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Application of the multi-objective optimization method for designing a powered Stirling heat engine: Design with maximized power, thermal efficiency and minimized pressure loss

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ABSTRACT

In the recent years, numerous studies have been done on Stirling cycle and Stirling engine which have been resulted in different output power and engine thermal efficiency analyses. Finite speed thermodynamic analysis is one of the most prominent ways which considers external irreversibilities. In the present study, output power and engine thermal efficiency are optimized and total pressure losses are minimized using NSGA algorithm and finite speed thermodynamic analysis. The results are successfully verified against experimental data.

1. Introduction

One of the greatest issues for the societies in the near future is security of sustainable energy [1]. Great amount of enterprise will be vital to satisfy future energy requirements with climate-friendly energy technologies [2–5], comprises electricity produced from solar and wind energy [6–8], bio-fuels [9,10], and carbon dioxide (CO_2) capture and storage (CCS) [11–14]. In this regard, scrutinized planning with respect to the prospect plays an important role toward better future.

Carbon dioxide emission is one of the restrictions of applying fossil fuels in all over the world which motivates expansion of higher efficiency and maximal electric energy per 1 kg CO_2 emitted technologies [15,16]. Use of Stirling cycles can lead to reduce the CO_2 emissions to the atmosphere.

Stirling cycle is one of the main primitive standard air cycles for heat engines [17,18]. External heat source and high efficiency are the Stirling engines advantages. Stirling engines can use solar energy which is available in one-third of the day, in the result solar/fuel hybrids are recommended. The combustion of the Stirling engine is continuous process and can burn all types of fuel with any quality [18–20]. The Stirling engine can theoretically be a highly efficient engine to convert heat into mechanical work at the Carnot efficiency when the ideal regeneration, isothermal compression and expansion are considered. The thermal limit for the operation of a Stirling engine depends on the working temperatures of the heater and cooler sides. In most instances, the engine operates with a heater and cooler temperature of 923 and 338 K, respectively [21]. The engine efficiency varies from about 30 to 40% which results in forming a typical temperature range of 923–1073 K, and normal operating speed range from 2000 to 4000 rpm [22–27]. The influence of the regenerator effectiveness, the dead volume on the power output and the thermal efficiency are studied by Kongtragool and Wongwises [24].

Carlson et al. provided a non-isothermal heat exchanger model which eliminates the necessity for infinite heat transfer time correspond to slow engine speed that is impractical [28].

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Organ studied the effects of various parameters such as diameter, length and materials on regenerator performance, irreversibilities and temperature gradient in Stirling engine regenerator while the regenerator is optimized [29,30].

Martaj et al. presented a thermodynamic analysis of a low temperature differential Stirling engine at steady state operation, and energy, entropy and exergy balances were presented at each main element of the engine [31].

Formosa and Despesse modeled engine power output and efficiency due to dead volume by implementing of the isotherm model [32].

Timoumi et al. developed a numerical model based on lumped analysis approach which takes into account losses and is implemented for optimization of GPU-3 Stirling engine [33–35].

The effects of heat transfer, regeneration time, and imperfect regeneration on the performance of the irreversible Stirling engine cycle are investigated by Wu et al. [36]. Li 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 the irreversibility of regenerator and optimized the absorber temperature and corresponding thermal efficiency [37]. Tlili studied the effects of regenerating effectiveness and heat capacitance rate of external fluids in heat source/sink at maximum power and efficiency [38]. The effects of addressed irreversibilities of regeneration and heat transfer of heat/sink sources were investigated by Kaushik and Kumar [39,40].

