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Multi-objective thermodynamic-based optimization of output power of Solar Dish-Stirling engine by implementing an evolutionary algorithm

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ABSTRACT

A solar-powered high temperature differential Stirling engine has been considered for optimization with multiple criteria. A mathematical model based on the finite-time thermodynamics has been developed so that the output power and thermal efficiency and the rate of entropy generation of the solar Stirling system with finite rate of heat transfer, regenerative heat loss, conductive thermal bridging loss and finite regeneration process time are obtained. Furthermore, imperfect performance of the dish collector and convective/radiative heat transfer mechanisms at the hot end as well as the convective heat transfer at the heat sink of the engine are considered in the developed model. Three objective functions including the output power and overall thermal efficiency have been considered simultaneously for maximization and the rate of entropy generation of the Stirling engine are minimized at the same time. Multi-objective evolutionary algorithms (MOEAs) based on NSGA-II algorithm has been employed while the Effectiveness's of regenerator, the Effectiveness's of the low temperature heat exchanger, the Effectiveness's of the high temperature heat exchanger, heat capacitance rate of the heat sink, heat capacitance rate of the heat source, temperatures of the working fluid in the high temperature isothermal process and temperatures of the working fluid in the low temperature isothermal process are considered as decision variables. Pareto optimal frontier has been obtained and a final optimal solution has been selected using various decision-making approaches including the fuzzy Bellman–Zadeh, LINMAP and TOPSIS methods.

1. Introduction

The Stirling engine is a simple type of external-combustion engine that uses a compressible fluid as a working fluid. The Stirling engine can theoretically be a very efficient engine to convert heat into mechanical work at Carnot efficiency. The thermal limit for the operation of a Stirling engine depends on the material used for its construction. In most instances, the engines operate with a heater and cooler temperature of 923 and 338 K, respectively [1]. Engine efficiency ranges from about 30% to 40% resulting from a typical temperature range of 923–1073 K, and normal operating speed range from 2000 to 4000 rpm [2].

Urieli and Berchowitz [3], Reader and Hooper [4] and Hargreaves [5] among others all provide isothermal models similar to Schmidt's original work. Carlson et al. [6] developed an ideal model with non-isothermal heat exchange. Models of this type suggest an improvement on the isothermal model as they eliminate the necessity for infinite heat transfer and impractically slow engine speed associated with isothermal working spaces. Urieli and Kushnir [7] showed that this analysis can be utilized in order to evaluate the various practical effects of non-ideal regenerators, heat exchangers, including heat transfer and pressure losses. Martaj et al. [8] presented a thermodynamic analysis of a low temperature Stirling engine at steady state operation, and energy, entropy and exergy balances were presented at each main element of the engine. The major goals of the Stirling engine designers can be mentioned in three categories: maximum efficiency; maximum power; minimum costs. Markman et al. [9] studied the thermal-flux and mechanical-power losses of a 200 W beta-configuration of the Stirling engine to optimize and increase the engine efficiency.

A miniature Stirling engine with 4 W output power in 0.1 MPa pressure and 900 rpm rotation speed was studied and made by Kagawa et al. [10]. Brandhorst and Chapman [11] developed a 5 kW engine for use as a power generator in space applications. Ataer [12] employed the Lagrangian method to the analysis of regenerators of Stirling cycle machines. The governing equations

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Nomenclature

A	area (m^2)
C	heat capacitance rate ($W\,K^{-1}$)
C_v	specific heat capacity ($J\,mol^{-1}\,K^{-1}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
I	direct solar flux intensity ($W\,m^{-2}$)
K_0	heat leak coefficient ($W\,K^{-1}$)
M	proportionality constant (–)
n	number of mole
N	number of heat transfer units (–)
P	power output (W)
Q	heat (J)
R	the gas constant ($J\,mol^{-1}\,K^{-1}$)
S	entropy (J/K)
T	temperature (K)
t	time (s)
U	overall heat transfer coefficient ($W\,K^{-1}\,m^{-2}$)
V	volume of the working fluid (m^3)
W	output work (j)
Subscripts	
0	ambient
1	inlet
1,2,3,4	state points
2	outlet
app	collector aperture
ave	average
c	cold side
dis	distance
H	heat source
h	hot side
L	cold side/heat sink
R	regenerator
rec	absorber
Greek	
η	thermal efficiency [–]
ε	effectiveness and emissivity factor [–]
λ	ratio of volume during the regenerative processes [–]
δ	Stefan's constant [$W\,m^{-2}\,K^{-4}$]
σ	entropy production [$W\,K^{-1}$]

