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Imperfect regeneration analysis of Stirling engine caused by temperature differences in regenerator

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ABSTRACT

The Stirling engine has drawn much attention as it can utilize sustainable energy such as solar, waste heat, and biomass. Although the Stirling cycle has the same theoretical efficiency as the Carnot cycle, the thermal efficiency of an actual Stirling engine is lower than that of the ideal Carnot cycle owing to their reversibility. Previous finite-time thermodynamic models of Stirling engines are mainly focused on the temperature difference between the working substance and heat reservoirs. However, there is also a temperature difference between the working substance and the regenerator, which has merely been reported in previous literatures. In this study, we analyzed the regenerative processes of the Stirling engine using finite-time thermodynamics. Using an even distribution temperature assumption, the regenerative effectiveness and its limitations were obtained. For an uneven distribution temperature assumption, the regenerator was modeled by dividing it into n sub-regenerators. Two cases, for either constant or varying temperatures of the sub-regenerators, are discussed in detail, and the same regenerative effectiveness was obtained for the limit $n \to \infty$. Furthermore, the thermal efficiency and output power were obtained, and the effects of the parameters on the performance of the Stirling engine were investigated.

1. Introduction

Presently, with a reduction in fossil energy and an increase in environment-related problems, the search for a productive way to utilize renewable energy is imperative [1–3]. Stirling engines are appealing engines for this goal because they have low emissions, low noise, and high efficiency compared with other types of heat engines [4]. Moreover, the Stirling engine shows superiority in renewable energy utilization, micro-cogeneration applications, and low-grade heat recovery [5–7].

In the early nineteenth century, Robert Stirling devised the Stirling engine in Scotland [8], and its practical virtue as a simple, dependable, and secure engine was recognized for a century following its invention [9]. In analyzing and designing Stirling engines, researchers proposed several models using classical thermodynamics [10–12]. After Curzon and Ahlborn [13] studied Carnot engines with finite-rate heat transfers, finite-time thermodynamics (FTT) was developed and applied to many engines, including Stirling engines [14,15]. Compared with classical thermodynamic models, FTT models take the finite-time and finite-rate heat transfer into consideration. As a result, the engine can produce a positive power output rather than zero power output, which differs from that obtained by classical thermodynamics.

Researchers have presented many studies on theoretical models of Stirling engines using FTT; these models assumed that the regenerator of the Stirling engine is ideal. Assuming the irreversibility in the external heat transfer process is the only irreversible process, Blank et al. [16,17] analyzed an endoreversible Stirling engine with FTT. The optimum power in a finite duration and the corresponding efficiency were obtained by applying the heat transfer theory to the rates of the external heat transfer processes. Based on heat transfer equations, energy balance equations, and mass balance equations, Ladas et al. [18] modeled the Stirling engine with FTT and studied the effects of regeneration and transfer time on the efficiency and output power. Senft [9] developed a mathematical model of a Stirling engine with internal heat losses between the two internal extreme temperatures, mechanical friction losses, and limited heat transfer. They considered the heat loss inside the Stirling engine and assumed it occurred between the two ultimate temperatures of the working substance.

Many researches devoted to enhancing heat transfer in external heat exchangers [19,20]. However, the regenerator is also a crucial part of the Stirling engine. Without it, the thermal efficiency of a Stirling engine is far from that of a Carnot cycle. However, a practical regenerator is not without its faults, as the rate of heat transfer between the working substance and the regenerator is finite. Considering the imperfection of

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Nomenclature

A	heat transfer area [m^2]
c	isochoric heat capacity [J/K]
C_v	constant volume specific heat capacity [J/(g·K)]
h	convective heat transfer coefficient [W/(m^2·K)]
k	ratio of the specific heat of the working substance [–]
m	mass of working substance [g]
n	number of sub-regenerators [–]
P	power [W]
Q	heat [J]
S	entropy [J/K]
T	temperature [K]
V	volume [m^3]
w	$(k-1)\ln\gamma/(1-\eta_r)$
x	$(k-1)\ln\gamma$

Greek symbols

α_h	thermal conductance [W/K]
α_r	h_rA_r [W/K]
β	temperature ratio of heat sink to that of heat source [–]
γ	volume compression ratio [–]
η_r	regenerative effectiveness [–]
η	efficiency [–]
Σ	relaxation time c_f/α_r [s]
τ	duration [s]
φ	$\alpha_h\tau_h/[c_f(1-\eta_r)]$ [–]
χ	$\{1-e\hat{}[-\alpha_h\tau_r(1/n_f/c_f+1/n_r/c_r)]\}i\ /(n_fc_f/n_r/c_r+1)$ [–]
ψ	$\alpha_l\tau_l/[c_f(1-\eta_r)]$ [–]