This paper concentrates on the evaluation of the losses because of the irreversibilities in the Stirling cycle which is an issue of substantial interest to those concerned with the performance and analysis of heat engines. Our researches and latest studies by others [41,42] have scrutinized that irreversibilities in the thermodynamic cycle have a specific significance in forecasting the performance of Stirling engines. Remarkable attempts have been made over the past years to completely recognize the irreversibilities associated losses [43,44]. Finite Speed of the piston, Friction and Throttling in the regenerator cause the internal irreversibilities which have to be taken into account for validating of any design of solar Stirling engines computation. One of the earliest efforts for a validation of the solar Stirling engines scheme of computation has been done by Costea et al. [45]. More exactly validation has been possible to accomplish through a validation of the schemes of computation for as many as possible Stirling engines. Probably, it can be done by using the new branch of irreversible thermodynamics, so-called “Thermodynamics with Finite Speed, and the Direct Method” [46].

Based on this, in 2002 it became possible to obtain the most powerful validation of a scheme of computation of the performances (efficiency and power) for 12 Stirling engines (the most performing in the world) working in 16 regimes [47]. Only with such a powerful “tool” it is possible to obtain a validation for a scheme of computation of solar Stirling engines performances for 5 solar Stirling engines [48–50].

This method has been employed in a number of models for the analysis and optimization of Stirling engines including the impact of irreversibilities in the cycle, successfully. However, analyses that are based on the entropy generation or exergy techniques do not relate the irreversibilities to the physical phenomena that cause them. The model presented here directly associates the irreversibilities to the operation of the cycle at finite speed. On the basis of the entropy generation techniques, for the studying of Stirling engine cycle performance, Costea et al. [48,49] have included the impacts of heat transfers, imperfect heat regeneration and irreversibilities of the cycle including pressure loss associated with the finite speed of the piston and Displacer throughout processes as gas passes through the regenerator, heater and cooler, and finally mechanical friction due to the motion of the moving parts.

For considering all mentioned issues, we have studied three objective functions: output power, the thermal efficiency of the entire solar Stirling system and pressure losses. In Addition, the multi-objective optimization is conducted with eleven decision variables including the temperatures of heat source and heat sink and their difference with working fluids, rotation speed, mean effective pressure and stroke.

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 [51]. 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 [52]. 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 thermodynamic and energy systems has been paid attention by researchers nowadays [53–58].

2. Stirling system

As shown in Fig. 1, Stirling cycle consists of four major processes. Process 1-2 is an isothermal process, in which the compressing working fluid rejects the heat at constant temperature (T_C) to heat sink which has a constant temperature (T_L). Then the working fluid crosses over the regenerator and is warmed up to T_h in an isochoric process 2-3. In process 3-4, the working fluid expands at a constant temperature, T_h, and obtains the heat from the heat source at a constant temperature (T_H). Last process (4-1), is an isochoric cooling process, where the regenerator absorbs heat from the working fluid. In an actual cycle it is impractical to have an ideal heat transfer in the regenerator in which the entire amount of absorbed heat (in the process 4-1) is transferred to the working fluid into the isochoric heating process (process 2-3).

3. Analysis of the Stirling engine cycle with irreversibilities

The pressure losses presented in this task is as follows [45–49]:

$$\sum \Delta p_i = \Delta p_{throt_R} + \Delta p_f + \Delta p_w \tag{1}$$

where Δp_{throt_R} is the pressure drop coming of the internal friction of the current which takes place in the regenerator and is insignificant in heat exchangers (coolers and heaters) [45–50].

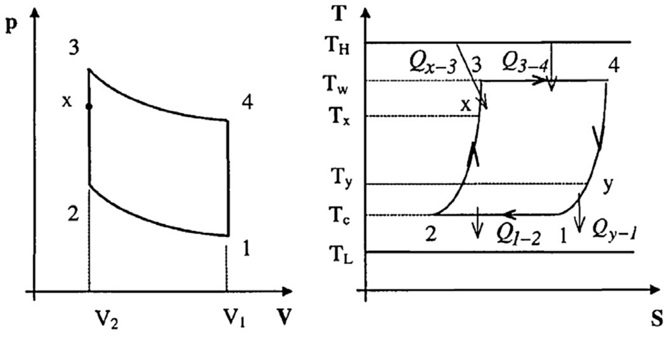

Fig. 1. *P*–*V* and *T*–*S* diagrams of an isothermal Stirling engine cycle [48].