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Designing a solar powered Stirling heat engine based on multiple criteria: Maximized thermal efficiency and power

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ABSTRACT

A solar-powered high temperature differential Stirling engine was considered for optimization using multiple criteria. A thermal model was developed so that the output power and thermal efficiency of the solar Stirling system with finite rate of heat transfer, regenerative heat loss, conductive thermal bridging loss, finite regeneration process time and imperfect performance of the dish collector could be obtained. The output power and overall thermal efficiency were considered for simultaneous maximization. Multi-objective evolutionary algorithms (MOEAs) based on the NSGA-II algorithm were employed while the solar absorber temperature and the highest and lowest temperatures of the working fluid were considered the decision variables. The Pareto optimal frontier was obtained and a final optimal solution was also selected using various decision-making methods including the fuzzy Bellman–Zadeh, LINMAP and TOPSIS. It was found that multi-objective optimization could yield results with a relatively low deviation from the ideal solution in comparison to the conventional single objective approach. Furthermore, it was shown that, if the weight of thermal efficiency as one of the objective functions is considered to be greater than weight of the power objective, lower absorber temperature and low temperature ratio should be considered in the design of the Stirling engine.

1. Introduction

Stirling cycle is one of the important primitive standard air cycles of heat engines [1,2]. Suitable efficiency and wide range of fuels that can be used for heating can be pointed out as some advantages of this type of engine [2–4]. The Stirling engine can theoretically be a very efficient engine to convert heat into mechanical work at the Carnot efficiency when the ideal regeneration and isothermal compression and expansion processes are considered. Thermal limit of the operation of the Stirling engine depends on working temperatures on the heater and cooler sides. In most instances, the engine operates with heater and cooler temperatures of 923 and 338 K, respectively [5]. Engine efficiency ranges from 30% to 40% coming from a typical temperature range of 923–1073 K and the normal operating speed range of 2000–4000 RPM [6–11]. Kongtragool and Wongwises [8] studied the influence of regenerator efficiency and dead volume on the work as well as efficiency of the machine. However, this study did not include heat transfers through the temperature difference at the heat source and sink.

The idea of coupling for solar concentrators to Stirling engines is a new technology which facilitates conversion of solar energy into electric power. In this regard, a dish collector with the parabolic arrangement of its mirrors is used to concentrate solar radiations on the focal point of the collector, in which heat absorber of the engine is located. Therefore, solar energy is collected and concentrated towing to a parabola of mirrors.

In recent years, studying the optimum performance of energy systems with thermodynamic models has been an attractive option for researchers [12–34]. It is believed that the results obtained using the FTT lead to a more realistic design of the actual solar energy systems in comparison to the prior conventional thermodynamic equilibrium methods. Ladas and Ibrahim [28] defined a finite-time parameter as the ratio of working fluid contact time to the engine time constant which evolves heat transfer characteristics of the given design of Stirling engine. They conducted a numerical study and plotted variation of the power output versus finite-time parameter and change of the power output versus efficiency. Kaushik et al. studied effects of irreversibilities of the regenerator and heat transfer process in heat/sink sources [29]. Sieniutycz and von Spakovsky [32] generalized thermal exergy to the finite-time processes. Sahin and Kodal [33] introduced a new thermoeconomic performance analysis based on an objective function defined as the power output per unit total cost. Tlili investigated effects of regenerating effectiveness and heat capacitance

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Nomenclature

A_{rec}	absorber (recuperate) area
A_{app}	aperture area
C	concentration ratio
C_V	molar specific heat capacity (J mol^{-1} K^{-1})
d	deviation index
d_{i+}	deviation or distance of *i*th solution from the ideal solution
d_{i-}	deviation or distance of *i*th solution from the non-ideal solution
h	heat transfer coefficient,(W K^{-1} or W K^{-4} or W m^{-2} K^{-1})
I	direct solar flux intensity (W m^{-2})
i	*i*th objective
j	*j*th solution
n	mole number of the working fluid (mol)
p	power (W)
Q	heat transfer (J)
R	universal gas constant (J mol^{-1} K^{-1})
T	temperature (K)
W	work (J)
t	cyclic period (s)
k_0	conductive thermal bridge loss coefficient (W K^{-1})
x	temperature ratio of the Stirling engine
X	vector of decision variables

