Journal of the Energy Institute 88 (2015) 36–42

Contents lists available at ScienceDirect

Journal of the Energy Institute

journal homepage: http://www.journals.elsevier.com/journal-of-the-energy-institute

Performance optimization of a linear phenomenological law system Stirling engine

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ARTICLE INFO

Article history:
Received 25 August 2009
Accepted 25 August 2009
Available online 26 April 2014

Keywords:
Stirling heat engine
Mechanical losses
Brake thermal efficiency
Finite time thermodynamics
Performance optimization

ABSTRACT

The power and efficiency performance analyses and optimization of a Stirling engine with heat resistance, heat leakage, regeneration loss and mechanical losses are carried out in this paper by using the combination of Senft's mechanical efficiency model with finite time thermodynamics analysis method. The analytical formulae for indicated power, shaft power, thermal efficiency and brake thermal efficiency for the Stirling engine are derived by assuming that the heat transfer at finite temperature difference between the heat reservoirs and the working fluid obeys the linear phenomenological heat transfer law. The optimal operating regions for shaft power and break thermal efficiency are obtained and the influences of heat leakage, regeneration loss and mechanical friction losses on cycle performance are investigated through numerical calculations. The obtained results are expected to provide theoretical guidelines for the optimal design and operation of practical Stirling engines.

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1. Introduction

The Stirling engine is a simple type of external-combustion engine with good development prospects. It has the advantage of high efficiency, low vibration levels, simple structure and can run on any combustible fuels [1–3]. So, more and more attention has been paid to research work of Stirling engine. Kolin [4] had shown that with perfect regeneration, the thermal efficiency of an ideal Stirling engine can attain the maximum, i.e. the Carnot efficiency.

In recent years, the thermodynamic researches on the performance of the Stirling engine include many aspects. For example, one is the mechanical efficiency model developed by Senft [5–12]. Senft [5–12] studied the mechanical efficiency model of heat engine and applied to the performance analysis of the Stirling engine. He studied the characteristics of a fair-comparison class of reciprocating engines including Stirling engine and found that the ideal Stirling engine has the maximal mechanical efficiency. Thus taken together, the Stirling engine is seen to have the maximal brake-thermal efficiency in all reciprocating engines. Another is the finite time thermodynamic theory [13–22] developed by Andresen et al. Meanwhile, much work has been carried out on the finite time thermodynamic performance of the Stirling engine cycle and many new findings have been obtained [23–41]. Endoreversible Stirling engine model with heat resistance loss and irreversible Stirling engine model with losses of heat resistance, imperfect regeneration, heat leakage and internal irreversibility were built. The power, efficiency, exergoeconomic performance, ecological criteria and entropy generation of the common or solar-driven Stirling engines coupled to infinite or finite heat-capacity reservoirs with general working medium and quantum working medium were optimized.

Senft [39] examined the power and efficiency performance of the Stirling engine with heat resistance, internal heat leak and mechanical losses, in which heat transfer obeys the Newtonian heat transfer law $q \propto \Delta(T)$ by using the combination of his mechanical efficiency model [6–12] with the irreversible model in finite time thermodynamics [25,27,29,34]. The irreversibility of heat transfer is one of the most important facts in finite time thermodynamics. Many researchers [40–45] have shown that heat transfer law has a great influence on the optimal performance of endoreversible and irreversible Carnot and Stirling engine cycles. On the basis of Refs. [12,35,39], a further step

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http://dx.doi.org/10.1016/j.joei.2014.04.008
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List of symbols

B	buffer space
C	specific heat, W K
C_i	associated heat leakage coefficient, W K
E	transmission force engine mechanism efficiency
F	flywheel
K_1	slope coefficient of temperature–time variation law in regenerator, K s^{-1}
M	mechanism
n	mole number, mol
P	piston/power output of the engine cycle, W
Q	the amount of heat transfer, J
R	regenerator
R_g	universal ideal gas constant, J mol^{-1} K^{-1}
T	temperature, K
t	time duration of the process, s
V	volume, m^3
W	work, J
x	working fluid temperature ratio
x_m	the optimal working fluid temperature ratio at maximum power output and maximum thermal efficiency
x_m^*	the optimal working fluid temperature ratio at maximum shaft power and maximum brake thermal efficiency
α,β	associate heat conductances, W K
λ	volume compression ratio
η	efficiency
τ	cycle period, s

Subscripts

B	buffer space
c	compression
e	expansion
F	flywheel
H	hot side/high temperature heat reservoir
L	cold side/low temperature heat reservoir
m	optimal efficiency at maximum profit rate
max	maximum value
me	mechanical efficiency
opt	optimal value
P	power/piston
p	pressure
R	regenerator
RL	regeneration heat loss
s	shaft
t	thermal
0	ambient
1	isothermal expansion process/hot side working fluid
2	isothermal compression process/cold side working fluid
3	regenerative heating process
4	regenerative cooling process

made in this paper is to analyze the shaft power and brake thermal efficiency of the irreversible Stirling engine with heat resistance, heat leakage, regeneration loss and mechanical losses, in which the heat transfer between the heat reservoirs and the working fluid obeys the linear phenomenological heat transfer law $q \propto \Delta(T^{-1})$ by using the combination of Senft's mechanical efficiency model with finite time thermodynamics. The results obtained can provide theoretical guidelines for the design and optimization of practical Stirling engines.

2. Stirling engine model

The Stirling engine model working with two constant-temperature heat reservoirs is shown in Fig. 1. The temperatures of the high temperature and low temperature side heat reservoirs are T_H and T_L. The working fluid is assumed to be the steady-flowing ideal gas. Between the cold- and hot-side working fluids, there exists a regenerator R. Heat resistance, heat leakage and regeneration loss are considered here. However, some kinds of irreversibilities, such as intern heat rate losses transferred by fluid and solid conduction, pressure losses caused by internal friction and fluid escape are not considered in this model.

2.1. Linear phenomenological heat transfer law

Heat transfer between the working fluid and the heat reservoirs obeys the linear phenomenological heat transfer law. So, in case of isothermal expansion and compression Stirling engine process, the heat transferred into (Q_1) the engine from the hot heat reservoir and out of (Q_2) the engine to the cold heat reservoir per cycle are, respectively

$$Q_1 = \alpha\left(T_1^{-1} - T_H^{-1}\right)t_1 = nR_gT_1 \ln \lambda \tag{1}$$

$$Q_2 = \beta\left(T_L^{-1} - T_2^{-1}\right)t_2 = nR_gT_2 \ln \lambda \tag{2}$$

where α and β are the associated heat conductances between the engine and the reservoirs, T_1 and T_2 are the temperatures of the working fluid in the expansion and compression process, t_1 and t_2 are the time duration of the expansion and compression process, n and R_g are the mole number and the universal ideal gas constant of the working fluid, and $\lambda = V_2/V_1$ is the volume compression ratio. Here, Q_1 and Q_2 are supposed in absolute values.

3. Regeneration heat loss

Because of internal irreversibility, the efficiency of the regenerator is less than unity and the process is not an ideal regeneration process. So the regeneration heat loss is determined by [35,45]

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