CHAPTER 6

CONCLUSIONS AND SCOPE FOR FUTURE WORK

6.1 Conclusions

The objective of this study is to develop a new configuration of solid oxide fuel cell (SOFC) –gas turbine (GT) – steam turbine (ST) integrated combined cycle power plant system with a single pressure bottoming ST cycle. This thesis also presents the development of a thermodynamic model based on the proposed system. The proposed SOFC integrated combined GT–ST based power system has been simulated using a mathematical model. Subsequently, the proposed system with single pressure ST cycle has been analyzed based on both the first and second laws of thermodynamics. A parametric analysis of the variation of CPR, FFR, AFR, current density, boiler pressure, STIT and particularly the burning of additional fuel in the combustor is conducted to identify the importance of these operating parameters on energy and exergy based performance (power, efficiency and system irreversibility) of the hybrid SOFC combined GT–ST system. Generally, in a SOFC integrated combined GT–ST power system, the power produced by the GT and particularly the ST plant is considerably less to make their integration economically feasible. Moreover, small sized micro GT and especially the ST are not exceedingly efficient at comparatively small sizes. Therefore, as a possible means to increase the GT and ST power, the effect of additional fuel burning was studied at various CPR and it was observed that bypassing certain amount of the fuel and burning it in the combustor results in significant increase in the GT and ST power. However, the efficiency of the plant also reduces simultaneously.

A parametric analysis based on the variation of CPR is first conducted to evaluate the energy and exergy based performance (power, efficiency and system irreversibility) of the hybrid SOFC combined GT–ST system. Varying the CPR from 6 to 14 it was observed that the efficiency of the hybrid SOFC–GT–ST system increases with regard to the CPR for both the cases with and without additional fuel burning. The SOFC and GT plant produces more power at comparatively high CPR while the ST power reduces with increase in CPR. The overall net power output and system efficiency increases with the CPR. Considering 50% additional fuel burning, it was observed that the gain in total power increases from 19.73% at CPR 6 to 27.54% at CPR 14 with corresponding decrease in efficiency from 20.91% to 15.77% at CPR 6 and 14, respectively. Further, it was observed that the gain in total power increases with CPR while the loss of efficiency decreases. Therefore, such a combined plant with additional fuel burning requires to be operated at a comparatively high pressure for power gain from the bottoming GT and ST plants and to avoid higher loss of efficiency. Moreover at CPR 14, a gain of 91.78% and 126.87% in the GT and ST power plants, respectively, was noticed with 50% additional fuel burning. It was also found that the SOFC, combustor and PR of the topping SOFC–GT cycle and HRSG of the bottoming ST plant primarily contribute to the overall system irreversibility. However, on increasing the CPR, the loss of exergy in these components decrease significantly that essentially implies the importance of operating a hybrid SOFC–GT–ST plant at comparatively high pressure to obtain maximum benefit from the plant.

Based on the parametric variation of single level boiler pressure in the bottoming ST plant, the optimized boiler pressure was observed to be 40 bar with 50% additional fuel burning. At this pressure, maximum power is produced by the ST plant and also by the proposed SOFC integrated combined plant at a given CPR. The HRSG irreversibility reduces but the irreversibility in the topping SOFC–GT cycle components and the exhaust exergy loss do not change considerably; however, the irreversibility in the other bottoming ST cycle components increase with the boiler pressure, hence the total system irreversibility is more at a comparatively high boiler pressure.

Increase in the FFR directly affects the net power production and efficiency of the power plant but it also simultaneously increases the irreversible losses in the plant components including the exhaust irreversibility. Increased AFR and current density have negative effects on the overall system performance, although a comparatively large amount of air assists in the SOFC stack cooling at times. The current density directly affects the SOFC stack temperature that increases with increase in the current density. The SOFC and ST plants produce more power at comparatively high STIT and thus the overall power and plant efficiency increases with the STIT. Moreover, the total system irreversibility is less at higher STIT and the maximum STIT is limited by metallurgical considerations.

On comparing the performance between the FRAOAR and ARAOFR SOFC–GT–ST configurations, FRAOAR demonstrates better performance. It was also observed that the exergy efficiency of the combined plant was less compared to the energy efficiency. Based on the combined energy and exergy analysis, it can be concluded that the proposed hybrid SOFC–GT–ST would work efficiently if operated at comparatively high pressure with minimum irreversible losses in the overall system. Further, certain amount of additional fuel burning in the combustor bypassing the SOFC might be considered to boost the power output from the GT and ST plant for their effective downstream integration without substantial loss of efficiency. This will also fulfill the thermo–economic criteria of integration of the bottoming GT and ST cycles.

Based on known net power, efficiencies (energy and exergy) and total system irreversibility of the SOFC–GT–ST system at CPR 6 and 14, next, an inverse analysis is conducted to estimate the six operating parameters simultaneously viz. FFR, additional FFR, AFR, boiler pressure, current density and STIT. A DE based inverse method, which is found to be an appropriate algorithm for estimating the unknown operating parameters is applied for the inverse analysis. The net power, efficiencies (energy and exergy) and total system irreversibility were selected as objective functions for the inverse analysis. Up to 100 iterations were considered and only five test runs were executed for all objective functions at CPR 6 and CPR 14. It was observed that multiple combinations of operating parameters satisfy a particular objective function and these parameters satisfying a given objective function are unique within a prescribed range. This method imparts significant scope for selection of suitable operating parameters from various combinations that fulfill a particular objective function. Therefore, it can be concluded that the DE based inverse method is a useful technique to obtain solutions of inverse CC power system modelling involving a SOFC.

