Energy Conversion and Management 84 (2014) 88–96

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Thermodynamic design of Stirling engine using multi-objective particle swarm optimization algorithm

Chen Duan [a], Xinggang Wang [b], Shuiming Shu [a,*], Changwei Jing [a], Huawei Chang [a]

[a] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Department of Electronics and Information Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 7 January 2014
Accepted 2 April 2014
Available online 4 May 2014

Keywords:
Stirling engine
Thermodynamic analysis
Irreversibility parameter
Particle swarm optimization
Multi-objective optimization

ABSTRACT

In the recent years, the interest in Stirling engine has remarkably increased due to its ability to use any heat source from outside including solar energy, fossil fuels and biomass. A large number of studies have been done on Stirling cycle analysis. In the present study, a mathematical model based on thermodynamic analysis of Stirling engine considering regenerative losses and internal irreversibilities has been developed. Power output, thermal efficiency and the cycle irreversibility parameter of Stirling engine are optimized simultaneously using Particle Swarm Optimization (PSO) algorithm, which is more effective than traditional genetic algorithms. In this optimization problem, some important parameters of Stirling engine are considered as decision variables, such as temperatures of the working fluid both in the high temperature isothermal process and in the low temperature isothermal process, dead volume ratios of each heat exchanger, volumes of each working spaces, effectiveness of the regenerator, and the system charge pressure. The Pareto optimal frontier is obtained and the final design solution has been selected by Linear Programming Technique for Multidimensional Analysis of Preference (LINMAP). Results show that the proposed multi-objective optimization approach can significantly outperform traditional single objective approaches.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Due to the dramatic consumption of fossil fuels, remarkable attention is drawn to the renewable energy and energy-efficient conversion systems. The world needs a clean energy revolution in order to break dependence on fossil fuels. Such a revolution would enhance globe energy security, promote enduring economic growth and tackle environmental challenges [1]. In this regard, the Stirling engine is one of the most promising sustainable energy technologies in recent years [2–4].

The Stirling engine is a simple type of external combustion engine which operates over a closed, regenerative thermodynamic cycle with the ability to use a wide variety of energy sources such as solar energy, geothermal and industrial waste heat. It plays an important role on environmental protection and also has significance for moderating the pressure on fossil fuels supplies in the world. With ideal regeneration and isothermal processes, the Stirling engine can theoretically convert heat into mechanical work at Carnot efficiency. The thermal limit for the operation of Stirling engine depends on the performance of heat resistant materials used for its construction. In most instances, Stirling engines operate with a heat source and heat sink temperature of 923 and 338 K, respectively [5]. The engine thermal efficiency varies from about 30% to 40% resulting from a typical temperature in range of 923–1073 K, and normal operating speed range from 2000 to 4000 rpm [6–10].

The invention of the Stirling engine preceded modern thermodynamic theory to a degree exemplified by the fact that it was not until fifty years after its invention that a reasonable analysis of the cycle was published. This analysis was made by Gustav Schmidt in 1871 [11] and has been reported in a more comprehensive form in the book of Israel Urieli [12]. The analysis, however, is limited in that it assumes isothermal working spaces and ideal heat exchangers, and thus it calculates the efficiency as being only temperature-dependent (i.e., Carnot efficiency). In 1960, Finkelstein presented an ideal analysis, in which he assumed adiabatic working spaces but maintained the heat exchangers as ideal [13]. The effects of heat transfer and imperfect regeneration on the performance of the irreversible Stirling engine was investigated by Wu et al. [14]. As the efforts to reduce certain loss mechanisms can tend to increase the detrimental impact of others, complementary approaches are needed. It is noted that a practical Stirling cycle always departs significantly from the ideal cycle, mainly

* Corresponding author. Tel.: +86 027 87542718; fax: +86 027 87540724.
E-mail address: fei@hust.edu.cn (S. Shu).

http://dx.doi.org/10.1016/j.enconman.2014.04.003
0196-8904/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

C_V	specific heat at constant volume (J/kg K)
e	regenerator effectiveness
E_S	Stirling engine thermal efficiency
K	factor defined by Eq. (9)
k	specific heat ratio
k_{DH}	hot space dead volume ratio
k_{DR}	regenerator dead volume ratio
k_{DC}	cold space dead volume ratio
m	total working fluid mass contained in the engine (kg)
p	charge pressure (N/m^2)
Q_{in}	total heat added from an external heat source (J)
Q_{out}	total heat rejected to an external heat sink (J)
R	gas constant (J/kg K)
R_S	irreversibility parameter
T_3	working fluid temperature in the hot space (K)
$T_{3'}$	working fluid temperature at the regenerator outlet (K)
T_1	working fluid temperature in the cold space (K)
$T_{1'}$	working fluid temperature at the regenerator inlet (K)
T_R	effective working fluid temperature in regenerator dead space (K)
V_{DH}	hot space dead volume (m^3)
V_{DR}	regenerator dead volume (m^3)
V_{DC}	cold space dead volume (m^3)
V_D	total dead volume (m^3)
V_E	expansion volume (m^3)
V_C	compression volume (m^3)
W_{net}	engine net work (J)