of the regenerator are derived in terms of the displacement of the displacer, so that time does not appear in the equations. The equations, which include pressure fluctuations owing to flow reversals and longitudinal conduction, are solved numerically by a digital computer using a finite difference method. Nakajima et al. [13] developed a 10 g micro-Stirling engine with an approximately 0.05 cm^3 piston swept volume. An engine output power of 10 mW at 10 Hz was reported. The problems of scaling down were discussed.

Aramtummaphon [14] examined an open cycle Stirling engines by using steam heated from producer gas. The first engine generated an indicated power of about 1.36 kW at a maximum speed of 950 rpm, while the second engine, improved from the first one, produced an indicated power of about 2.92 kW at a maximum speed of 2200 rpm. Fukui et al. [15] has designed and constructed a micro-engine, and its experimental examination was performed; however, the micro-engine performance cannot be scaled to practical engine. Experimental determination of the effect of operating variables on Stirling engine is complicated and time consuming. Iwamoto et al. [16] comprised low temperature and high temperature Stirling engine efficiency with others. They determination exhibited that efficiency of LTD Stirling engine is around 50% of Carnot efficiency with same situation. Wu et al. [17] showed the effects of heat transfer, regeneration time, and imperfect regeneration on the performance of the irreversible Stirling engine cycle. Erbay and Yavuz [18] analyzed the real Stirling heat engine for maximum power output conditions using polytropic processes. They also determined the efficiency and compression ratio at maximum power density and ascertained the thermal design bounds. Ahmadi and Hosseinzade [19] investigated of Solar Collector Design Parameters Effect onto Solar Stirling Engine Efficiency. Ahmadi et al. [20] developed intelligent approach to figure power of solar Stirling heat engine by implementation of evolutionary algorithm.

Yaqi et al. and Sharma et al. developed a mathematical model for the overall thermal efficiency of solar powered high temperature differential dish Stirling engine with finite heat transfer and irreversibility of regenerator and optimized the absorber temperature and corresponding thermal efficiency [21,22]. Tlili investigated effects of regenerating effectiveness and heat capacitance rate of external fluids in heat source/sink at maximum power and efficiency [23]. Kaushik et al. studied the effects of irreversibilities of regeneration and heat transfer of heat/sink sources [24–27]. Solution of the multi-objective optimization problems is an extremely difficult goal which requires the simultaneous satisfaction of a number of different and even conflicting objectives. Evolutionary algorithms (EA) were initially extended and employed during the mid-eighties in an attempt to stochastically solve problems of this generic class [28]. 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 [29]. Multi-objective optimization problems in general show a possibly uncountable set of solutions namely as Pareto frontier, whose evaluated vectors represent the best possible trade-offs in the objective function space. In this term, multi-objective optimization of different themodynamic and energy systems have been paid attention by researchers nowadays [30–37]. In this work, by implementing multi-objective optimization algorithms output power and Stirling engine's thermal efficiency are maximized and rate of entropy generation of the Solar-Dish Stirling engine minimized. Also final solutions of different multi-objective optimization were compared with Ref. [24] data. At end it should be mentioned that, error analysis were implemented to figure robustness and precision of final solutions of different decision making approaches out.

2. System description

In Solar-Dish Stirling systems, mirrors of the parabolic shaped concentrator focuses the sun light on the focal point of the concentrator where the hot end of the Stirling engine is located. Therefore, the solar energy with a relatively high temperature is transferred to the hot side heat exchanger of the Stirling engine. Fig. 1 illustrates a schematic for a Solar-Dish Stirling engine connected to a solar dish concentrator. The Solar-Dish is equipped with a sun tracker which tracks the sun in order to have maximum solar energy transfer to the engine when sun moves during days. Hence,