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Parametric investigation and thermo-economic multi-objective optimization of an ammonia–water power/cooling cycle coupled with an HCCI (homogeneous charge compression ignition) engine

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ABSTRACT

A parametric study and multi-objective optimization strategy are performed for a bottoming cycle of a trigeneration system with an HCCI (homogeneous charge compression ignition) engine as prime mover. To assess the influences of decision parameters on the performance and total cost of cycle, a parametric investigation is conducted. Two different multi-objective optimization scenarios are carried out to determine the best design parameters. For the first scenario, the objective functions which are utilized in the optimization study are exergy efficiency and the sum of the unit costs of the system products. The system cost criteria is minimized while the cycle exergy efficiency is maximized using an evolutionary algorithm. Exergy efficiency increases about 16.34% and reduction in the unit costs of the system products is about 10%. However, it is found that cooling capacity of the system is reduced to 83%. For the second scenario, the objective functions are considered to be the sum of the unit costs of the system products, net power generation, and exergy flow rate of refrigeration output. Employing the second scenario improved both power generation and cooling capacity of the system. The increase in exergy efficiency is 5.61%. These are achieved with even a slight reduction in the system cost criteria.

1. Introduction

Reduction of fossil fuels and global warming are two major concerns on sustainability of future energy systems. Demand for energy is steadily increasing while the available renewable energy resources are limited. Hence, the effort for more efficient use of energy systems is growing and researchers in the field of energy conversion have prompted to seek ways to design systems with low energy consumption, high performance and low environmental emissions [1].

Currently, the need to use energy resources more efficiently has encouraged researchers to conduct various studies in design and optimization of energy conversion systems.

Numerous studies were reported in the literature dealing with the utilization of ICE (internal combustion engines) as prime mover in the cogeneration and trigeneration systems [2]. Examples of the use of ICEs in energy systems are as follows.

The implementation of the HCCI (homogeneous charge compression ignition) engines in small scale cogeneration systems were investigated by Aceves and Martinez-Frias [3]. A comparison of the use of HCCI (homogeneous charge compression ignition) engine as prime mover with various prime movers like SI (spark ignition) and CI (compression ignition) engines and also micro turbines according to the energy and cost analysis and NO_x emissions were studied. HCCI (homogeneous charge compression ignition) engine was introduced as a promising tool for cogeneration systems.

Jonsson and Yan [4] examined the performances of different configurations of ammonia–water cycles as a bottoming cycle for heat recovery of exhaust gases from gas engine or gas diesel engine. They concluded that ammonia water is more efficient than Rankine cycle, as a bottoming cycle. Also, since the temperature of exhaust gases of gas engines are higher than gas diesel engines, the combination of ammonia–water bottoming cycles with gas engine has higher performance in comparison with the case that of gas diesel engines.

Lin et al. [5] set up a trigeneration system utilizing a diesel engine and an absorption refrigerator with the purpose of producing power, heat and cooling. They found that, at engine full load condition, the efficiency of the system increased up to 67.3% compared

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to 22.1% efficiency of single power generation diesel engine. Also, carbon dioxide emission per unit (kW h) of useful energy output reduced considerably for the trigeneration system in comparison with a single generation.

Vaja and Gambarotta [6], to settle the best working fluid and ORC (organic Rankine cycle) configuration and the principal variables of the thermodynamic cycles, did an energetic and exergetic analysis. Several configurations of organic Rankine cycles in conjunction with a stationary internal combustion engine were combined. The results show that a combination of ORC with an IC engine can improve efficiency up to 12.5% in comparison with base case. Furthermore, lower critical temperature of the working fluid leads to higher irreversibilities because of the greater temperature difference between exhaust gases and working fluid in the heater or evaporator.

The performance of a household size trigeneration system with an ICE fueled by hydrogen as prime mover is studied by Wang et al. [7]. The work demonstrated the feasibility of Hydrogen-fueled diesel engines to be used in trigeneration systems. It was found that the system with cogeneration of heat and power has higher efficiency in comparison with trigeneration system. However, cooling potential of trigeneration system is an advantage.

Optimization of energy systems only from thermodynamics point of view, such as optimizing the system based on energy or exergy, may result in an increase in the overall costs of the system rendering the cost of the product becomes higher. Thermoeconomic analysis of such systems is a promising tool to overcome this deficiency in which a combination of exergy and economic concepts is used to assess and enhance the energy, exergy and cost of the system [8].

