CHAPTER 7

CONCLUSIONS AND SCOPE FOR FUTURE WORK

7.1 Conclusions

In this thesis, two ST based CPC systems, one with a single effect and the other with a double effect H_2O–LiBr VARS have been proposed. The topping cycle in both the cogeneration systems is a ST based VPC which is reheat regenerative type. The topping RRVPC consists of the usual power plant components such as boiler, ST, condenser, pumps, cooling tower (CT) etc., where coal is used as fuel for steam generation in the boiler. The VPC employs a reheater for steam reheating and two regenerative feed water heaters (one open and one closed) for boiler feed water preheating. The CPC systems use a CT in the topping RRVPC for supplying cold water to the condenser of the RRVPC, and also to the VARS condenser, absorber and evaporator. The chilled water from the VARS evaporator passes through the AC apparatus and finally mixes with the hot return water streams from the VPC condenser, VARS condenser and absorber in a mixing chamber. The mixed hot water stream is then pumped to the CT for cooling purpose.

In the first configuration, the steam extracted from the ST of the topping RRVPC is used as heat source for driving the single effect H_2O–LiBr VARS. The single effect H_2O–LiBr VARS consists of a single generator, a condenser, an evaporator, an absorber, a solution pump, a SHE, a solution reducing valve and a refrigerant expansion valve. In the other configuration however, it is the exhaust heat of the boiler leaving hot flue gas that is utilized for driving the double effect H_2O–LiBr VARS. The double effect H_2O–LiBr VARS is a series flow type with two generators (one high pressure generator (HPG) and one low pressure generator (LPG)), two SHEs, two solution reducing valves, two refrigerant expansion valves and other common components. No external source of heat is utilized for vapor generation in the LPG of the double effect H_2O–LiBr VARS. The HPG off primary vapor provides the latent heat of condensation required for secondary vapor generation in the LPG from HPG off medium concentration solution.

In this research study, thermodynamic modelling and analyses have been presented separately for the above mentioned CPC systems. The modelling equations are formulated to perform energy and exergy analyses of the proposed CPC systems. First, the energy analysis is done for the combined RRVPC and the single effect H_2O–LiBr

VARS. A detailed parametric study has been carried out to evaluate the effects of boiler pressure, fuel flow rate, VARS evaporator cooling load (CL) and operating temperatures on performance of the CPC system. The fuel flow rate is varied from 5 kg s^{-1} to 20 kg s^{-1} in a step of 5 kg s^{-1} keeping the boiler pressure fixed at 150 bar. The boiler pressure is changed from 100 to 200 bar and during this variation; the fuel flow rate is kept fixed at 20 kg s^{-1}. During fuel flow rate and boiler pressure variations, the VARS CL, and component temperatures (generator, condenser, evaporator and absorber temperatures) are maintained at 4000 TOR, 80 °C, 35 °C, 10 °C and 35 °C respectively .The performance of the topping RRVPC is determined based on net power produced and overall efficiency. Additionally, Rankine cycle efficiency, ST power, BFP and CT side pumping power, steam extraction rate from ST and steam generation rate in the boiler are also evaluated. The VARS performance parameters is measured in terms of COP. Detailed variation regarding component heat loads, SP power, mass flow rates of the refrigerant (H_2O), LiBr salt, weak and strong solution etc. are also presented. It has been observed that the steam generation rate in the boiler increases with increase in fuel flow rate and boiler pressure. Net power output from the topping RRVPC also increases with increase in fuel flow rate. However, the maximum efficiency is found at a fuel flow rate of 10 kg/s and further increase fuel flow rate results in decrease of efficiency. With boiler pressure, the maximum net power and efficiency of the RRVPC has been found at 150 bar. In fact, it has been found that the efficiency of the RRVPC is not affected much by fuel flow rate and boiler pressure variation. Moreover, variation of these two parameters has no impact on performance of the bottoming VARS. Contrary to this, the performance of both the topping RRVPC and bottoming VARS is affected by evaporator CL and components' operating temperatures of the VARS. It has been found that the steam extraction rate from the ST increases with increase in VARS evaporator CL and consequently the power and efficiency of the topping RRVPC decrease at higher CL. However, the VARS COP is not affected by CL variation although it shows proportionate increase in heat loads of the other VARS components (except evaporator), SP power and mass flow rates of refrigerant, LiBr salt, weak and strong solutions.

