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Multi-objective optimization of a Stirling heat engine using TS-TLBO (tutorial training and self learning inspired teaching-learning based optimization) algorithm

Vivek Patel*, Vimal Savsani

Department of Mechanical Engineering, Pandit Deendayal Petroleum University, Gujarat, India

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ABSTRACT

In the present work, TS-TLBO (tutorial training and self learning inspired teaching-learning-based optimization) algorithm is proposed and investigated for the multi-objective optimization of a Stirling heat engine. The exploration and exploitation capacity of the basic MO-TLBO (multi objective teaching-learning-based optimization) is enhance by introducing the concept of tutorial training and self motivated learning. The multi-objective TS-TLBO algorithm uses a grid-based approach to adaptively assess the non-dominated solutions maintained in an external archive. Optimization of a Stirling heat engine is carried out by considering two and three objective functions simultaneously for the maximization of thermal efficiency, output power and minimization of total pressure drop of the engine. Application examples are presented to demonstrate the effectiveness and accuracy of the proposed algorithm.

1. Introduction

Energy conservation is one of the important means to save the scarce energy in today's world where demand for energy as well as price of fossil fuel used to generate energy is expected to increase continuously. At the same time, it is also necessary to reduce the pollution caused by the exhaust emissions during the power generation. Therefore, applying more efficient energy conversion processes are necessary to minimize the negative environmental impact. In the recent years, the Stirling engines have attracted a lot of attentions due to its high capability [1,2]. A Stirling engine presents a reasonable theoretical efficiency which can be closer to the Carnot efficiency, compared to other reciprocating thermal engines.

A Stirling engine is a closed cycle regenerative heat engine operating by cyclic compression and expansion of air or other gases at different temperature levels so that net conversion of heat energy to mechanical work takes place [3–5]. Unlike internal combustion engines, heat is applied externally to the Stirling engine. Regenerator is one of the important parts of the Stirling engine which provides the thermal storage. It is the inclusion of a regenerator that differentiates the Stirling engine from other closed cycle hot air engines. As the Stirling engine relies on an external heat source, any alternative or renewable heat source is used with the Stirling engine [6–8]. This compatibility of Stirling engine with alternative and renewable energy sources catch the attention of the researchers for its performance improvement. It is observed from the literature survey that in most instances the engine is operated between temperature ranges 338 K–923 K and its efficiency is higher than 30% [4,5,8,9].

Kongtragool and Wongwises [7] investigate the performance of a low-temperature differential Stirling engine. Variations of engine torque, shaft power and brake thermal efficiency with engine speed and engine performance at various heat inputs are presented by the authors. Petrescu et al. [10] carried out design and optimization of solar Stirling power plant with hydrogen/oxygen fuel cells. Costea et al. [11] determine the effect of pressure losses and actual heat transfer on the performance of a solar Stirling engine. The model presented by the authors includes the effects of both internal and external irreversibility of the cycle. The authors analyzed solar

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* Corresponding author.
E-mail addresses: viveksaparia@gmail.com (V. Patel), vimal.savsani@gmail.com (V. Savsani).

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Nomenclature

A_r	heat transfer area of regenerator (m^2)
B	parameter to calculate regenerator loss co-efficient
b	distance between wires in the regenerator (m)
C_p	constant pressure specific heat (J/kg K)
C_v	constant volume specific heat (J/kg K)
C_r	specific heat of regenerator material (J/kg K)
D	diameter (m)
d	regenerator wire diameter (m)
f	co-efficient of friction
h	heat transfer co-efficient (W/m^2 K)
L	length of regenerator (m)
M	parameter to calculate regenerator loss co-efficient
m	mass (kg)
N	rotational speed (rpm)
N_r	number of regenerators per cylinder
n_r	number of gauges of regenerator matrix
P	output power (W)
p	pressure (MPa)
p_m	mean effective pressure (MPa)
Pr	Prandtl number
Δp	pressure drop (kPa)
Q	heat transfer rate (W)
R	gas constant (J/kg K)
s	stroke length (m)
T	temperature (K)
ΔT	temperature difference (K)

