Abstract

Energy is the key to the sustainability of human existence. It is also the measure of prosperity and development in a society. However, the rapid growth in population and industrialization has increased the global energy demand in terms of electricity, heating and cooling to a great extent and resulted in energy crises. Furthermore, around 80% of the current global energy consumption is fossil fuel-based despite the substantial progress over the last few decades in the field of renewable energy. Thus, to meet the growing demand, fossil fuel, which is already limited in nature, is burned excessively. As a result, the pollution caused due to the burning of fossil fuels, especially the emission of greenhouse gases like CO_2, has led to many environmental issues, such as global warming and climate change. Besides, conventional power plants are relatively inefficient and, could convert only about 30%-35% of the fuel's available energy into power and, a large portion of the remaining energy is rejected to the ambient in the form of low-grade heat that eventually adds up to thermal pollution. In this regard, the use of cutting-edge technologies to reduce global warming and improve the efficiency of energy systems is a crucial goal, and several nations have proposed and implemented solutions to achieve them. Trigeneration systems are one such option that has the potential to meet growing energy demands in a cleaner and more cost-effective manner. Trigeneration systems employ the waste heat recovery principle to simultaneously generate electricity, heating, and cooling from the same fuel source. Particularly, the gas turbine-based trigeneration system finds ample industrial applications, mostly in the process industries, due to its high efficiency, low pollution levels, low capital cost, wide flexibility, and multigenerational capability.

In this thesis, four novel gas turbine-based trigeneration systems (Combined Cooling, Heating, and Power (CCHP) systems) are proposed for the simultaneous generation of electricity, chilled water, and hot water. The topping cycle is a recuperative gas turbine cycle and the bottoming cycle includes a steam turbine cycle, an organic Rankine cycle (ORC) and absorption cooling systems. The innovative

aspect of this study is the thorough modelling, analyses, and optimization of the suggested systems, which have never been examined in any prior literature. The development of the CCHP systems is carried out in three stages. In the first stage, four configurations of gas turbine-based Combined Power and Cooling (CPC) systems are proposed for the combined production of electricity and chilled water. The CPC system configurations include a simple gas turbine cycle as the topping cycle (prime mover) and a steam turbine cycle, a recuperative organic Rankin cycle and absorption cooling systems 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 (system-I and system-II), back-pressure steam turbines and organic Rankine cycles are used; however, in system-III and system-IV, organic Rankine cycles are completely replaced with the condensing-type steam turbines. Additionally, system-I and system-IV include two absorption cooling systems, one driven by wet steam and the other by flue gas. System-II and system-III, on the other hand, only have one flue gas-driven absorption cooling system. The performance of the CPC systems is evaluated using energy and exergy analyses. Then in the second stage, the four CPC systems are retrofitted into more advanced CCHP systems with three architectural modifications.

The first modification is the replacement of a simple gas turbine cycle with the recuperative gas turbine cycle as the prime mover. This is carried out because the recuperative gas turbine cycle outperforms the simple gas turbine cycle in terms of efficiency and cost-effectiveness.It has also been found in the literature that there exist four different ORC layouts *viz.,* basic ORC, recuperative ORC, regenerative ORC, and recuperative regenerative ORC (RR-ORC). Among the aforementioned layouts, the RR-ORC is found to have the maximum efficiency. However, no prior study has discussed the performance comparison of the ORC layouts based on exergoeconomic analysis. Therefore, this thesis also presents a comparative analysis of the four ORC layouts based on exergoeconomic assessment. 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 from optimization. The multi-criteria decision analysis is carried out using the technique for order of preference by similarity to the ideal solution (TOPSIS). Moreover, it has been found that the demand for process heat is also growing especially in process industries.

Therefore, the third modification involves the addition of a water heater to prevent any extra heat from the gas turbine exhaust from escaping into the environment and to provide additional hot water to meet the heating demand.

The feasibility of the modified CCHP systems is then accessed in third stage by using energy, exergy, exergoeconomic and environmental (4E) analyses. In fact, the 4E performance of the CCHP systems is also compared with the previously proposed CPC systems. Thereafter, multi-objective optimization and multi-criteria decision analysis are performed to obtain the optimal operating conditions of the CCHP systems. 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 (system cost + environmental cost) as the objective functions. 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. The CCHP system configurations are then ranked using the TOPSIS decision-maker, giving each criterion equal priority. It is observed that the first configuration (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.

It is believed that the findings from this study would gather more insight into the gas turbine-based trigeneration systems and would provide valuable outcomes for the future development of efficient, clean, and cost-effective energy systems.

Keywords— *4E analyses, Tri-objective optimization, Gas turbine, ORC, Absorption cooling system, CCHP systems*