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On the exergoeconomic assessment of employing Kalina cycle for GT-MHR waste heat utilization

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ABSTRACT

Exergoeconomic concept is applied to compare the performance of the Gas Turbine-Modular Helium Reactor (GT-MHR) plant with a proposed combined GT-MHR/Kalina cycle in which the waste heat from the GT-MHR is recovered by the Kalina cycle for power generation. Thermodynamic and exergoeconomic models are developed to investigate the cycles' performance and assess the unit cost of the products. A sensitivity analysis is performed prior to the optimization of the cycles' performances from the view points of thermodynamics and economics. The results indicate that, when the performances of the two cycles are optimized economically, the efficiency and total product unit cost of the combined cycle is 8.2% higher and 8.8% lower than the corresponding values for the GT-MHR. It is interesting to note that, under these conditions, the total investment cost rate for the combined cycle is just slightly higher than that of the stand alone GT-MHR.

1. Introduction

The growing energy demand for world development necessitates designing more efficient and economical power producing plants. To do so, optimization is needed from the viewpoint of exergoeconomics for these systems. An exergoeconomic assessment considers not only the thermodynamic inefficiencies but also the monetary losses associated with these inefficiencies and the required investment expenditures [1]. Exergoeconomics rests on the notion that exergy is the only rational basis for assigning monetary costs to the interactions that a system experiences with its surroundings and to the sources of thermodynamic inefficiencies within it [2].

In recent years, among the gas-cooled high temperature nuclear reactors, the Gas Turbine Modular Helium Reactor (GT-MHR) has been paid a lot of attention because of its promising features such as good safety, improved economics and very high proliferation resistance. EL-Genk and Tournier [3] investigated the characteristics and limitations of the noble gases as working fluids for the GT-MHR cycle. In another work reported by these authors, the attributes and limitations of noble gases and binary mixtures, as potential working fluids for the GT-MHR is studied [4]. They concluded that the required compression work for helium is significantly lower than that for the He–Xe mixture. Van den Braembussche et al. [5] described the aerodynamic design and explored the performance limits of a 600 MWth multistage helium turbine for a high temperature nuclear reactor coupled to a closed gas turbine cycle. Using multiple reheat and inter-cooling states for the sodium cooled fast reactors; Zhaoand Peterson investigated the performance of helium Brayton cycles and reported a cycle thermal efficiency ranging from 39% to 47% [6].

In the GT-MHR system the nuclear reactor is coupled with a closed Brayton cycle to produce power. With a helium temperature of 850 °C at the reactor exit (turbine inlet), the thermal efficiency of GT-MHR cycle can reach 48% [7] which is significantly higher than the efficiency of steam cycles based on light water reactors. However, employing a closed Brayton cycle brings about a rejection of about 300 MW low grade thermal energy from the pre-cooler [3]. This thermal energy can be utilized by an appropriate system to improve the overall energy conversion efficiency. In this regard some research works have been carried out in literature. Nisan et al. [8–11] showed that utilizing the waste heat from nuclear power plant for seawater desalination is more profitable than using fossil fuel for this purpose. The utilization of the GT-MHR waste heat for power production was proposed by Yari and Mahmoudi [12] who suggested using Organic Rankine Cycles (ORCs) for this purpose. These authors reported that the first and second law efficiencies of the GT-MHR system, with an inter-cooled compressor, can be improved by 3% points by this

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Nomenclature

AWM	ammonia–water mixture	*CI*	capital investment
$\dot{C}$	cost rate ($ h^{-1})	COD	cost optimal design
c	cost per exergy unit ($ GJ^{-1})	*CRF*	capital recovery factor
$\dot{E}$	exergy rate (kW)	D	destruction
e	specific exergy (kJ kg^{-1})	E	evaporator
f	exergoeconomic factor	KC	Kalina cycle
h	specific enthalpy (kJ kg^{-1})	*OM*	operation and maintenance
i_r	interest rate	*ph*	physical
$\dot{m}$	mass flow rate (kg s^{-1})	pp	pinch point
P	pressure (bar)	HTR	high temperature recuperator
pre	pre-cooler	LTR	low temperature recuperator
$\dot{Q}$	heat transfer rate (kW)	Sup	superheater
r	pressure ratio, relative cost difference	TOD	thermodynamic optimal design
s	specific entropy (kJ kg^{-1} K^{-1})		
T	temperature (°C or K)	*Greek symbols*	
X	ammonia concentration	ε	effectiveness
Z	investment cost of components ($)	τ	annual plant operation hours
$\dot{Z}$	investment cost rate of components ($ h^{-1})	η_p	pump isentropic efficiency
		η_t	turbine isentropic efficiency
Subscripts and abbreviations		$\eta_{P,C}$	compressor polytropic efficiency
0	ambient	$\eta_{P,GT}$	gas turbine polytropic efficiency
ch	chemical		