Greek letters

λ	volumetric ratio during regeneration process
μ'	factor depend on volumetric ratio
ρ	density (kg/m^3)
η	efficiency
ε_r	regenerator effectiveness
τ	temperature ratio
γ	specific heat ratio
ν	kinematic viscosity (m^2/s)

Subscripts

C	heat sink
c	cylinder, related to Carnot cycle
g	gas
H	heat source
h	hot side
l	cold side
r	regenerator

Stirling engine using a mathematical model based on the first law of thermodynamics. Petrescu et al. [12,13] analyzed irreversible Stirling cycles using thermodynamics with finite speed, and the direct method. The method developed by authors has been employed in a number of models for the analysis and optimization of Stirling engines including the impact of irreversibilities. Organ [14,15] carried out the optimization of Stirling engine regenerator and analyzed the effect of regenerator diameter, length and materials on regenerator performance in Stirling engine. Martaj et al. [16] carried out thermodynamic study of a low temperature difference Stirling engine at steady state operation. The authors presented energy, entropy and exergy balances at each main element of the Stirling engine.

Formosa and Despesse [17] develop analytical thermodynamic model of Stirling engine considering heat losses and irreversibilities of the engine. The authors also investigate the effects of the technological and operating parameters on Stirling engine performance. Timoumi et al. [18–20] carried out design and performance optimization of Stirling engines. A second-order Stirling model, which includes thermal losses, has been developed by the authors and used to optimize the performance and design parameters of the engine. Wu et al. [21] carried out an optimal performance analysis of a Stirling engine with heat transfer and imperfect regeneration irreversibilities. Li. et al. [22] carried out optimization of solar-powered Stirling heat engine with finite-time thermodynamics. The authors developed a mathematical model for the overall thermal efficiency of the solar-powered high temperature differential dish-Stirling engine with finite-rate heat transfer, regenerative heat losses and conductive thermal bridging losses. Tlili [23] studied endoreversible Stirling heat engine at maximum power conditions using finite time thermodynamic. Kaushik and Kumar [24,25] investigate finite time thermodynamic analysis of an endoreversible Stirling heat engine. The authors applied finite time thermodynamics to maximize the power output and the corresponding thermal efficiency of an endoreversible Stirling heat engine. Puech [26] provides a thermodynamic analysis of a Stirling engine with linear and sinusoidal variations of the regenerator dead volume.

Babaelahi Sayyaadi [27] developed a thermal model of Stirling engine (called Simple II) based on the based on modification of the original simple analysis and employed for thermal simulation of a prototype Stirling engine. Babaelahi Sayyaadi [28] developed a new thermal model of Stirling engine based on polytropic analysis of Stirling engine with various losses (called PSVL) and applied to a prototype Stirling engine. Hosseinzade and Sayyaadi [29] developed the thermal model of Stirling engine based on the combination of adiabatic analysis and finite speed thermodynamics (called CAFS). This model considered the effect of finite speed of piston, pressure throttling in heat exchangers and regenerator and piston's mechanical friction. Hosseinzade et al. [30] developed closed-form thermal model of Stirling engine (called PFST) based on the combination of polytropic analysis of expansion/compression processes and the finite speed thermodynamics. Babaelahi Sayyaadi [31] carried out the modification of PFST and developed second order model thermal model of Stirling engines (called modified PFST) based on convective-polytropic heat transfer of working spaces.

Recently few works had been reported on the optimization of Stirling engine using advanced optimization algorithms. Ahmadi et al. [32] applied NSGA (Non-dominated Sorting Genetic Algorithm) for the multi objective optimization of Stirling heat engine. The authors had considered maximization of output power, engine thermal efficiency and minimization of total pressure losses as objective functions. Ahmadi et al. [33] used NSGA-II for the optimization of solar-powered high temperature differential Stirling engine. The authors had considered maximization of output power and engine thermal efficiency as objective functions. Shazly et al. [34] presents the modeling and simulation of solar-powered Stirling engine working at the low temperature range. The authors developed a mathematical model for the thermal analysis of the solar-powered low temperature Stirling engine with heat transfer.

Ahmadi et al. [35] carried out multi-objective thermodynamic-based optimization of solar dish Stirling engine using NSGA-II.