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Energetic and exergetic analyses of a new energy system for heating and power production purposes

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ABSTRACT

Energetic and exergetic analyses are performed for a proposed cogeneration cycle of heat and power. The cycle includes a STC (steam turbine cycle) to produce power and saturated steam, an AHT (absorption heat transformer) cycle to produce hot water and a HCCI (homogeneous charge compression ignition) engine as prime mover. Furthermore, the cooling water of the engine is used for heating purposes. The effect of variation of the cycle variables on the performance of the STC and AHT cycles are evaluated in details. The results show that the integrated system improves the energy utilization factor from 44.65% for the HCCI engine to 86.01% for the proposed system. Also, the exergy efficiency of the system increases from 39.49% for the HCCI engine to 48.56% for the proposed system. The maximum exergy destruction for the HCCI engine happens in the combustion chamber and for the STC occurs in turbine and for the case of the AHT cycle takes place in the absorber. Results of parametric study show that the exergy efficiency increases by increasing pressure ratio of the STC. The COP (coefficient of performance) of the AHT cycle increases as the condenser and absorber temperatures increase, but slightly decreases by increasing the evaporator temperature.

1. Introduction

Recently, the energy – environment connection has been shown to be an important part of energy schemes leading to conduct a significant amount of research for reduction of greenhouse gas emissions and also, the development of more efficient energy conversion systems. In this regard, as a key solution, CHP (combined heating and power) systems as well as CCHP (combined cooling, heating and power) systems are getting more attention [1–4].

The reciprocating engines are getting benefit of low capital cost, quick starting as well as load following. An additional benefit of reciprocating engines is their potential to run with comparatively high partial load efficiency and generally high reliability [5,6]. As a result, they are widely utilized in many distributed generation applications, like the industrial, commercial and institutional facilities for power generation and also co/trigeneration systems. HCCI (homogenous charge compression ignition) combustion is a spontaneous auto-ignition of premixed fuel-air mixture. These engines can run with extremely lean or very dilute fuel-air mixtures. HCCI is a promising technology utilized in ICEs (internal combustion engines) to achieve very low NOx levels and almost zero soot emissions together with high thermal efficiency [7–9]. Another benefit of HCCI engine is its potential to burn a variety of fuels with considerable variations in physical properties and chemical composition [10] as well as the blend of various fuels [11–13]. Also, due to absence of spark plugs or a three-way catalyst in HCCI engines, these engines are expected to have lower maintenance costs than SI (spark ignition) engines. Furthermore, the combustion in HCCI engines is a low temperature combustion and also, the maximum peak cylinder pressure and rate of pressure rise are low. Therefore, knock in HCCI engines does not result in increased maintenance or shortened engine life. In general, the described advantages of HCCI engines, including high thermal efficiency, low NO_x and PM (particulate matter) emissions, low cost and low maintenance requirements, offer these engines as a new option for small scale cogeneration or tri-generation systems [14]. Numerous studies were reported in the literature dealing with the utilization of internal combustion engines as prime mover in the cogeneration and tri-generation systems [15]. Some examples of the use of ICEs in energy systems are provided in the following paragraphs.

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An analysis of a CCHP system including an internal combustion engine and an absorption machine was carried out by Longo et al. [16]. The waste heat from the exhaust gases of an Otto engine was used to drive a double-effect LiBr/water cycle, and also the cooling water of the engine was utilized to drive a single-effect LiBr/water cycle. The work demonstrated that a coefficient of performance around 1 could be achieved with the absorption machine, which is extremely close to the performance of a traditional double-effect absorption chiller with steam or a gas burner as prime movers. The performance of different configurations of a CCHP system including a turbocharged diesel engine and an absorption refrigeration unit was examined theoretically by Talbi and Agnew [17]. Four different configurations were considered. The work suggested that a pre- and inter-cooled turbocharged engine configuration cycle is a promising configuration which results to high power generation and consequently high thermal efficiency and less specific fuel consumption compared to other configurations. Easow et al. [18], investigated the potential of the micro tri-generation system to be applied in the distributed cooling, heating and power. They set up a micro tri-generation system utilizing a liquefied petroleum gas driven Bajaj 4-stroke IC engine as prime mover. The results showed an overall efficiency about 96% in terms of fuel energy conversion into other useful forms rendering less fuel energy loss for the micro tri-generation system. Zhao et al. [19] described a CHP system with an IC engine fueled by natural gas as prime mover. To recover the energy, the exhaust gas of the engine drives an absorption heat pump and the engine jacket heat is recuperated through the jacket water heat exchanger. A 10% increase in the heat utilization efficiency achieved with proposed CHP system in comparison with conventional systems in winter.

