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Research Paper

Study of heat transfer in oscillatory flow for a Stirling engine heating tube inserted with spiral spring

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HIGHLIGHTS

- A heating tube inserted with spiral spring was employed to Stirling engine heater.
- The mechanism of heat transfer enhancement for enhanced tube was investigated.
- Effects of geometric parameters of on flow and heat transfer were investigated.
- The benefits of enhanced tube under oscillatory far outweigh its costs.

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ABSTRACT

The heater of Stirling engine transfers heat from external heat sources to working gas. Improving its heat transfer performance is favourable to save external heat sources and decrease dead volume of engine. In this study, the flow and heat transfer characteristics of reciprocating oscillatory flow in a tube inserted with spiral spring in a Stirling engine heater were investigated. The results indicate that the Nusselt number (*Nu*), friction factor (*f*) and performance evaluation criterion (*PEC*) increased with spiral height (*h*) and decreased with spiral pitch (*p*) for enhanced tube within the range of parameters in this study. For the optimal enhanced tube, the *PEC* was equal to 1.22 and the outlet temperature was significantly improved compared to smooth tube. The maximum improvement was 115 K in entry process and 94 K in return process, and the average improvement was 64 K in entry process and 34 K in return process. The extra pressure consumption in the optimal enhanced tube was less than 0.0013 MPa compared to smooth tube, which could be negligible contrasting to the overall pressure in heating tube (1.5 ~ 2.5 MPa). Thus, the benefits are apparent for heating tube inserted with spiral spring in Stirling engine.

1. Introduction

The Stirling engine is a continuous external-combustion engine with multi-fuel capability including solar, geothermal, biomass energy, industrial waste heat, etc. Compared to conventional engines, incomplete combustion hardly occurs and fewer pollutants are generated in the Stirling engine. Thus, Stirling engine is considered as a significant green energy device and an important solution to the global warming problem. Stirling engine is also extremely silence in operation without explosion sound. The theoretical heat efficiency can be high equivalent to that of the Carnot cycle. In addition, the application of the Stirling engine has great advantages in remote areas, where providing small requirement of electric power through the grid is not economical [1–4]. Due to its unique features, the Stirling engine may become more popular in the future.

In the past several years, extensive studies have been conducted to explore different impact factors on the performance of Stirling engine, such as internal radiative heat transfer [5], multifarious loss [6], different kinds of working gas [7], and so on. Studies regarding the optimal design for Stirling engine were carried out using different methods. For instance, Xiao et al. [8] presented a sensitivity analysis of Beta type Stirling model and reported a method of multi-objective optimization for maximizing thermal efficiency and output power and minimizing flow resistance power loss in a Stirling engine. Shendage et al. [4] optimized geometrical parameters of a Beta configuration Stirling engine by combining the net power output and the efficiency. In addition, studies about cyclic thermodynamic of Stirling machine were also performed [9–11]. For Stirling engine, the expansion and compression of working gas are the driving force which derived from heating and cooling of fluid. Thus, the performance of heat exchanger is

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Nomenclature

c_p	specific heat (J kg^{-1} K^{-1})
d	inner diameter of heating tube (mm)
d_0	diameter of insert (mm)
f	frequency (Hz) or the friction factor
F_1	blending function
h	spiral spring height in the vertical section (mm) or heat transfer coefficient (W m^{-2} K^{-1})
k	turbulent kinetic energy (m^2 s^{-2})
L	overall length (mm)
l_1	end length (mm)
l_2	middle length (mm)
Nu	Nussle number
P	pressure (Pa)
p	pitch of spiral spring (mm)
P_0	average pressure in a cycle (Pa)
P_1	amplitude of pressure in a cycle (Pa)
$\widetilde{P_k}$	production limiter to prevent the build-up of turbulence in stagnation regions (kg^2 m^{-1} s^{-3})
q	heat flux (W m^{-2})
r	radius (mm)
Re	Reynolds number
Re_{max}	maximum Reynolds number
Re_ω	kinetic Reynolds number
S	invariant measure of the strain rate (s^{-1})
t	time (s)
T	temperature (K)
u	velocity (m s^{-1})
$u_{m,max}$	amplitude of bulk mean velocity (m s^{-1})
e	turbulent dissipation rate (m^2 s^{-3})

