Energy, Exergy, Exergoeconomic and Environmental (4E) analyses and Multi-objective Optimization of four Gas Turbine based Trigeneration systems

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Chapter 6

Conclusions and future scopes

6.1 Conclusions

This thesis proposes four novel gas turbine (GT)-based trigeneration systems (combined cooling heating and power (CCHP) systems) for the generation of electricity, chilled water, and hot water. The topping cycle is a recuperative GT cycle and the bottoming cycle includes a heat recovery steam generator (HRSG), a steam turbine (ST) cycle, a recuperative-regenerative organic Rankine cycle (RR-ORC) and absorption cooling systems (ACSs). The novel feature of this study is the detailed modelling, analyses, multi-objective optimization, and multi-criteria decision analysis of the proposed system configurations, which have never been investigated in any prior literature. The CCHP systems are developed in three phases. In the first phase, four layouts of GT-based combined power and cooling (CPC) systems are proposed that simultaneously generate power and cooling outputs. The four configurations of CPC systems include a simple GT cycle as the topping cycle (prime mover) and an ST cycle, a recuperative-ORC and ACSs as the bottoming cycle. The four systems are different in terms of subsystem layouts and integration schemes in the bottoming cycle. In two of the systems (CPC system-I and CPC system-II), back-pressure steam turbines and recuperative-ORC are used; however, in CPC system-III and CPC system-IV, recuperative-ORCs are completely replaced with the condensing-type steam turbines. Additionally, CPC system-I and CPC system-IV include two ACSs, one driven by wet steam and the other by flue gas. CPC system-II and CPC system-III, on the other hand, only have one flue gas-driven ACS. The performance of the CPC systems is evaluated using energy and exergy analyses. The four CPC system configurations are then retrofitted into more advanced CCHP systems with three architectural modifications in the second phase. The CCHP systems are not directly presented in this thesis but rather shown in three stages of modification to show how architectural changes may improve an energy conversion system's overall performance.

The first modification is the substitution of a recuperative GT cycle for a simple GT cycle. Since the recuperative GT cycle has been shown in the literature to be more efficient and cost-effective than the simple GT cycle. Additionally, it has been found that there are four potential ORC architectures, namely basic ORC, recuperative ORC, regenerative ORC, and recuperative-regenerative ORC. The recuperative-regenerative ORC is discovered to be the layout with the highest efficiency among those mentioned above. The exergoeconomic performance of the recuperative-regenerative ORC, however, has not been covered in any prior research. Therefore, this thesis also provides a comparative analysis of the four ORC layouts using energy, exergy, and exergoeconomic analyses. The performance of the ORC layouts is evaluated in their optimal operational condition, which is established through the use of multi-objective optimization by applying Pareto Envelope-based Selection Algorithm-II (PESA-II) with exergy efficiency and system cost rate as the objective functions. In addition, multi-criteria decision analysis is used to choose the final optimal solution from the set of optimal solutions obtained through optimization. The multi-criteria decision analysis is carried out using the technique for order of preference by similarity to the ideal solution (TOPSIS).

Realizing the importance of heating requirements in process industries, additionally, a water heater is integrated to prevent any extra heat from the GT exhaust from escaping into the environment and to provide additional hot water to meet the heating demand. Trigeneration of power, cooling and heating is achieved finally through the integration of the water heater into the system configurations. Then in the third phase, the viability of the modified CCHP systems is determined using a combined 4E assessment, which includes energy, exergy, exergoeconomic, and environmental evaluations. In fact, the 4E performance of the CCHP systems is also compared with those of the CPC systems with identical operating conditions. The optimal operating conditions for the CCHP systems are then obtained through the use of multi-objective optimization and multi-criteria decision analysis. Prior to that, a parametric study is carried out to determine the impact of key operating conditions on the performance of the four CCHP systems. Then those operating conditions are used for performing a multi-objective optimization by applying PESA-II with energy efficiency, exergy efficiency and total cost rate as the objective functions. The system cost rate and the environmental cost rate are both included in the total cost rate. Thereafter, multi-criteria decision analysis is performed using the TOPSIS decision-maker to determine the best optimal solution from the Pareto front. Further, to show the benefit of optimization, the values of the objective functions are compared at the optimal and the base case conditions. Finally, the energy efficiency, exergy efficiency, and total cost rate evaluated under the optimal operating conditions are chosen as the criteria to compare the performance of the four CCHP system configurations. Then using the TOPSIS decision-maker the CCHP systems are ranked, giving each criterion equal priority. The first system configuration (system-I) is found to be the best-performing CCHP system.

The following conclusions are drawn in this PhD thesis from the energy and exergy analyses conducted on four configurations of CPC systems, exergoeconomic analyses on the four ORC layouts and 4E analyses on CCHP systems operating at optimal conditions.

