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Energetical, exergetical and economical optimization analysis of combined power generation system of gas turbine and Stirling engine

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ABSTRACT

One of the promising methods to increase exergoeconomic performance and decrease effects of environmental adverse of energy systems is integration of energy systems. Gas turbine power plant is one of the favorable power generation systems because of its acceleration in start-up and low investment cost. However, the thermal efficiency of gas turbine cycle is low because of the significant heat loss due to high-temperature effluent gas exhausted from the stack. Therefore, if this huge heat loss is recovered by another heat engine coupled with gas turbine cycle the total efficiency will increase, considerably. Stirling engine owing to its high efficiency is one of the promising candidates which can be used as a part of the combined system. Hence, an optimization analysis on standalone gas turbine cycle, as well as combined cycle of gas turbine and Stirling engine are considered in this paper to find out the optimal operational point, thermodynamically and economically. Both single-objective and multi-objective genetic algorithm is performed to optimize the overall plant parameters, subjecting three optimization scenarios of maximizing exegetic efficiency, minimizing levelized cost of electricity and exergo-economic optimization. A comprehensive comparison of gas turbine and Stirling engine combined cycle and standalone gas turbine cycle was performed for these optimization scenarios. Results show a significant improvement in power output and reduction of levelized cost of electricity in combined cycle of gas turbine and Stirling engine. In the optimal point of this hybrid system, levelized cost of electricity reduces by 10.3% and exergetic efficiency improves by 16.1% compared with the optimal point of standalone gas turbine cycle.

1. Introduction

In the last decades, energy consumption and emissions have been increased, due to the population and welfare growth. This has led the various industrial units to consider a high priority for improving the overall efficiency of their facilities [1]. One of the applicable solutions is integration of industrial processes or combination of power plant cycles. Integration and combination can reduce energy consumption and increasing productivity via heat recovery or reduction exergy loss [2]. The waste heat recovery systems have been used to improve energy efficiency. Transfer of energy from waste heat to useful energy results in the reduction of overall energy consumption of systems as well as cost saving. By combining inline two systems, downstream system utilizes the waste heat of the upstream system which results in energy recovery. In this approach, the total energy consumption, the maintenance and operation costs and the pollutant emission are diminished, and therefore, the exergy efficiency increases compared with the standalone system. Since 1959, investigation on energy conservation have been concentrated on waste heat recovery systems as well as the electricity generation influences on the green house. Hammons [3] explained the effect of producing electricity on the Europe environment. If some of this waste heat energy can be recovered, a significant amount of primary fuel can be maintained [4]. Selection of the waste heat recovery system depends entirely on the temperature of the waste heat and the economic feasibility of the system.

Gas turbine (GT) cycle is one of the nimble system in electricity generation. It is owing to the short construction period, as well as the fast startup and shutdown time of GT cycle. But in term of exergy efficiency it has a considerable deficit compared to other existing cycles. Separately, waste heat of gas turbine power plants has always been one of the considerable disadvantages in GT power plant. The temperature of the waste heat of the GT cycle is in the range of 450–600 °C. Therefore, there is high heat potential which that can be recovered to generate power. Many researchers suggest different approaches in their studies to increase the efficiency of gas turbines by proposing a hybrid system of GT cycle with other cycles.

One of the well-known commercial system that combines with the GT cycle is heat recovery steam generator to produce steam water for

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Nomenclature

c_f	fuel cost ($/MJ)
CRF	capital recovery factor
$\dot{E}$	exergy flow rate (kJ/s)
LHV	low heat value of fuel (MJ)
$\dot{m}$	mass flow rate (kg/s)
n	plant life span (year)
N	operational hours in year (h)
R	compressor pressure ratio
r	interest rate
T	temperature (K)
V_d	shifted volume of SE (m^2)
V_c	displacement volume of SE (m^2)
Z	investment costs (USD)
$\dot{z}$	operation costs (USD/h)

Greek symbols

ϵ	compression ratio
η	energetic efficiency
κ	heat capacity ratio
ϕ	repair coefficient
ρ	density (kg/m^3)
ψ	exergetic efficiency