method [12]. In another work, they reported that the simple ORC is better than the other ORC configurations for waste heat recovery from GT-MHR [13]. The utilization of waste heat from the GT-MHR for cogenerating of power and pure water is investigated by Zare et al. [14]. Employing an ammonia–water power/cooling cogeneration cycle for waste heat recovery from GT-MHR, Zare et al. [15] concluded that, under the optimum conditions, the second law efficiency of the GT-MHR is enhanced by around 4%. Later, these authors carried out an exergoeconomic analysis for the proposed combined cycle and showed that the total product unit cost for the combined cycle is 5.4% lower than that for the GT-MHR [16]. Soroureddin et al. [17] utilized the waste heat from GT-MHR for power/cooling cogeneration, by means of organic Rankine and ejector refrigeration cycles, in three different configurations.

From the above survey it is evident that the waste heat from GT-MHR system is an ideal energy source to run a bottoming cycle and therefore, improves the energy conversion efficiency. To our knowledge, making use of the Kalina cycle for waste heat recovery from the GT-MHR, for producing extra power, has not been investigated yet. However, the interesting features of the Kalina cycle (KC) have urged investigators to pay more attention on this cycle. Among these features is its working fluid (ammonia–water mixture) with a variable evaporation temperature. The use of this working fluid brings about a good thermal match between the source and the working fluid temperature profiles and therefore, less irreversibility occurs during the waste heat recovery process. Thus the KC can be an alternative for waste heat recovery from GT-MHR. In present work, the performance of a proposed combined GT-MHR/KC is investigated exergoeconomically and compared with the stand alone GT-MHR cycle performance. As expected, the thermodynamic performance of the combined cycle will be better than that of the GT-MHR because of the waste heat recovery. However, making a right decision from the economic perspective needs a detailed exergoeconomic analysis for both the GT-MHR and the proposed combined cycle. Exergoeconomics is the branch of engineering that appropriately combines, at the level of system components, thermodynamic evaluations based on the exergy concept with economic principles, in order to provide a system designer with useful information to design a cost-effective system [2]. In the present paper, parametric studies are performed to assess the influence on exergoeconomic performance of the GT-MHR and combined cycles of decision variables. The cycles are then optimized from the viewpoints of both thermodynamics and economics using the EES (Engineering Equation Solver) software [18].

2. System description and assumptions

Schematic diagrams of the GT-MHR cycle and the proposed combined GT-MHR/KC, in which the waste heat from the GT-MHR is recovered by a Kalina cycle, are shown in Fig. 1. In the GT-MHR cycle the helium is the reactor coolant as well as the working fluid. In this cycle, as Fig. 1(a) shows, the helium is heated in the nuclear reactor before being expanded in the turbine to drive the generator and the compressor. The helium exiting the turbine flows through the hot side of the recuperator where it is cooled to a temperature of around 100–200 °C. The helium then enters the pre-cooler where it is cooled further to a temperature of around 28 °C. This temperature drop causes a reduction in the required compression work [3]. As mentioned before, the heat rejected in the pre-cooler can be utilized to run the KC. Referring to Fig. 1(b), the helium exiting the hot side of the recuperator enters the superheater and the evaporator of the KC before entering the pre-cooler. The heat rejected from the helium passing through the superheater and evaporator is the input energy to the KC. Thus, in the combined cycle some part of the GT-MHR waste heat is recovered for producing power by the KC. Depending on the application, several configurations have been proposed for the KC, in literature. The arrangement selected for the KC in the present work is the one tested in Húsavik (Iceland), the first operating ammonia–water geothermal power plant [19]. The details of the processes occurring in the KC have been described by Ogriseck [19].

Although there is no GT-MHR plant installed in full capacity yet, it is a very interesting topic in the nuclear power generation arena because of its excellent features and the plan is to build and operate the first 4-module GT-MHR by 2015 [28]. However, some Kalina cycle-based plants are operating for generating power from