Performances of both the topping RRVPC and bottoming VARS change with increase in the VARS generator temperature (T_G). With evaporator CL, SHE efficiency and other component operating temperatures fixed at the chosen values, the maximum net power and efficiency of the topping RRVPC and maximum VARS COP have been obtained at T_G =80 $^{\circ}$C during T_G variation from 70 $^{\circ}$C to 100 $^{\circ}$C. However, the topping and bottoming cycle performance with respect to T_G variation is subject to vary with the chosen values of the other fixed operating parameters.

With increase in VARS condenser and absorber temperatures, the topping RRVPC shows marginal reduction in its net power and efficiency. The VARS COP also decreases with increase in VARS condenser and absorber temperatures. The trend is however opposite with VARS evaporator temperature. With increase in evaporator temperature, net power and efficiency of the topping RRVPC increase marginally while the VARS COP increases. There is also reduction in SP power, VARS components' thermal load and mass flow rates of refrigerant, LiBr salt, weak and strong solutions at higher evaporator temperature.

The effect of the above parameters on topping and bottoming cycle performance has also been checked through a sensitivity analysis. From the sensitivity analysis, it has been found that that the power of the topping RRVPC is not very sensitive to the change in boiler pressure and VARS operating temperatures. Net power of the RRVPC however changes significantly with fuel flow rate showing direct proportionality between the two. VARS COP is not at all dependent on fuel flow rate and boiler pressure. COP is more sensitive to the change in condenser and absorber temperatures compared to the change in generator and evaporator temperatures.

A performance comparison has also been done between the CPC system and the RRVPC alone. The power only cycle (RRVPC) is the cycle with the bottoming single effect VARS disintegrated from the CPC system. Upon removal of the VARS, the necessity of steam extraction from ST of the topping RRVPC does not arise and hence ST develops more power and accordingly the RRVPC produces more net power output. This has been observed at all the boiler pressures considered in the study. The loss in developed ST power due to VARS integration with the RRVPC has been evaluated. With increase in boiler pressure, initially, more steam extraction is required for the VARS generator; hence ST power loss also increases. The rate of steam extraction however slightly reduces at 200 bar and hence the ST power loss also reduces at 200 bar. The net power of the RRVPC mainly increases due to the fact that one of the two CT side pumps installed between the CT and the mixing chamber of the CPC system is not required in the system without VARS. This causes significant reduction in the CT side pumping power. For both the systems, the minimum CT side pumping power has been found at a boiler pressure of 150 bar. The pump that is used for pumping condensates from the VARS generator is also removed in the RRVPC without VARS. However, this does not affect much in the total BFP pumping power. In fact the BFP pumping is slightly higher for the VARS integrated CPC system. The overall efficiency of the power only cycle is also slightly more than the CPC system at all boiler pressures. The maximum efficiency has been found at 150 bar.

Comparative performance analysis has also been provided for the power only cycle i.e. the RRVPC without VARS. The comparison has been done to quantify the change in performance of the RRVPC with and without CWH, for the same amount of fuel burnt in both the cases. It has been found that the net power of the RRVPC increases significantly when the CWH is considered in the plant. This is due to water preheating in the CWH that the water enthalpy at the boiler inlet increases and therefore, more steam is generated in the boiler when the CWH is put in the plant. This gain in net power however decreases with increasing boiler pressure, the gain varying from 5.92 MW at a boiler pressure 100 bar to 4.88 MW at 200 bar. At a given boiler pressure, actually the total pumping power requirement is more in the plant with the CWH than the plant without CWH. But the ST develops comparatively more power in the CWH integrated plant due to production of relatively more amount of steam in the boiler. Hence, the net power output is more from the plant with CWH. With increase in boiler pressure however, the difference between total pumping powers of the two plants increases. Simultaneously, the difference between powers developed by the STs of the two plants also decreases. This causes a reduction in net power gain at higher boiler pressure.

