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Multi-objective thermodynamic optimization of a free piston Stirling engine using response surface methodology

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ABSTRACT

In this study, response surface methodology (RSM) and the desirability approach are applied to study and optimize the performance of a free piston Stirling engine (FPSE). A regression model is presented to investigate the influences of operating and structural parameters of the FPSE on its performance. The analysis of variance (ANOVA) is conducted to describe the rationality of the regression model and examine the statistical significance of factors. Also, the relationship between output power, thermal and exergy efficiency and these parameters of Stirling engine is presented via 2D contour and 3D surface plots. Moreover, the operating and structural parameters of FPSE are optimized to achieve maximal output power, thermal and exergy efficiencies simultaneously. The multi-objective optimal results are confirmed by Sage software simulation results. It is found that the errors between the Sage modeling and RSM values for output power, thermal and exergy efficiency are 0.37%, 1.51% and 1.40%, respectively. Therefore, the model based on the RSM method is an efficient and fast way for the design and optimization of the FPSEs.

1. Introduction

Free piston Stirling engines have attracted great attention for their high efficiency, ultra- reliability, mechanical simplicity, low wear and a series of other advantages with the increasingly grim situation of energy shortage and environmental protection [1,2]. FPSE relies only on the gas pressures and adopts springs to impart the correct motions to the reciprocating components [3]. Besides, compared with the kinematic Stirling engine, FPSE is unconstrained such that the displacer and piston move separately owing to the pressure variation of the working fluid, meaning that the movement of the piston and displacer is independent [4]. Meanwhile, FPSE has the advantages of low cost, freedom of working gas leakage, long operating life without the need for lubrication and non-contact operation over the kinematic Stirling engine [5]. In general, FPSEs can be classified into three major types (namely: alpha, beta, and gamma-type). In the beta-type FPSE, a displacer and a piston are placed in the same cylinder, and both are reciprocating in coaxial direction. It is very compact and has a higher power density compared with the other two types [6,7]. This study mainly focuses on the beta-type FPSE.

In recent years, different models and methods have been used to optimize the Stirling engines. Kongtragool and Puech built a FPSE based on the isothermal model, and the parametrical effect of the regenerator was studied numerically [8,9]. Formosa modeled the output power and thermal efficiency of a Stirling engine due to dead volume of the heat exchangers using the isothermal model [10]. Timoumi optimized the performance of a GPU-3 Stirling engine by developing a numerical model based on the lumped analysis approach [11,12]. He developed a mathematical model for the thermal efficiency of solar dish Stirling engine with finite heat transfer and irreversibility of the regenerator and optimized the absorber temperature and thermal efficiency [13]. Snyman developed a design analysis and synthesis tool for optimization of the Stirling engine and applied three different methods (namely: the method of Schmidt, the adiabatic and the simple analysis [14]).

During the current years, many researchers have paid attention to the multi-objective optimization of the Stirling engines. Mohammad developed a thermal model for maximizing the output power and thermal efficiency of the solar Stirling system, considering the finite rate of heat transfer, regenerative heat loss, conductive thermal bridging loss, finite regeneration process time [15]. Ahmadi optimized output power, thermal efficiency, and pressure loss of a solar dish Stirling engine by adapting NSGA-II [16,17]. Meanwhile, they developed finite time thermos-economic analysis and NSGA-II for optimizing dimensionless thermos-economic objective function, thermal efficiency and dimensionless power output for a solar-powered Stirling engine

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[18,19]. Patel and Savsani investigated TS-TLBO of the Stirling engine, they considered the thermal efficiency, output power and total pressure drop of the engine for optimization [20]. Rao used the TLBO algorithm for multi-objective optimization of the Stirling engine [21]. Punnathanam used Non-dominated Sorting Genetic Algorithm-II and genetic algorithm for the multi-optimization of the Stirling engine systems [22,23]. Rao explored the use of self-adaptive Jaya algorithm for maximizing output power, thermal efficiency and minimizing pressure losses of the Stirling system [24]. Mou used the dimensionless power to optimize the bore-stroke ratio, heat source temperature, phase angle and the frequency of FPSE [25].

Based on the literatures above, single objective or multi-objective (two or more) has been extensively used in thermodynamic optimization of the Stirling engine. However, little work has been conducted on the multi-objective optimization of the FPSE through response surface methodology (RSM). A desirability approach, which combines with the RSM is one of the most widely applied methods in the industry for the multi-objective optimization response processes. RSM is applied to generate the design of experiments (DOE) and achieve the prediction model for the FPSE, and desirability approach can search for the optimal combination by considering complicated effects [26,27], and it has the advantages of small calculation amount, high reliability, and precision for the product. Therefore, this method can quickly and accurately determine the optimal combination of several parameters for the FPSE.

