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Research Paper

Exergoeconomic evaluation and optimization of a novel combined augmented Kalina cycle/gas turbine-modular helium reactor

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HIGHLIGHTS

- A novel gas turbine-modular helium reactor/new Kalina cycle is proposed.
- Exergoeconomic analysis is performed for the combined cycle.
- The product unit cost is reduced by 11.3% by waste heat utilization.
- Augmented Kalina cycle performs better than Kalina cycle 34 economically.
- Exergy efficiency of gas turbine-modular helium reactor is enhanced by 8.7%.

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ABSTRACT

A new combined system including Gas Turbine-Modular Helium Reactor (GT-MHR) and an augmented Kalina cycle (AKC) is proposed, analyzed and optimized thermodynamically and economically. The simulation is performed using the conservation of energy, exergy balance and cost equations for each system component. For comparison purposes the previously published data for the combined cycle consisting of the GT-MHR and a conventional Kalina cycle (GT-MHR/KCS34), are also presented. Parametric studies are carried out to show the influences on exergy efficiency and total product unit cost of such decision parameters as compressor pressure ratio, pump pressure ratio, ammonia concentrations at different state points and separator temperature. The results indicate that the maximum exergy efficiency of the proposed system is 8.7% and 0.64% higher compared to the corresponding values for the GT-MHR and GT-MHR/KCS34, respectively. The results also show that the minimum total product unit cost for GT-MHR/AKC is 11.3% and 2.53% lower than the corresponding values for the GT-MHR and GT-MHR/KCS34, respectively. It is observed that, under optimized condition, the helium mass flow rate in GT-MHR is reduced as the system is combined with the AKC. This is significant in reducing the size of system and consequently having more economically efficient system.

1. Introduction

Effective use of energy is a challenge for thermal system designers as it is an important issue concerning the world development and environmental pollution. In this regard, a lot of attention has been paid to recovering waste heat from energy converting systems to produce more power, cooling, heating or distilled water. The Gas Turbine-Modular Helium Reactor (GT-MHR), among the new options for power production, attracts interest of investigators owning to its encouraging aspects such as better economics, safety and proliferation resistance. In order to reduce the compression work in the GT-MHR system, the working fluid should be cooled so that around 300 MWth low grade thermal energy is rejected in the pre-cooler of the system with an input energy of 600 MWth [1,2]. In order to increase efficiency, attempts have been made in literature to utilize this energy for running some bottoming cycles.

Utilization of waste heat from the GT-MHR was first suggested by Yari [3] who proposed an organic Rankin cycle (ORC) for recovering waste heat from the GT-MHR. He reported that the combined cycle efficiency is around 10% higher than that of the GT-MHR. Yari and Mahmoudi [4] proposed a combined cycle including the GT-MHR employing a two-stage compressor and two ORCs. They reported an enhancement of 3% points in the efficiency when the ORCs are combined with the GT-MHR cycle. These authors, in another work employed three different configurations of ORC to recover the waste heat from GT-MHR and reported that the simple ORC performs better that the other configurations [5]. Zare et al. [6]

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Nomenclature

$\dot{C}$	cost rate ($ h^{-1})
C	cost per exergy unit ($ GJ^{-1})
$c_{p,total}$	total product unit cost
$\dot{E}$	exergy rate (kW)
E	specific exergy (kJ kg^{-1})
F	exergoeconomic factor
H	specific enthalpy (kJ kg^{-1})
i_r	interest rate
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (bar)
Pre	precooler
$\dot{Q}$	heat transfer rate (kW)
R	pressure ratio
S	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (°C or K)
$\dot{W}$	power (kW)
X	ammonia concentration
Z	capital cost ($)
$\dot{Z}$	capital cost rate ($ h^{-1})

Subscripts and abbreviations

0	environmental state
1, 2, 3, ...	state points
AKC	augmented Kalina cycle
AWM	ammonia-water mixture
C	compressor
Ch	chemical
CI	capital investment
COD	cost optimal design
CRF	capital recovery factor
D	destruction
Exe	exergetic
Kct	Kalina cycle turbine
KCS34	Kalina cycle system 34
P	product, pump
HE	heat exchanger
SH	super heater
T	turbine
TOD	thermodynamic optimal design