Based on the estimated parameters and the forward program, new performance parameter values were derived. It was first observed that the total system irreversibility is proportional to the net power; higher the net power of the plant, more is the total system irreversibility. This is evidently true at a fixed CPR, although in reality the total system irreversibility reduces with the increase in CPR and the SOFC–GT–ST plant produces more power with increased efficiency at a comparatively high CPR. However, in certain estimations corresponding to the total system irreversibility at CPR 6 and CPR 14, it was observed that the objective functions relating to the system irreversibility are exactly satisfied but with comparatively high net power output and efficiencies. The DE based inverse method was quite successful in estimating the operating parameters of the hybrid SOFC–GT–ST plant and sometime better combination of parameters could be obtained from the inverse analysis.

Next, a thermodynamic model was developed to analyze the energy and exergy based performance of a SOFC integrated combined cycle power system with a triple pressure reheat ST cycle. A parametric analysis based on the CPR variation was conducted to evaluate the net power, efficiencies (energy and exergy) and irreversibility of this novel hybrid SOFC–GT–ST system. Further, thermodynamic modelling was developed for two other systems with dual pressure reheat and single pressure ST cycles for performance comparison amongst all, under identical conditions. In this modelling, pinch point principle was used in modeling HRSG of the three bottoming ST cycles. Further, an OWH was used for feed water heating in the bottoming ST cycles which was not there in the previously analyzed SOFC–GT–ST system with single pressure ST cycle. The performance comparison among the systems with three different bottoming ST cycles demonstrated that the system with single pressure ST cycle performs better compared to the dual and triple pressure reheat cycles. The power and efficiency of the system with single pressure ST cycle was the highest among the three and the total irreversibility was also minimal for this cycle. The lowest power and efficiency were obtained for the system with triple pressure reheat cycle and it produced the highest total irreversibility. It is evident that the system with triple pressure reheat cycle will be more complex than the one with single pressure ST cycle. The total cost of this plant including the capital, operating and maintenance cost will be high owing to more number of components in it. Therefore, based on this point of view, the SOFC–GT–ST system with single pressure ST cycle will be the most appropriate. Future studies based on the thermo–economic optimization, maximizing performance or minimizing irreversibility, and the total cost of the three configurations will provide a better understanding in this regard. Evidently, the present observations are useful in providing a thorough comprehension of the performance of the three systems based on the first and second laws of thermodynamics. Moreover, these are outcomes of the selected range (15–20°C) of temperature difference at the superheater inlet of all the cycles. The obtained results are also significant owing to the pinch point temperature difference of 20°C, selected between flue gas and saturated water at the evaporator inlet of (i) HRSG low pressure stage (3 bar) of the triple pressure cycle, (ii) second stage (40 bar) of the dual pressure reheat cycle and (iii) the single stage (40 bar) of the single pressure ST cycle.

6.2 Scope for future work

The following related works may be carried out in future to enhance the possibility of using the proposed SOFC integrated CC power system.

1. The current research may be extended for performing thermo–economic/exergo–economic analysis of the proposed SOFC integrated CC power systems.
2. Thermo–economic/exergo–economic optimization studies will reveal more details about the optimum performance of the proposed systems. Thermo–economic and optimization studies aimed at evaluating an optimal design for these plants can be another significant area of future research in this field.
3. New SOFC based co/tri/multigeneration systems be configured and thermodynamic analysis be carried out. Future studies on comparative parametric based performance analysis of various such SOFC based configurations could reveal numerous details with regard to performance of these hybrid SOFC plants both from the first law and second law analysis point of view.
4. Further, these new design configurations of SOFC based multigeneration systems might be analyzed to evaluate their economic feasibility via thermo–economic/exergo–economic analysis. These comparatively new systems can later be optimized to determine the optimal parameters with regard to both design and part load conditions for maximizing the power and efficiency and minimizing the total irreversible losses and cost.
5. Certain dynamic/transient analyses on hybrid SOFC–GT systems have been conducted but this an area of study not entirely developed yet and there is sufficient scope of research, particularly regarding comparatively new hybrid SOFC–GT–ST configurations. Dynamic modelling can be developed to evaluate the performance of the hybrid SOFC systems and design suitable control strategies in transient conditions such as start up, shut down, severe load changes.

List of Publications

- **Pranjal Sarmah** , T.K. Gogoi, Performance comparison of SOFC integrated combined power systems with three different bottoming steam turbine cycles, Energy Conversion and Management,132 ,2017

- **Pranjal Sarmah** , T.K. Gogoi, R. Das, Estimation of operating parameters of a SOFC integrated combined cycle using differential evolutionary based inverse method, Applied Thermal Engineeringt,119 ,2017

- T. K. Gogoi, **Pranjal Sarmah**, D. Deb Nath. Energy and exergy based performance analyses of a solid oxide fuel cell integrated combined cycle power plant, Energy Conversion and Management, 86, 2014.

- **Pranjal Sarmah** and T.K. Gogoi, Exergy analysis of a solid oxide fuel cell (sofc) integrated combined power cycle, in the Proceedings of the 17th ISME Conference on Advances in Mechanical Engineering held during October 3-4, 2015 at IIT Delhi, New Delhi.

- T. K. Gogoi and **Pranjal Sarmah**, Exergy analysis of a hybrid solid oxide fuel cell -gas turbine configuration. In Proceedings of International Conference on Environment and Energy (ICEE) IJNTUH, Kukatpally, Hyderabad, 2014.

- **Pranjal Sarmah** and T. K. Gogoi, Parametric analysis of a hybrid solid oxide fuel cell -gas turbine plant. In Proceedings of International Symposium on Aspects of Mechanical Engineering & Technology for Industry, NERIST, Arunachal Pradesh, 2014.