In this research, RSM and the desirability approach are applied to evaluate and optimize the performance of the FPSE. Nine operating and structural parameters that influence the performance of FPSE are selected while the output power (W_{net}), thermal (η_{th}) and exergy efficiency (η_{ex}) are selected as the response and optimized. The significant effects of parameters are investigated by ANOVA (analysis of variance) while the optimal combination of the parameters is obtained to maximize W_{net}, η_{th}, and η_{ex}. Finally, the multi-objective optimal results are further validated by comparing with Sage simulation.

2. Mathematical model

2.1. Model of the FPSE

Fig. 1 presents the schematic diagram of the beta-type free piston Stirling converter (FPSC), and it consists of a FPSE and a linear generator. A displacer and piston oscillate in a pressurized cylinder, the thermal energy is input at the heater. The piston and displacer are supported by flexures. It consists of two areas: the working space and backspace. When the displacer oscillates through the three heat exchangers (heater, regenerator, and cooler), the thermal energy exchange happens in the working space.

In this paper, a one-dimensional software Sage, which was developed by Gedeon Associates is applied, and it is the most widely used Stirling cycle analysis code [28–30]. The model of the FPSE represented in Sage [31] is shown in Fig. 2. The components of the model are connected by several connectors, such as mass flow, heat flow. This model consists of a displacer, a piston, a rectangular fin heater, a regenerator, and a cooler, as well as expansion, compression and backspace. In the Sage model, some losses were added, such as the displacer seal loss, displacer shuttle loss, conductive losses (regenerator wall, displacer shell, and displacer cylinder), and fluid resistance losses (three heat exchangers). This model assumed an isolated boundary condition on a solid surface node within the FPSE. The axial temperature distribution along the base of the finned exchangers are set as the input. Then the Sage model iterates after inputting all the parameters of the components.

The technical specifications of the FPSE are given in Table 1.

As for the governing equations for the Sage model, the flow and heat transfer in the beta-type FPSE are unsteady and periodic. The working gas is compressible. The equations solved in gas models are designed for one-dimensional internal flow with space and time-variable flow area. They are derived from the integral-form compressible gas dynamic equations. These equations were reported in Ref. [32].

2.2. Objective functions

In this paper, a multi-objective optimization is carried out between conflicting thermodynamic objectives. Maximization of output power, thermal and exergy efficiency of FPSE are considered as the objectives. The output power of FPSE is expressed as

$$W_{net} = \eta_{th} Q_{in} \tag{1}$$

where Q_{in} is the amount of heat to working gas, it is defined as

$$Q_{in} = Q_h + Q_{cylind} + Q_{dis} + Q_{reg} + Q_{shuttle} \tag{2}$$

where Q_h is the heat transfer to working gas, η_{th} is the thermal efficiency of FPSE, Q_{cylind}, Q_{dis}, Q_{reg} are conductive losses of displacer cylinder, displacer shell and regenerator wall, respectively. $Q_{shuttle}$ is the shuttle loss. The fluid resistance losses of three heat exchangers and seal loss are considered.

In order to analyze its irreversibility, the second law based thermodynamic analysis is being taken into account. The FPSE is simplified as a closed system, and its exergy efficiency of the FPSE is obtained as

$$\eta_{ex} = \frac{Q_{in}-Q_{rej}}{E_{xQh}-E_{xQc}} = \frac{Q_{in}-Q_{rej}}{Q_{in}(1-\frac{T_0}{T_h})-Q_{rej}(1-\frac{T_0}{T_c})} \tag{3}$$

where Q_{rej} is the amount of heat received by the cooling water, it is obtained by

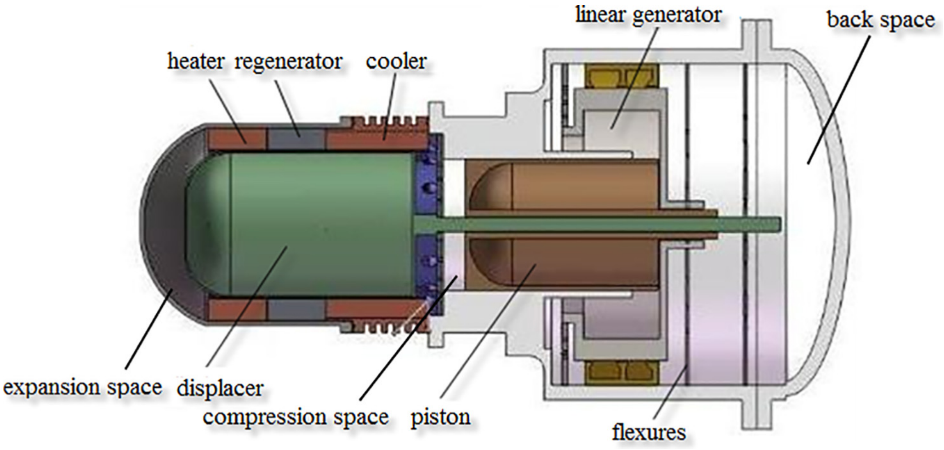

Fig. 1. The schematic illustration of the FPSE.