due to the performance of the heat exchanger and the regenerator. A detailed analysis with practical values and examples of the engine were given by Organ [15]. The similarity and scaling approach developed by Organ provides a simpler way of creating the preliminary design for the prototype engine. In 2000, Kaushik and Kumar presented an investigation of a finite-time thermodynamic analysis of a Stirling engine in which the power output and the corresponding thermal efficiency were maximized [16]. Petrescu and Costea [17] conducted a technique for calculating the efficiency and power of Stirling engines based on the First law of thermodynamics for processes with finite speed [17,18]. In 2008, Timoumi and Tlili developed a second-order Stirling model which includes thermal losses and is applied for the optimization of GPU-3 Stirling engines [19]. Leonardo Scollo [20] presented an alpha-type Stirling engine by using a similar design method. A numerical model for beta-type Stirling engine with rhombic drive mechanism was developed by Cheng et al. [21]. The energy equations of the control volumes in the working chambers and heat exchangers were derived and solved by taking into account the non-isothermal effects, the thermal resistance of the heater head and the effectiveness of the regenerative channel [21]. Formosa et al. [22] developed an analytical model taken into account the heat losses and irreversibilities on Stirling engines which could be used in a dynamical analysis for preliminary design [22]. In 2011, a semi-analytical dynamic model of free piston Stirling engine was developed by Formosa [23]. The thermodynamic model is used to define the thermal variables which are used in dynamic model which evaluates the kinematic results. Recently, Aksoy and Cinar [24] conducted a theoretical investigation on dynamic and thermodynamic analysis of a beta-type Stirling engine with rhombic drive mechanism by implementing nodal analysis method [24]. Solmaz and Karabulut [25] presented a novel configuration of beta-type Stirling engine which was driven by a lever mechanism. The performance of the novel engine was compared with rhombic drive engine via nodal analysis [25]. Abdollahpour et al. [26] developed a thermodynamic model and an optical model of a parabolish dish collector for Stirling engine. The collector has the ability to be coupled with different type of Stirling engine and used in various fields like air conditioning and solar water heater in the following of generate electricity from Stirling engine [26].

Although a large number of studies have been done on the optimization of Stirling cycle and Stirling engine, most of them are merely focused on single impact factor. Previous work has been done on dynamic and thermodynamic analysis of Stirling engine by the authors [27,28]. In this paper, we have studied three objective functions simultaneously: engine power output, thermal efficiency of Stirling engine, and the cycle irreversibility parameter which has previously been proved to be significant in predicting the performance of Stirling engine in the thermodynamic cycle [29]. Meanwhile, ten decision variables including temperatures of heat source and heat sink, volumes of expansion space and compression space, total dead volume, volume ratios of three heat exchangers, effectiveness of regenerator, and mean effective pressure are considered during the multi-objective optimization process.

Problems with multiple objectives are present in a great variety of engineering optimization problems. It is quite common that in these problems there are several conflicting objectives to be optimized and it is difficult to identify what the best solution is. Despite the considerable diversity of techniques in Operation Research developed to tackle these problems, their intrinsic complexity calls for alternative approaches. Recently, Ahmadi et al. [30–35] conducted a series of works on multi-objective optimization method for designing a power Stirling engine by implementing the second-version Non-dominated Sorting Genetic Algorithm (NSGA-II) which is known as a tributary of evolutionary algorithm. In this study, a superior technique that has been adopted for dealing with multi-objective optimization problems is Particle Swarm Optimization (PSO) [36], which is a relatively heuristic inspired by the choreography of a bird flock. This method was applied in the area of designing Stirling engine for the first time. The study developed by Coello [37] demonstrated that PSO is highly competitive and can be considered a viable alternative to solve multi-objective optimization problems. In addition, the exceptionally low computational times required by PSO approach make it a very promising approach to problems (e.g., engineering optimization) in which the computational cost is a vital issue.

2. Stirling system description

The ideal Stirling cycle satisfies the Carnot requirement of reversibility and can be described with reference to Fig. 1. One of the mechanical configurations for realizing the Stirling cycle is shown, being known as the Alpha arrangement. The regenerator generally comprises a matrix of fine wires, porous metal or sometimes simply the metal wall surface enclosing an annular gap.

The position of the pistons are shown at the four extreme state points of the cycle as seen in the pressure-volume and temperature-entropy diagrams. Process 1–2 is the isothermal compression process during which the heat is removed from the engine at the cold sink temperature. Similarly, process 3–4 is the isothermal expansion process during which heat is added to the engine at the hot source temperature. Process 2–3 and 4–1 are the constant

Download English Version:

https://daneshyari.com/en/article/763789

Download Persian Version:

https://daneshyari.com/article/763789

Daneshyari.com