The implementation of the HCCI engines in small scale cogeneration systems were investigated by Aceves and Martinez-Frias [14]. A comparison of the use of HCCI engine with various prime movers like spark-ignition and compression-ignition engines and also micro turbines according to energy and cost analysis and NO_x emissions was studied. HCCI engine was introduced as a promising tool for cogeneration systems. In another work, Sarabchi et al. [20] investigated the waste heat recovery of a HCCI engine to drive an AWCC (ammonia-water cogeneration cycle) and to produce hot water to be used in heating purposes. The work demonstrated that under optimized condition, a 5.2% enhancement in the exergy efficiency can be achieved through the proposed system compared to the single power generation. Also, they showed that this combination could reduce the CO_2 emission about 4.1% in comparison with the conventional separate thermodynamic systems.

The present work introduces a novel energy system for heat and power generation purposes. The waste heat from exhaust gases of the natural gas fueled HCCI engine is used to run a STC (steam turbine cycle) and an AHT (absorption heat transformer) cycle. Also, the cooling water of the engine is used for heating purposes. The operation cycle of AHT is reverse to that of absorption heat pump, and it is used to upgrade low temperature waste heat to be used in a secondary process. Through implementing the AHT system it is possible to raise the water temperature over that of the waste heat source. Absorption cycles mostly utilize natural fluids (like H_2O—LiBr and NH_3—H_2O) as working pairs, which do not contribute to global warming or ozone depletion [21]. There are several review papers in the literature dealing with absorption heat transformers such as refs. [22–24]. Examples of recycling waste heat energy using absorption heat transformers are as follows.

Horuz and Kurt [25] analyzed an application of the AHT system to an industrial company where waste heat at 90 ± 2 °C is recovered to supply hot water at 120 °C. The work demonstrated that almost 50% of the waste heat can be utilized. In order to improve COP (coefficient of performance) and hot water production, the basic AHT system was modified and different configurations were proposed. It was found that a 14.1% increase in the COP can be achieved utilizing the new configuration. Also, the absorber heat transfer and the produced hot water were increased 158.5% and 3.59%, respectively, in comparison with the basic AHT system. Huicochea et al. [26] analyzed a cogeneration system consisting of a fuel cell and an absorption heat transformer which is joined to a water purification system. The results of the study showed that the integrated system can increase the efficiency of the fuel cell by 12.4%. Also, the efficiency of the cogeneration can reach up to 57.1%. Zare et al. [27] investigated the waste heat recovery of a GT-MHR (gas turbine-modular helium reactor) to drive two ORCs (Organic Rankine Cycles) and an AHT (absorption heat transformer) which was integrated to a water purification system. The work showed that under an optimized condition, based on the first law of thermodynamics, the efficiency of the integrated system was around 7% higher than that of the GT-MHR cycle. It was found that while in about 2.5–4% increase in the thermal efficiency was achieved for each 50 °C increase in the gas turbine inlet temperature, however, this would result to a 6.5% reduction in the pure water production rate.

In the current work, an integrated energy system is proposed which is based on HCCI engine as topping cycle and the STC and AHT bottoming cycles. The reason to study such a system is that since for process industries, uninterrupted steam supply becomes a necessity, such configuration can provide the required steam through the steam turbine. Also, after driving the STC, some energy was still wasted in exhaust gases at a temperature of around 90 °C. Although these exhaust gases are not hot enough (low grade energy) to be utilized in energy conversion systems efficiently, but they are not worthless [27]. In order to upgrade this low temperature waste heat an AHT cycle is used, so that it can be used for heating purposes (e.g. the pressurized dying machines that require hot water [28] or water desalination which is the most widely used technique to produce pure water [29]). The AHT system can effectively recover about 50% of this waste heat. Therefore, the advantages of such a kind of configuration is increasing the overall efficiency of the base system up to 86% by providing useful heat (steam and hot water at 120 °C) for heating applications. According to the authors' knowledge energetic and exergetic analyses as well as application of AHT and STC in a CHP system based on HCCI engine as prime mover has not been reported in the literature while it seems to be promising. In most of available works in the literature, internal combustion engines were modeled using the processes of the air standard Otto or diesel cycles [30] or the combustion process assumed to occur as complete combustion through a simple reaction to introduce the composition of the exhaust gases [31,32]. But, in current work, a detailed chemical kinetics mechanism has been considered similar to the author's previous studies [20,33]. The GRI-Mech. 3.0 chemical kinetic mechanism [34], kinetic reaction mechanism, consisting of 53 species and 325 reactions, are chosen for the oxidation of NG (natural-gas). The natural gas fueled HCCI engine combustion is calculated through a SZCM (single-zone combustion model) which is considered as a real engine cycle. Such a calculation leads a more accurate and reliable results for calculation of engine performance and more importantly, the composition of the exhaust gases rendering precise energetic and exergetic study of exhaust gas and consequently the whole cycle.

In this regard, the key specific objectives for this study are listed as follows:

- A new integrated of AHT and STC in a CHP system based on HCCI engine as prime mover is developed and analyzed in detail through energetic and exergetic approaches.
- Exergy destructions are calculated for all components to investigate the possibility of improving the proposed system.