Greek letter

λ	ratio of volume during the regenerative processes (volumetric ratio)
η	thermal efficiency
ε_R	effectiveness of the regenerator
ε	emissivity factor
δ	Stefan–Boltzman coefficient

Subscripts

H	absorber (heater)
HC	convection on the high temperature side heat exchanger
HR	radiation on the high temperature side heat exchanger
L	heat sink
m	entire solar-dish Stirling system
R	regenerator
t	Stirling engine
0	ambient condition, optics
4 – 1	process states

rate of external fluids at the heat source/sink on the maximum power and efficiency [34].

Yaqi et al. developed a mathematical model for the output power and overall thermal efficiency of the high temperature differential solar dish Stirling engine with the finite heat transfer and a non-ideal regenerator and found expressions for the optimal absorber temperature which led to the maximized power output of the Stirling engine. They evaluated the corresponding thermal efficiency to the maximized power and studied effect of variations in engine parameters on the obtained values of the maximized power and its corresponding thermal efficiency [17]. They also optimized the solar-dish Stirling engine mathematically in a single objective optimization approach with only one design parameter (decision variable).

This paper was an extension of the work performed by Yaqi et al. [17] with simultaneous consideration of two objective functions instead of the single objective function. In this regard, two objective functions including output power and thermal efficiency of the entire solar-dish Stirling system were simultaneously considered. Furthermore, multi-objective optimization was conducted with three decision variables including solar absorber temperature and the highest and lowest temperatures of the working fluid in the heat engine.

Solving multi-objective optimization problems is a very difficult goal which requires simultaneous satisfaction of a number of different and even conflicting objectives. Evolutionary algorithms were initially extended and applied during the mid-eighties in an attempt to stochastically solve problems of this generic class [35]. A reasonable solution to a multi-objective problem is to investigate a set of solutions, each of which satisfies the objectives at an acceptable level without being dominated by any other solution [36]. Multi-objective optimization problems generally show a possibly uncountable set of solutions, namely Pareto frontier, the evaluated vectors of which represent the best possible trade-offs in the objective function space. During this term, multi-objective optimization of different thermodynamic and energy systems has been considered by researchers nowadays [16,37–42].

In this paper, a thermodynamic model was developed for evaluating the output power and thermal efficiency of a solar-dish Stirling engine. The developed model considered convective and radiative heat transfers at the hot end of the engine as well as the convective heat transfer at the cold end of the engine. Moreover, non-ideal regeneration performance and conductive thermal bridge loss between the heat source and heat sink were taken into account. The cyclic time of the engine was evaluated based on the time spent on the compression, expansion and regeneration processes. This model was applied to evaluate the output power and thermal efficiency of the entire solar-dish Stirling system for the multi-objective optimization process. Considering three design parameters (decision variables) including the absorber temperature and the highest and lowest temperatures of the working fluid in the engine, aforementioned objective functions were optimized (maximized) using the multi-objective evolutionary algorithm (MOEA) and the Pareto frontier was obtained in the objective space (power and efficiency space). One class of efficient MOEA, namely non-dominated sorting genetic algorithm i.e. NSGA-II, was employed for maximizing the output power and thermal efficiency simultaneously. A final optimal solution from available solutions located on the Pareto frontier was selected using three decision-making approaches including the fuzzy Bellman–Zadeh, LINMAP and TOPSIS methods. The final solution obtained by each decision maker was compared with the corresponding optimal solutions introduced by other decision making tools and the optimal solution introduced in the single objective optimization as shown in [17]. The superiority of solutions obtained using the multi-objective approach over the corresponding results obtained by the conventional approach ([17]) was discussed and emphasized. Sensitivity of the results against variation of the solar-dish Stirling engine parameters including the solar collector concentration ratio, effectiveness of the regenerator, conductive thermal bridge loss coefficient, volumetric ratio and solar flux intensity was also studied in detail.

2. Solar-dish Stirling system

In solar-dish Stirling systems, a mirror of the parabolic shaped concentrator focuses solar light on the focal point of the concentrator where hot end of the Stirling engine is installed. Therefore, solar energy with a relatively high temperature is transferred to the hot