An exergoeconomic analysis was carried out by Temir and Bilge [9] for a trigeneration system with a gas engine as prime mover, an absorption chiller and a waste heat boiler. They found that the gas engine has the highest irreversibility and the highest capital investment and O&M (operating and maintenance) costs in the system. The work also demonstrated that since the ACU (absorption cooling unit) has high capital investment and O&M costs with less exergy destruction, it is not rational to use ACU equipments with higher efficiency.

An exergetic and economic study was reported by Huangfu et al. [10] for a trigeneration system utilizing a small scale ICE. The work emphasizes that in order to achieve an efficient system, it is required to enhance the electrical efficiency of the ICE unit.

Abusoglu and Kanoglu [11,12] performed an exergetic and economic analysis of diesel engine powered cogeneration. The results showed that the engine is greatly the most destructive equipment in the system. The work emphasized that by identifying the component with higher exergy destruction and by enhancement of these components through a better design and operation and also by decreasing costs of investment and exergetic destruction it is possible to achieve better exergy efficiency and cost effectiveness of the system.

On the basis of a simple method, a trigeneration system studied by Ghaebi et al. [13] from the first and second laws of thermodynamic and thermoeconomic points of view. The work investigated the effects of variation in the decision parameters on the performance and exergy destruction in each of the components.

Exergoeconomic analysis and optimization of a cogeneration system with the purpose of electricity and steam generation were studied by Sahoo [14]. The work employed exergoeconomic principles and evolutionary programming. The work exhibited that a 9.9% reduction in the cost of electricity and produced cost can be achieved in the case of optimized system compared to the original system. Although this improvement obtained by 10% increase in capital investment cost, however, it is emphasized by the author that this extra investment cost may be pay back in 3.23 years.

Utilization of waste heat from the HCCI (homogeneous charge compression ignition) engine, to generate power and cooling via an AWM (ammonia–water mixture) cycle, has been reported in a previous work [15]. Generating higher efficiency, in comparison to the other systems which produce power and cooling separately, is one of the main advantages of the AWCC (ammonia–-water cogeneration cycle). Furthermore, because of owning relatively lower exergy destruction, the AWCC is becoming a promising tool for heat recovery. Improving the performance of the system while reducing the produced power and cooling unit costs is one of the ultimate goals of thermal system designers. To the authors knowledge the multi objective optimization of such a system has not reported in the literature. The current study is an effort to address this lack of information. In this study, in order to get insight to the impact of design parameters on the performance and unit cost of the AWCC, a parametric study is conducted. Furthermore, two different scenarios for multi-objective optimization are carried out to optimize the cycle, which renders the improvement of the overall performance of the previously proposed trigeneration system. The first scenario would be useful when the AWCC is utilized for either cooling or power generation while the second one is preferred when the AWCC is used to generate power and cooling simultaneously.

2. Thermodynamic analysis

Fig. 1 displays the schematic diagram of the considered trigeneration system. In order to evaluate the system from thermodynamic point of view, the conservation of mass principal along with the first and second laws of thermodynamics are applied to each component of the system which is considered as a control volume. The detailed description of the system and the energetic and exergetic relations for the components of the system were provided in the previous study [15]. In current study, the cycle is modeled employing a developed code in MATLAB. It should be mentioned that, the study of the bottoming cycle requires the thermodynamic properties of an ammonia–water mixture. These properties are taken from Ref. [16]. Also, the bubble point and dew point temperatures of the ammonia–water mixture are found from the correlations developed by Patek and Klomfar [17]. Table 1 provides the results of the AWCC model calculated in this work, which are compared with the data reported in Ref. [18]. The results reveal that there is an acceptable agreement between the simulated results of this work and the results reported in Ref. [18]. The reason that the validation shows an acceptable agreement could be mostly because of the fact that the properties in the present work and ref. [18] are taken from the same source. The only differences is at the employed equations for calculation of the bubble point and dew point temperatures which have very small deviation with the results of equations used in Ref. [18].

It is worth noting that, a more meaningful criterion to evaluate the cycle performance is the exergy efficiency which discriminates the values of heat and work and evaluates the effectiveness of the system from the viewpoint of second law of thermodynamics. In order to measure the performance of the combined cycle in a proper way, the refrigeration produced by the cycle should be taken as the electric power equivalent to generate the same cooling effect by a conventional refrigeration system [18–20].

$$\eta_{II,AWCC} = \frac{\dot{E}_{evap} + \dot{W}_{net,AWCC}}{\dot{E}_{in}} \quad (1)$$

$$\dot{E}_{in} = \dot{m}_{exhaust}[(h_6 - h_0) - T_0(s_6 - s_0)] \quad (2)$$