Next, thermodynamic formulations have been developed to perform exergetic performance analysis of the combined RRVPC and single effect H_2O–LiBr VARS. Irreversible losses in various system components of the topping RRVPC and bottoming VARS have been calculated. Exergy efficiency has been determined separately for the RRVPC and VARS and also for the combined system. The EUF of the CPC system has also been evaluated. Parametric analysis has been carried out to show the system performance variation with fuel flow rate, boiler pressure, evaporator CL and VARS components' temperatures. It has been found that increase in fuel flow rate not only increases the net power output of the topping RRVPC but simultaneously the irreversible losses also increase in the power cycle components including the irreversibility of the flue gas exhaust. Irreversibility in VARS components is not affected by fuel flow rate variation. With increase in boiler pressure, the boiler irreversibility which contributes maximum to the total irreversibility actually decreases. In the ST and one of the mixing chambers (MC1) however, irreversibility shows an increasing trend with boiler pressure. In some other components (power cycle condenser, CT, CTPs, MC3), the irreversibility variation with boiler pressure is such that the minimum irreversibility has been found at 150 bar. Irreversible losses with the exhaust flue gas don't vary with boiler pressure. In the VARS components, boiler pressure variation affects the irreversible losses only in the VARS generator where irreversibility has been the minimum at 150 bar. Thus it has been observed that it is not only the net power of the combined system which is the maximum, but the total irreversibility is also the minimum at 150 bar.

With evaporator CL, the net power output, energy and exergy efficiency of the topping RRVPC slightly reduces including the exergy efficiency of the CS. The EUF of the CS however increases marginally due to increase in the amount of cooling produced. More cooling is possible at higher evaporator CL, however with reduction in net power from the topping RRVPC. Irreversibility in the power cycle components has mixed response to CL variation. Irreversibility decreases in the ST, OWH, CT and MC1 while it increases in the MC3 and the CTPs. Irreversibility in the boiler, CWH, BFPs and the exhaust irreversibility is not affected at all due to CL variation. In the VARS components however, irreversibility shows an increasing trend and consequently the total irreversibility of the CS becomes more at higher CL.

With generator temperature T_G, the irreversible losses in the CS components vary in such a way that the minimum total system irreversibility has been found at T_G =80 °C. In the topping RRVPC, boiler, CWH and exhaust irreversibility has not been found to vary with T_G. Similarly, the irreversibility in the evaporator, AC apparatus and the expansion valves of the VARS also is not affected by T_G variation. In the ST, MC3, CT CTPs of the topping RRVPC and SHE of the bottoming VARS, the irreversibility has been the minimum at T_G =80 °C. Hence, the exergy efficiency of the topping RRVPC and also the CS has been the maximum at T_G =80 °C. Irreversibility in the VARS generator, condenser and absorber however, increases with increase in T_G. Thus the VARS exergetic efficiency has also been found to decrease with increasing T_G. Only in the OWH of the topping RRVPC and solution pump of the bottoming VARS, the irreversibility shows a continuously decreasing trend with increasing T_G.

The performances of the topping RRVPC, bottoming VARS and the CS, although not very sensitive, but have been found to decrease marginally with increase in T_C. Net power output, energy and exergy efficiency of the RRVPC; COP and exergy efficiency of the VARS; EUF; exergy efficiency of the CS: all decrease with increase in T_C. However, the total system irreversibility has been found minimum at T_C =37.5 °C.

Same trend has also been observed with T_A variation. The performances of the RRVPC, VARS and the CS decrease slightly with increase in T_A. The total system irreversibility is also the lowest at T_A =35 °C.

With increase in T_E however, an opposite trend has been observed. The RRVPC, VARS and the CS shows slight improvement in their performances when T_E is increased from 5 °C to 15 °C. Thus, the minimum total system irreversibility has been found at T_E =15 °C.

Irreversibility distributions among the RRVPC and the VARS components have been shown separately. The highest exergy loss has been found with the boiler leaving flue gas exhaust. The boiler and the ST of the RRVPC also contribute significantly to the total irreversibility. In the bottoming VARS, exergy destruction has been the highest in the generator. The next major contributors are the absorber, condenser and the evaporator respectively.

After performing exergy analysis on the combined RRVPC–VARS, next energy and exergy analyses have been performed on a combined RRVPC–VCRS to compare its performance with that of the RRVPC–VARS. Performance comparison has been shown for same evaporator CL of the two systems and also with respect to CL variation. R–134a has been used as working fluid in the VCRS. From the comparative analysis, better performance has been observed in respect of the combined RRVPC–VCRS. Net power and efficiencies of the topping RRVPC, COP and exergy efficiency of the bottoming cooling system are higher for the combined RRVPC–VCRS than those of the RRVPC–VARS. The total system irreversibility is also less in the VCRS integrated CS compared to that of the VARS based CS. In the R–134a based VCRS, the highest irreversibility has been found in the condenser followed by exergy destruction in the evaporator, compressor and the expansion valve.