Subscripts

0	environment dead state
AC	air compressor
acc	after combustion chamber
avai	available
bcc	before combustion chamber
c	Stirling min volume
C	cold resource
CC	combustion chamber
ch	chemical
co	combine
cv	control volume
d	displacement
D	destruction
e	exit, output
exh	exhaust gas
f	fuel
Gen	generator
GT	gas turbine
H	hot resource
HR	recovery system heat exchanger
i	in, input
ph	physical
PH	preheater
Q	heat
S	dead volume
SE	Stirling engine
tot	total
surf	surface
W	work

Abbreviations

CHP	combined heat and power
GT	gas turbine
LCOE	levelized cost of electricity
ORC	organic Rankine cycle
SE	Stirling engine
TOPSIS	technique for order of preference by similarity to ideal solution

power generation in steam turbine [5]. Thermodynamic review of combined GT cycle in power generation field, carried out by Dilliwar [6]. Bianchi [7] used the waste heat of GT cycle to power in his study. Also, Ahmadi [8] and Eveloy [9] show that GT cycle can combine with desalination units to produce water in areas that there is a shortage for potable water. Cogenerating heat and power (CHP) system is one of the regularly used systems which directly uses GT cycle's waste heat to warm-up the residential environment [10]. Generally, GT cycle can be combined with any cycles or processes that need heat for operating, like petrochemical processes or refinements. Moreover, GT cycle can combine at downstream of high temperature working system like solid oxide fuel cell, which in this case fuel cell will supply the required heat for GT cycle, instead of using fuel and combustion chamber [11]. Using waste heat to useful energy conversion technique, the overall efficiency of the hybrid cycle increased by 6%. Kang Sanggyu has investigated the dynamic model of the combined gas turbine and fuel cell system [12]. In another study, integration of solid oxide fuel cell and GT cycle plant have been optimized [13]. By optimization of this integrated system, the exergy efficiency increases from 62.85% to 64.5%. Also, this optimization decreases the product cost about 14%.

Nami and Akrami [14] used the energy - exergy method to investigate a GT hybrid system for generating hydrogen, electricity and steam. They could increase the production rate and reduce the production cost by optimization of the system to improve overall system efficiency more than 50 percent. Yue [15] has performed exergy and economic analyzes on a system consists of power generation combined with the solar systems. In a hybrid GT cycle based cogeneration system with 30 MW shaft output power, 14 kg/s of steam can be produced by recovering the waste heat from the turbine exhaust gases [16].

In addition to the aforementioned systems, GT cycle can also be combined with the Stirling engine (SE) which was not concerned strongly, yet. Just at the very recent research, combination of GT and SE was proposed and was investigated, thermodynamically [17]. In this research, the operational parameters especially regenerator length of SE were considered in the analysis. Stirling engine needs heat energy to generate power which can be provide by GT cycle. The advantages of the Stirling engine are due to the reasons such as low noise production, working fluid single phase operation, easy start-up and existence of the bearing and seal only on the engine cold side, which cause this engine to be considered in many applications [18]. For instance, cars, ships and submarines have been using the SE to produce power from exhaust of their internal combustion engines. Hyrata and kawada [19] designed a SE with an output of 20 MW of power which utilized the ship's diesel engine exhaust heat as a heat source. Wail and Alahmar [20] also employed the SE to generate power from the waste heat of an internal combustion engine's exhaust gas.

In recent studies, SE was modeled using solar energy as a heat source [21]. Furthermore, Toro et al. [22] analyzed the performance of SE for space power generation. Stirling engine has combined with other energy systems to improve overall performance and efficiency by many researchers. Rokni [23] performed a thermodynamic and economic analysis on a fuel cell coupled with a SE. Szczygieł [24] analyzed Stirling engine design parameters such as heat regenerator and dead spaces to achieve optimal power generation and efficiency. As electricity generator, SE has been connected to a solar energy system as heat source [25].

Stirling cycle can also be combined with Rankine cycle. The Stirling engines release a lot of energy to the environment from the cold section