- The energy and exergy analysis of the CPC systems revealed that, at the same operating state, the condensing type ST produces more power than the back-pressure type ST. It is because the steam is expanded up to a condenser pressure that is typically lower than atmospheric pressure in the condensing type ST, and thus more power is generated. However, the steam is expanded well above atmospheric pressure in the back-pressure type of ST, resulting in less power generation. The exergy destruction is also found to be greater in the condensing type of ST than in the back-pressure type of ST. Yet again, the cause for greater exergy destruction in the condensing type of ST is due to greater steam expansion, which results in more irreversibility due to fluid friction and heat transfer. Additionally, when the ST cycles are compared on a subsystem basis, the condensing type of ST cycle exhibits significantly higher overall exergy destruction as compared to the back-pressure type of ST cycle due to the presence of the condenser and open water heater.

- The physical exergy calculated at each unique state point of a system is typically evaluated as a positive quantity during exergy analysis. However, it is noted in this study, the physical exergy is negative at state points corresponding to the inlet and outlet of evaporators as well as across the expansion valves of the ACSs of the four CPC systems. Particularly for system-I, the physical exergy at the inlet (state 25) and outlet (state 26) of the evaporator (EVA-I) is negative because the temperature (278.11 K) and pressure (0.87 kPa) at those sites are both lower than the dead state temperature (298.15 K) and pressure

(101.15 kPa). The physical exergy across the expansion valve (EV-Ib) (states 31 and 32) is negative because, despite the higher temperatures (321.9 K) there than in the dead state, the pressure is lower (5.65 and 0.87 kPa) than the dead state pressure.

- The combustion chamber (CC) has the highest irreversibility of all system components among all four CPC system configurations, with the highest exergy destruction rate as well as the highest exergy destruction ratio. As we are aware, three main factors lead to irreversibility: chemical reactions, heat transfer through finite temperature difference, and fluid friction, with chemical reactions being the predominant contributor. Since the combustion of natural gas and air occurs in the CC, all three of the aforementioned irreversibilities are present, leading to very high exergy destruction.

- The exergy flow diagram shows that the GT plant alone is responsible for the highest destruction of fuel exergy in all four CPC system configurations. The major contributor to the GT cycle is the CC followed by the GT and the air compressor. The ST cycle is the next in order followed by ACS-II. The ST is the primary contributor in the ST cycle, while in the case of ACS-II; the generator is the primary contributor. Additionally, it has been noted that a sizeable portion of the fuel exergy supplied to the system is lost to the environment with exhaust gas.

- Based on energy analysis, CPC system-I performs better than the other CPC systems, having the highest net energy output and energy efficiency. On the other hand, CPC system-III outperforms the remaining CPC systems based on exergy analysis with the highest exergy efficiency and lowest overall exergy destruction rate. It emphasises the important point that simply when an energy conversion system displays higher performance based on energy analysis, it does not necessarily follow that the system's performance will be the same based on exergy analysis.

- The parametric analysis of the four ORC layouts reveals that the overall energy efficiency of ORCs increases as evaporator temperature rises and eventually drops. The system cost rate of ORC layouts, on the other hand, decreases as the evaporator temperature rises until the minimum value is reached and then begins to rise again. Additionally, it is noted that the basic ORC's exergy efficiency peaks around 380 K, but the exergy efficiency of the remaining layouts peaks around 385 K. Furthermore, the system cost rate nearly reaches its lowest value for all ORC layouts at the same temperature (370 K). The parametric analysis further demonstrated that the exergy efficiency increases while the system cost rate drops linearly as the condenser temperature and PPTD of the ORC layouts increase.

- The Pareto fronts obtained from the multi-objective optimization of the ORC layouts are overlaid into the same objective space to compare the performance at their optimal conditions. It revealed that the range of exergy efficiency is highest and the range of system cost rate is lowest for the RR-ORC. Similarly, the basic ORC has the highest range of system cost rates and the lowest range of exergy efficiency. Regenerative ORC and Recuperative ORC are the next ORC configurations in order after the RR-ORC. In fact, the performance comparison of ORC layouts at their optimum conditions identified by multi-criteria decision analyses also showed that the RR-ORC is the best-performing layout with the highest exergy efficiency and lowest system cost rate.

- The exergoeconomic analysis of the CCHP systems showed that the CC is the most crucial component with the highest sum of exergy and non-exergy-related costs in all four system configurations. However, the cost associated with the exergy destruction is predominating in the CC. It is important to highlight that, despite being the most critical component; the CC's performance has been greatly enhanced in the CCHP systems as compared to the CC installed earlier in the CPC system configurations. In fact, the performance comparison between the CCHP systems and CPC systems revealed that by incorporating an air preheater into the simple GT cycle, the exergy destruction at the CC is reduced by 12.70%. It is because the installation of an air preheater at the inlet of the CC raises the temperature of the compressed air, thus reducing the irreversibility generated due to the combustion reaction and heat loss.