Further, one more novel combined RRVPC and H_2O–LiBr VARS has been considered for energy and exergy analyses. The bottoming VARS in this new configuration is a series flow type double effect system and this is driven by waste heat of the boiler leaving flue gas. Actually, the results of the above comparative analysis have been the source of motivation behind considering this new CPC system with the boiler exhaust as possible heat source for the bottoming double effect VARS. Thermodynamic modelling has been developed for evaluating energetic and exergetic performance of the CPC system. The performances of the topping RRVPC, bottoming double effect VARS and also the CS have been evaluated with respect to the HPG temperature which is varied from 120 °C to 150 °C in this study. From the obtained results, it has been found that the power and efficiencies of the topping RRVPC, COP and exergy efficiency of the double effect VARS decrease with increasing HPG temperature. This is obvious because flue gas and HPG temperatures are directly related and the boiler generates less steam when the flue gas leaves the boiler at relatively high temperature. The irreversible losses of the topping RRVPC components reduce due to less steam production at higher HPG temperature. However, the exergy loss with the HPG leaving flue gas increases. The irreversibility in the VARS components also shows an increasing trend and consequently, the total irreversibility of the CPC system increases with HPG temperature.

Next, a performance comparison of this boiler flue gas driven double effect VARS integrated CPC system has been provided with a similar boiler exhaust driven CPC system with single effect VARS. For performance comparison, same flue gas temperature (130 °C) has been considered in both the systems. Moreover, in the double effect VARS, the HPG and LPG temperatures are taken as 120 °C and 80°C respectively while in single effect VARS, the generator temperature is taken 80 °C. It has been found that the toping RRVPC performance does not change much with whether it is the double effect or the single effect VARS at the bottom. The COP and exergy efficiency of the double effect system are higher and more significantly, the irreversible losses have been much lower in the HPG and condenser of the double effect system. Due to presence of relatively more number of components and higher flue gas exergy loss, the total system irreversibility has been more in the double effect system. But magnitude wise, the difference between the total components' irreversibility (excluding flue gas exergy) of the two systems has not been that very significant.

Finally, the contributions of this research study may be summarized as follows:

- The possibility of using H_2O–LiBr based VARSs in combination with ST based power system is explored in this study.
- The various possibilities are considered and thermodynamic performance studies have been carried out not only from the energetic point of view but also from the exergetic performance viewpoint giving all the performance details.
- Effect of important system operating parameters has been evaluated through parametric studies.
- The energetic and the exergetic performance comparison is provided for a particular (single effect) steam driven VARS based CPC system with a conventional VCRS based CPC system. Important conclusions have been made regarding selection of appropriate CPC systems.
- The VCRS integrated CPC system has been found preferable in situation where higher net power output, minimum cost and minimum total system irreversibility are the sole criteria.
- The single effect steam driven VARS based CPC systems is undoubtedly useful in situations where there is excess and unutilized steam in the topping ST based power system.
- The double effect VARS is more appropriate for integration with the topping ST based RRVPC provided it is operated at appropriate temperature with the exhaust heat of the boiler leaving flue gas.

7.2 Scope for future work

The following related works may be carried out in future to enhance the possibility of using the proposed ST based cogeneration system integrated with salt solution based absorption refrigeration systems.

1. Thermo–economic/exergo–economic analysis is certainly one area in which the current research topic be extended.

2. Thermo–economic/exergo–economic optimization studies are also possible with the proposed ST based CPC systems.

3. The other possibilities of using boiler flue gas exhaust heat may be explored. Accordingly other heat driven co/tri/multi-generation systems may be considered for analysis.

4. Fuels other than coal may be considered for burning in the boiler furnace to possibly lower the flue gas temperature for using it for other purposes.

5. In case of VARS, other salt solution pairs be considered and different configurations of double and triple effect VARS be analyzed for evaluating their thermodynamic performance.

6. New GT/ST/combined GT–ST based co/tri/multigeneration systems be configured and thermodynamic analysis be carried out involving heat driven power or cooling systems.

7. Solar and other renewable energy based co/tri/multigeneration systems can also be analyzed to evaluate their thermodynamic performance.