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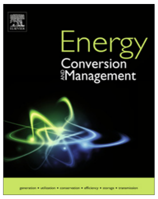

Optimization of powered Stirling heat engine with finite speed thermodynamics

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ABSTRACT

Popular thermodynamic analyses including finite time thermodynamic analysis was lately developed based upon external irreversibilities while internal irreversibilities such as friction, pressure drop and entropy generation were not considered. The aforementioned disadvantage reduces the reliability of the finite time thermodynamic analysis in the design of an accurate Stirling engine model. Consequently, the finite time thermodynamic analysis could not sufficiently satisfy researchers for implementing in design and optimization issues. In this study, finite speed thermodynamic analysis was employed instead of finite time thermodynamic analysis for studying Stirling heat engine. The finite speed thermodynamic analysis approach is based on the first law of thermodynamics for a closed system with finite speed and the direct method. The effects of heat source temperature, regenerating effectiveness, volumetric ratio, piston stroke as well as rotational speed are included in the analysis. Moreover, maximum output power in optimal rotational speed was calculated while pressure losses in the Stirling engine were systematically considered. The result reveals the accuracy and the reliability of the finite speed thermodynamic method in thermodynamic analysis of Stirling heat engine. The outcomes can help researchers in the design of an appropriate and efficient Stirling engine.

1. Introduction

In recent years, the primary research and development attempts have been conducted in the electricity production and pollutant reduction fields, with the focus on carbon dioxide mitigation. The Stirling engine has a high potential to be applied for converting heat into mechanical work with high energy efficiency. Low emission, high energy efficiency, coupling with a variety of different fuels, high specific work, low vibration, high reliability and little maintenance of the Stirling engines have made it popular among the other heat engines. Theoretically, the energy efficiency of a Stirling cycle might be as high as the Carnot efficiency when the regeneration process is perfect and main processes (two isothermal and two isochoric) of the cycle are reversible [1].

The Stirling engine is associated with the external combustion engine, and it could be powered by waste heat which is derived from an upper stream [1–7].

The Stirling cycle is a closed regenerative thermodynamic cycle, with cyclic expansion and compression of the working fluid at various temperature degrees [4–26]. In an external combustion heat engine, the working fluid is heated by an external heat source and the fluid expands and produces work in an expansion process. Then, the working fluid releases the heat to a cold reservoir in a compression process in which a fraction of produced work in expansion process is destructed. Consequently, the working fluid is repeatedly circulated to the expansion space.

Blank and colleagues [4] investigated the power optimization of an endoreversible Stirling cycle and provided an estimation of possible performance for a real engine. Thombare and Verma [5] gathered the available technologies and obtained achievements regarding the analysis of Stirling engines and eventually presented some suggestions for their applications. Formosa and Despesse [7] investigated the modeling by means of the isothermal model in

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Nomenclature

C_v	constant volume specific heat (J kg^{-1} K^{-1})
D	diameter (m)
d	wire diameter (m)
m	mass of the gas (kg)
N	number of gauzes of the matrix, number of regenerators per cylinder
n_r	rotation speed
p	pressure (pa)
Δp	pressure loss (pa)
p_m	mean gas pressure (pa)
P	output power (W)
$\dot{Q}$	heat transfer rate (W)
R	gas constant (J kg^{-1} K^{-1})
s	stroke (m)
T	temperature (K)
ΔT	temperature difference (K)

Greek letters

λ	ratio of volume during the regenerative processes (volumetric ratio)
ε_R	effectiveness of the regenerator
η	efficiency
η'	efficiency defined in Eq. (8a)
η_{II}	second law efficiency
γ	specific heat ratio
τ	ratio of the heat sources temperatures

Subscripts

c	cylinder, related to the Carnot cycle
f	friction
H	heat source
L	heat sink
SE	Stirling engine
II	related to the second law
$1-4$	the processes states
g	gas
$aver$	average
R	regenerator

order to evaluate the effects of dead volumes on the engine's output power and energy efficiency.