- The overall performances of the CCHP systems are compared with the previously proposed CPC systems. For unbiased comparison, the objective functions; energy efficiency, exergy efficiency and total cost rate for both CPC and CCHP systems are evaluated at the same base case condition. It was found that all four configurations of CCHP systems have higher energy and exergy efficiencies and lower total cost rates as compared to their CPC counterparts. This supports the claim that the changes made to CPC systems to convert them to CCHP systems have improved the overall performance and made the systems more efficient, cost-effective and environmentally friendly.

- The parametric analysis of the CCHP systems showed that, for all the operating conditions taken into consideration, trade-offs exist between the objective functions (energy efficiency, exergy efficiency, and total cost rate). It is important to note that among the objective functions, an improvement in energy efficiency and exergy efficiency is desirable, whereas an increase in the total cost rate is undesirable. The parametric results revealed that as the AC pressure ratio, AC isentropic efficiency, GT isentropic efficiency and APH outlet temperature increase, the energy efficiency and exergy efficiency also increase, but at the same time, the total cost rate of the systems increases too. In the meantime, as ST inlet pressure rises, energy and exergy efficiency rises and the total cost rate falls, but at higher ST inlet pressure, the energy efficiency begins to decline modestly. Lastly, it was also observed that as the PPTD rises, energy efficiency and total cost rate increase whereas the exergy efficiency reduces. The parametric analysis cannot give direct favourable operating conditions for the CCHP systems due to the presence of trade-offs. Therefore, multi-objective optimization is used to obtain the optimal operating conditions for the CCHP systems.

- The optimal operating conditions obtained through the use of multi-objective optimization and multi-criteria decision analysis give higher energy and exergy efficiency for all four CCHP systems with a lower total cost rate. It shows that the overall performance of the CCHP systems is improved while operating under optimal conditions. Furthermore, to observe the variations of the decision variables, the scattered distribution plots of the decision variables corresponding to all four CCHP systems were studied. The scattered distribution plots illustrate the distribution of the non-dominated population in the decision space. It shows how a decision variable affects the trade-offs that exist between the objective functions. From the assessment of the scattered distribution plots, it can be inferred that the key variables that have the greatest impact on the trade-off solutions are the AC pressure ratio, AC isentropic efficiency, APH outlet temperature, and PPTD.

- To compare the 4E performance of the CCHP systems, again energy efficiency, exergy efficiency, and total cost rates are considered as the decision criteria. The Entropy-TOPSIS decision-maker was then employed to rank the CCHP systems because it was difficult to establish a conclusive decision based on the observations. The optimum conditions were used to evaluate each criterion for the four CCHP systems. It was found that system-I is the best-performing CCHP system. Moreover, system-IV is found to be the second-best performing system, while system-II and system-III are the third and fourth-best CCHP systems, respectively. However, depending on the quantity of power, cooling, and heating required, other CCHP system configurations presented in this thesis can be implemented. In fact, if a facility does not require heating, the four recommended CPC system configurations can also be implemented.

6.1.1 Contributions of this research study

The contributions of this research study may be summarized as follows:

- In this study, the feasibility of utilising several subsystems, such as HRSG, ST cycle, ORC, ACS, and water heaters, is investigated to recover waste heat from the GT exhaust gas and improve the combined system's overall 4E performance.

- A comprehensive framework for multi-objective optimization and multi-criteria decision analysis based on 4E analyses of complex GT-driven trigeneration systems is presented.

- This thesis uses energy, exergy, and exergoeconomic (3E) analyses to establish that the RR-ORC is the best ORC configuration for waste heat recovery applications. For comparing the ORC layouts, the optimal operating conditions for each layout are also identified by applying multi-objective optimization and multi-criteria decision analysis.

- In this study, it was also demonstrated that with architectural modifications, the overall performance of an energy conversion system can be improved to a great extent.

- This thesis also demonstrates that the performance of a CC can be improved by preheating the compressed air at the outlet of the air compressor by incorporating a recuperator.

- It is shown that even though the condensing type ST produces more net power than the back-pressure ST, the purchase equipment cost of the condensing type ST is much greater.

- This thesis also demonstrates that the overall performance of energy systems can be further improved by applying multi-objective optimization and multi-criteria decision analysis.

6.2 Future research scope

The outcomes of this thesis also highlight several potential research areas, as listed below:

- To design and develop solar-assisted GT-based trigeneration systems.
- To conduct advanced exergy end exergoeconomic analysis to comprehend the impact of the avoidable and unavoidable parts of exergy destruction in each component of the trigeneration system. Furthermore, optimization should be carried out to minimize the avoidable exergy destruction in each component.
- To incorporate a solid oxide fuel cell with GT cycles for greater fuel usage and increased power generation capability.
- To perform the 4E analysis for various climatic conditions and inflation rates, as well as to explore the effect of relevant parameters on optimal results.
- A double-effect ACS should be used in place of a single-effect ACS in order to reduce the exergy destruction at the generators during heat recovery from the exhaust gas/steam.