comparative analysis indicates that the net power, EUF, efficiencies of the VCRS integrated CS are more than those of the VAR based system for the same operating conditions. Moreover, these are achieved in the VCR based CS with much lower total system irreversibility, higher COP and exergy efficiency of the bottoming RS.

Further, energy and exergy based performance analyses are performed on the combined RRVPC and boiler flue gas driven double effect H_2O–LiBr VARS. This is done to show the performance variation of both the topping RRVPC and the bottoming VARS with changing HPG temperature from 120 °C to 150 °C. The performance of this CPC system is also compared with a similar boiler flue gas driven system, integrated with the single effect VARS. Results show that the power and efficiency of the topping

RRVPC decreases with HPG temperature due to reduction in steam generation rate in the boiler. COP and exergy efficiency of the double effect VARS also reduces with increasing HPG temperature. The irreversible losses in the RRVPC components decrease while the total irreversibility of the CPC system increases with HPG temperature due to increase in exergy loss with the HPG leaving flue gas and irreversibility of the VARS components. Performance of the RRVPC does not vary much due to replacement of the double effect VARS with the single effect VARS, however higher COP and exergy efficiency of the double effect system are achieved with much lower irreversible losses in the HPG and VARS condenser of the double effect system.

The study reveals the possibility of integrating a H_2O–LiBr based VARS with a ST based VPC. There are two possibilities; either the steam extracted from a pass out ST or the boiler leaving flue gas exhaust could be the source of heat for the VARS. It would be appropriate to use the single effect VARS if it is to be driven by steam extracted from ST of the topping VPC. The double effect system would require steam extraction at high temperature; hence the power production from topping RRVPC will be less. In fact, the double effect VARS would be more appropriate for integration with the VPC if cooling at all is to be produced by using VARS without losing much power from the power cycle. Among the VCRS and VARS based CPC systems, the system with VCRS may be preferred if higher net power output and minimum total system irreversibility are the sole criteria. The single effect VARS based CPC system may be useful in case when excess steam is produced and lost unused in the topping VPC.