Subscripts

f	working substance
h	expansion process
H	heat source
l	compression process
L	heat sink
r	regenerator
rh	regenerator with a high temperature
rl	regenerator with a low temperature
i	ith sub-regenerator
1, 1′, 2, 3, 3′,4	state points

the regenerator, researchers developed many thermodynamic models of Stirling engines. Using a fraction to manifest the deviation from a perfect regeneration, Chen et al. [21] modeled and investigated the performance of a combined system composed of a Stirling engine and a solar collector. Wu et al. [22,23] performed an optimal performance analysis on a Stirling engine with finite-speed effects in the regenerative processes and finite heat transfers both in the expansion and compression spaces. They also determined the relationship between the optimum power and corresponding efficiency of the Stirling engine model. Using the FTT method, Kaushik et al. [24,25] developed a Stirling engine model subject to finite heat capacitance rates of working substances in heat exchangers, heat leak losses between the source and sink reservoirs, and regenerative losses. Ahmadi et al. [26] investigated the effect of design parameters such as the temperatures of heat reservoirs, efficiency of heat exchangers, and efficiency of the regenerator on the performance of a Stirling heat engine. Dai et al. [27] constructed a more realistic Stirling engine model with FTT and optimized it with a multi-objective optimization method. Based on the isothermal assumption, Kongtragool and Formosa [28–30] studied the effect of regenerative effectiveness and dead volume on a Stirling engine with an imperfect regenerator. Liao and Lin [31] analyzed a solar-driven Stirling heat engine system with the Lagrange multiplier method and irreversible thermodynamics. They studied the effect of regenerative effectiveness and pointed out that by increasing the effectiveness of the regenerator, the performance of solar-driven Stirling heat engine systems is improved. Based on an imperfect regenerator, Li et al. [32] and He et al. [33] applied FTT to optimize a Stirling engine with a single objective. As an effective and efficient artificial-intelligence-based technique, the genetic algorithm has been widely used in physical and engineering optimization [34–45]. Ahmadi et al. [46–53] performed many studies on the multi-objective optimizations of Stirling-cycle-based systems with a genetic algorithm. Compared with single-objective optimization, multi-objective optimization leads to a more advisable design of Stirling engines. Kahraman [43] developed a hybrid technique to solve the problems in AI-based nonlinear modeling approaches, which is promising in solving industrial modeling problems that have nonlinear features.

Although the imperfect regeneration of Stirling engines is considered in many papers, the description of regenerative processes is crude and the heat transfer process in the regenerator has never been systematically investigated. As far as we know, the temperature difference exists not only in isothermal processes but also in isochoric processes. In this study, we presented, for the first time in literature, an analysis of the regenerative processes of the Stirling engine using FTT. In addition, we determined the overall thermal efficiency and output power, and investigated the effect of parameters on the performance of the Stirling engine.

2. Analysis of Stirling engine cycle with FTT

A Stirling cycle consists of two isothermal branches connected by two isochoric regenerating branches. In classical thermodynamics, ideal Stirling engines are able to run with a high thermal efficiency equivalent to that of the Carnot cycle. However, because of the existence of thermal resistance between the working substance and heat reservoirs, the ideal Stirling engine must run for an infinite time, resulting in the production of zero work. By contrast, actual Stirling engines must produce work in a finite time. As depicted in Fig. 1, within a finite time limit, the temperatures of the heat source, heat sink, and regenerator are different from that of the working substance.

A regenerator invariably consists of a solid matrix. Generally, along

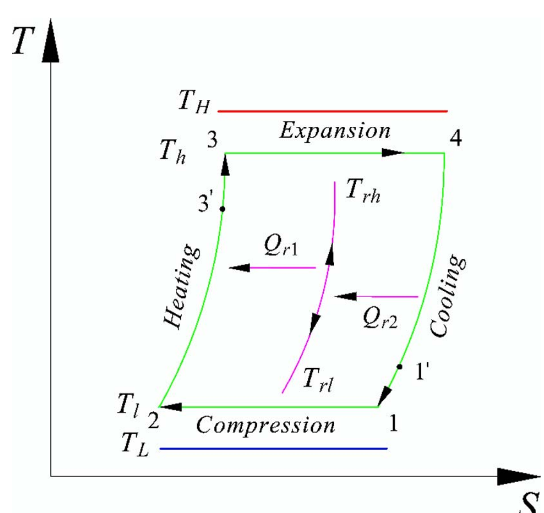

Fig. 1. Schematic *T-S* diagram of Stirling engine cycle.