Greek letters

ε	effectiveness
τ	annual operation hours
η	efficiency

suggested using a combined ammonia-water power/cooling system for recovering waste heat from the GT-MHR. They reported that the energy utilization factor and second law efficiency of the GT-MHR cycle are enhanced by 9–15% and 4–10%, respectively. These authors in another work [7] performed an exergoeconomic analysis and reported a reduction of 5.4% in the products unit cost as the ammonia-water power/cooling cycle is used for waste heat recovery from the GT-MHR. It is evaluated that the total investment cost rate is increased by 1% when the two cycles were combined. Zare et al. [8] also proposed utilization of waste heat for producing power and purifying water and concluded that the first law efficiency was enhanced by up to 7%. Soroureddin et al. [9] used the waste heat from GT-MHR to run an ejector refrigeration system as well as different configurations of ORC and reported an increase of about 2.6% in the exergy efficiency.

Mohammadkhani et al. [10] performed a comprehensive exergoeconomic analysis for waste heat utilization from GT-MHR by means of two ORCs. They reported that the pre-cooler and condenser, among the other components, have the worst exergoeconomic performance. A comparative exergoeconomic performance was assessed for the GT-MHR coupled with three types of ORC by Shokati et al. [11] who claimed that the lowest and highest unit product cost of the ORC turbine is achieved by the GT-MHR/RORC and GT-MHR/HORC, respectively. Zare et al. [12] combined a Kalina cycle with the GT-MHR and concluded that the product unit cost is lowered by 8.8% and the efficiency is enhanced by 8.2% in using the Kalina for recovering the waste heat from GT-MHR.

The variable boiling temperature of ammonia-water solution in a Kalina cycle brings about a good temperature matching in recovering the waste heat from GT-MHR so that less exergy is destructed in the waste heat recovery heat exchanger [13]. In recent years, a lot of attention has been paid to the Kalina cycle because of its peculiarities and different configurations have been proposed for this cycle to make it more convenient for being used for low, medium and high temperature heat sources. Among these configurations the KCS34 and AKC are convenient for being combined with the GT-MHR as the heat rejected in pre-cooler of GT-MHR is at medium temperature. The use of KCS34 configuration for waste heat recovery from the GT-MHR has been reported previously by the authors [12]. To the best of our knowledge, the AKC performance has not been investigated using exergoeconmic analysis. This lack of information makes the exergoeconomic analysis of the combined GT-MHR/AKC system seem to be more interesting and this forms the basis of the current study. Beside this, exergoeconomic comparison of the two GT-MHR/KCS34 and GT-MHR/AKC systems is accomplished in the present work. A parametric study is carried out to identify the effects on GT-MHR/AKC system performance of some decision parameters. The proposed system performance is also optimized for maximum efficiency or minimum unit product cost, applying the Direct Search Method in the Engineering Equation Solver (EES) software [14].

2. Systems description and assumption

2.1. GT-MHR/AKC

Fig. 1 shows the schematic diagram of proposed combined GT-MHR/AKC system and the T-s diagram associated with the processes in the system. The system actually consists of a GT-MHR cycle and an augmented Kalina cycle so that the waste heat from pre-cooler of the GT-MHR cycle is utilized to run the Kalina cycle. Helium as working fluid in the GT-MHR cycle is heated in the reactor before flowing to the turbine (state point 1) where it is expanded and produce power. The helium exiting turbine (state point 2) passes to the recuperator to preheat the helium entering the reactor. The helium then (state point 3) flows to the superheater (SH) and heat exchanger 6 (HE6) to heat the ammonia-water solution entering the Kalina turbine. The helium at the exit of HE6 (state point 5) is divided into two parts: one part (state point 7) flows to the heat exchanger 5 (HE5) and then to heat exchanger 3 (HE3) and the other part (state point 6) goes to the heat exchanger 4 (HE4). The two parts after passing the mentioned heat exchangers are mixed at the mixer 4 (MX4) and flows to the compressor after being cooled in the pre-cooler (state point 12). The helium exiting compressor (state point 13) then goes back to the recuperator to complete the GT-MHR cycle.