West [8] presented a new dimensionless number called Beal number by considering output power of the Stirling engine. It is worth to mention that Beal number has been employed to estimate output power of Stirling engines.

In recent years, different researches have been carried out on the Stirling cycle implementing the concept of finite-time thermodynamics. Moreover, FTT analysis is normally limited to the systems which are consisted of linear heat transfer laws with respect to the temperature differential in both of the reservoirs and the working fluid [9,10].

Yaqi and colleagues proposed a mathematical approach for the overall thermal efficiency of solar powered high temperature differential dish Stirling engine with the irreversibility of regenerator and finite heat transfer and optimized the absorber temperature and conforming thermal efficiency [11].

Kaushik and colleagues investigated the influences of heat transfer of heat sink/sources and irreversibilities on regeneration [12]. Kaushik and Kumar in (2000) [13], studied a comprehensive analysis of finite time thermodynamics of a Stirling heat engine with regenerative losses, finite heat capacity of external reservoirs and finite effectiveness of each of the heat exchangers [i.e. a low temperature heat exchanger (LTHEX) and a high temperature heat exchanger (HTHEX)]. Tyagi and colleagues, investigated a general analysis of FTT of an Ericsson refrigerators and cryogenic Stirling with both external and internal irreversibilities owing to finite temperature differences between the cycles and the source/sink reservoirs, regenerative losses, the finite heat capacitance, and the entropy generations within the cycles.

Hirata [15] proposed a model employing the air as working fluid in order to achieve a compact Stirling engine with reduced price. In order to achieve the highest output he calculated the mechanical losses for different values of load pressure. Cullen and McGovern [16] suggested an approach for hypothetical decoupled Stirling cycle engine employed for its limits on its real-world realization and the analysis of the ideal Stirling cycle engine. Puech and Tishkova [17] performed a hypothetical study regarding the thermodynamic analysis of Stirling engine with sinusoidal and linear changing of the volume. They explained that the regenerator dead volume didn't have any effect on the engine efficiency with perfect regeneration. Senft [18,19] investigated the effects of mechanical friction losses and internal heat losses and specified the maximum value of the mechanical efficiency besides the theoretic restrictions on the performance of Stirling engines. Scollo and colleagues [20] investigated the probability of a Stirling engine heater enhancement. They pointed out that in outside of expansion exchanger there was a deficit of heat exchange area. They comment was raised after construction and testing their engine. They suggest that by increasing the exchange area this problem can be solved.

Wongwises and Kongtragool [21] conducted an investigation on the determining of output power for a low temperature differential Stirling engine with gamma-configuration. They explained that the most proper formula for the determining of a gamma-configuration, low temperature differential Stirling engine power output is the mean pressure power formula. Iwamoto and colleagues [22] evaluated the performance of a low temperature difference Stirling engine with a high temperature difference Stirling engine. They deduced that at the same working circumstances the thermal efficiency of the low temperature difference Stirling engines will not achieve that of high temperature difference Stirling engines. Kongtragool and Wongwises [23] designed and assembled a two single-acting, four power pistons and twin power piston and low temperature differential Stirling engine with gamma-configuration. They examined the engine with different heat inputs. The changing of the engine torque, the brake thermal efficiency and the shaft power at different heat inputs with performance and engine speed were demonstrated. They deduced that the engine performance rises when the heat input increases. The engine torque, the brake thermal efficiency, the shaft power, the heater temperature, and the speed also increase with the rising heat input. As well, the Beale number of this engine rises in parallel with the increasing heater temperature or with the decreasing temperature ratio.

Tlili and colleagues [24] proposed a first law approach with additional factors for an internal irreversibility variable to determine the influences of irreversibility on output power and energy efficiency. Their irreversible parameters originate from the second law of thermodynamics for an actual cycle. Martaj and colleagues [25] studied a low-temperature differential Stirling engine at