Greek symbols

α	blending constant
β	blending constant
Δ	difference value
Φ	energy dissipation due to viscosity (W m^{-3})
λ	thermal conductivity (W m^{-1} k^{-1})
μ	viscosity (kg m^{-1} s^{-1})
μ_t	turbulent dynamic viscosity (kg m^{-1} s^{-1})
θ	phase angle (°)
ρ	density (kg m^{-3})
σ	blending constant
ω	specific dissipation rate (s^{-1}) or angular velocity (rad s^{-1})

subscripts

0	comparison object
ave	average
cold	cold end
hot	hot end
i	tensor
in	inlet
m	mean
max	maximum
min	minimum
out	outlet
w	wall

crucial for the output power and efficiency of Stirling engine. The heat exchanger in Stirling engine includes heater, cooler and regenerator, while most studies focused on the performance of regenerator [12–14].

However, the heater also has a significant effect on the performance of a Stirling engine. As a consequence of closed cycle operation, the heat energy driving a Stirling engine must be transferred from a heat source to the working medium by a heater. For the low-power Stirling engines, the hot-side heat exchanger may simply consist of the walls of an expansion chamber; however, for the larger power one, it requires a larger heating surface area between the working fluid and the heat source. Generally, tubular heat exchanger is used in Stirling engine heater because of its high heat transfer rate [3,15]. To date, only a few literatures regarding the design and optimization of heater in Stirling engine were reported. El-Ehwany et al. [15,16] designed a novel elbow-bend heating exchanger to decrease the pressure drop of Stirling engine. The effects of elbow-bend geometry and tube arrangement on the performance of air-to-water heat exchanger were studied by experiments, and the corresponding empirical correlations were also deduced for each design in this study. Ibrahim et al. [17] studied the pressure, velocity and temperature fields inside a free piston Stirling engine and measured the convective heat transfer coefficients between the heater wall and the flow. Hirao et al. [1] developed a new heat exchanger to improve the performance of Stirling engine, which was advantageous for decreasing the energy loss from combustion gas, reducing the engine weight and improving the specific power. Gheith et al. [18] reported that energy exchanged in the heater was significantly influenced by the frequency and heating temperature, while it was slightly enhanced with the increase of flow rate of cooling water.

From the above analysis, it is found that the studies regarding the heat transfer enhancement of heater were very limited. If the heat transfer between external heat source and working gas is enhanced, the energy consumption of heat source or the dead volume of hot end can be reduced, and the engine efficiency can be improved [19]. Extensive researches on the heat transfer enhancement of steady flow, such as developing heat exchanger with special surface structure [20–22] or with tube inserts [23–28], have been done. However, it is well known that the flow in Stirling engine is cyclic reversion and the flow parameters changes obviously with time. Therefore, the conclusions about the heat transfer enhancement characteristics for unidirectional steady flow cannot be directly applied to the Stirling engine heaters [19,29,30].

To date, only a few of studies on the heat transfer enhancement of oscillatory flow were reported. Kato et al. [31] studied the heat transfer of channel-shaped and flat-shaped heat exchangers in a Stirling engine and found that the former one was more superior in terms of the combination property. Kuosa et al. [32] investigated the enhancement of heat transfer and pressure loss of oscillatory flow with a few circumferential slots inside heat exchanger tubes in a Stirling engine. Kölling et al. [33] utilized a few tubes with special surface structure in Stirling heater to increase heat transmittance from heat source and reduce deposit formation of biomass fuels. Although some special surface structure could improve the heat transfer of heater, the deformation treatment of heater tube wall would weaken its resistance to high temperature and high pressure. Thus, comparing with special surface structure, tube inserts might be more suitable for Stirling engine heater. Besides, the method by tube inserts is more easily processed. Previous studies demonstrated that a tube with spiral inserts presented higher heat transfer than smooth tube for steady flow [34–36].

In this study, the spiral spring was designed and applied in Stirling heating tube. The flow and heat transfer characteristics in a tube inserted with spiral spring were studied under oscillatory flow by using a three-dimensional unsteady numerical simulation, and that of a smooth tube was also studied as reference. The mechanism of heat transfer enhancement in the tube inserted with spiral spring under oscillatory flow was evaluated. Further, the effects of geometric parameters of the spiral spring on the flow and heat transfer were discussed.