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# Numerical study on flow characteristics and heat transfer enhancement of oscillatory flow in a spirally corrugated tube

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ABSTRACT

The flow and heat transfer characteristics of oscillatory flow in a smooth tube and two-start spirally corrugated tube were investigated by using a three-dimensional unsteady numerical simulation. The simulation was performed under variable properties, pressure and velocity conditions, with helium (He) as the working medium. The results indicated that longitudinal swirl vortexes were generated with the guidance of a spirally corrugated channel in a two-start spirally corrugated tube in which the fluid flowed spirally forward. The heat absorption ($Q$) of a two-start spirally corrugated tube exceeded that of a smooth tube ($Q_0$). The difference in the average heat absorption was 561 W and the average of $Q/Q_0$ was 1.36. At the same inlet and wall temperatures of 575 K and 1000 K, the outlet temperature of the smooth and spirally corrugated tube increased by 205 K and 365 K, respectively. Therefore, the spirally corrugated tube presented a superior heat transfer performance when compared to that of the smooth tube. Two types of performance evaluation criterion (*PEC*) calculation methods in a cycle were used to evaluate the heat transfer enhancement of a spirally corrugated tube. The average value of transient *PEC* in a cycle was 1.69, and the *PEC* calculated by average parameters in a cycle was 1.38. When compared with the change of pressure in a MPa level in a heating tube, the pressure drop of hundreds of Pa was negligible. However, the outlet temperature of the heating tube could be subject to an additional temperature increase of hundreds of K with the negligible pressure drop of hundreds of Pa. Thus, the benefits were apparent for the heat transfer enhancement by using spirally corrugated tubes in the heater.

## 1. Introduction

An energy system is the foundation of human survival and development. An energy conversion device is one of the cores of the energy system. The operating conditions of several energy conversion machines including Stirling engines and refrigerators, reciprocating internal combustion engines, gas and refrigerant compressors, and pulse-tube refrigerators are under oscillatory flow [1,2]. Thus, it is crucial to study the performance of a heat exchanger under oscillatory flow because it is related to the energy conversion efficiency and energy saving benefits.

Previous studies on heat transfer and flow frictional loss used for the design of heat exchangers of these machines were mainly based on unidirectional steady flow conditions. Urieli et al. [3] simplified oscillatory flow in a cycle into a series of steady flow in several very short time intervals in Stirling engines and studied the heat and mass transfer in oscillatory flow by using a steady flow equation. Kanzaka et al. [4] studied the oscillatory flow in Stirling engines with a modified stable flow correlation. Paek et al. [5] investigated the thermal performance of heat exchangers in a thermoacoustic cooler and developed oscillatory flow heat transfer coefficients by using a steady-flow correlation and a modified Reynolds number (*Re*). However, there is significant difference between oscillatory flow and steady flow. The oscillatory flow is characterized by cyclic reversion and the obvious change in flow parameters including velocity, pressure, density, and temperature in a short period of time. Therefore, the heat transfer correlations for steady flow cannot be directly applied to the design of heat exchangers for oscillatory flow [6–8].

Recently, the heat transfer characteristics of oscillatory flow machines, such as Stirling engine, thermoacoustic refrigeration system, pulse tube refrigerators, and others, have caused increasing worldwide attention [9–12]. Xiao et al. [7], Ni et al. [13], and Kanzaka et al. [14] studied the heat transfer performance of a heater in a Stirling engine, and different oscillatory heat transfer correlations were proposed. Xiao et al. [15] and Wang et al. [16] studied the heat transfer performance of a regenerator in a Stirling engine. The former proposed a correlation equation for the duration of perturbation in regenerator, and the latter analyzed the

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## Nomenclature

| | |
|---|---|
| $c_p$ | specific heat (J $kg^{-1}$ $K^{-1}$) |
| $D$ | outside diameter (mm) |
| $d$ | hydraulic diameter (mm) |
| $D_\omega$ | cross-diffusion term (kg $m^{-3}$ $s^{-2}$) |
| $e$ | corrugation depth (mm) |
| $f$ | frequency (Hz) or the friction factor |
| $F_1$ | blending function |
| $G_k$ | production of $k$ due to mean velocity gradients ($kg^2$ $m^{-1}$ $s^{-3}$) |
| $G_\omega$ | generation of ω (kg $m^{-3}$ $s^{-2}$) |
| $h$ | heat transfer coefficient ($Wm^{-2}$ $K^{-1}$) |
| $k$ | turbulent kinetic energy ($m^2$ $s^{-2}$) |
| $L$ | length (mm) |
| $Nu$ | Nussle number |
| $P$ | pressure (Pa) |
| $P_0$ | average pressure in a cycle (Pa) |
| $P_1$ | amplitude of pressure in a cycle (Pa) |
| $\tilde{P}_k$ | production limiter to prevent the build-up of turbulence in stagnation regions ($kg^2$ $m^{-1}$ $s^{-3}$) |
| $Q$ | heat adsorption (W) |
| $r$ | radius (mm) |
| $Re$ | Reynolds number |
| $Re_{max}$ | maximum Reynolds number |
| $Re_\omega$ | kinetic Reynolds number |
| $s$ | screw pith (mm) |
| $S$ | invariant measure of the strain rate ($s^{-1}$) |
| $t$ | time (s) |
| $T$ | temperature (K) |
| $u_m$ | average velocity of fluid (m s) |
| $u_{m,max}$ | amplitude of bulk mean velocity (m s) |
| $Y_k$ | dissipation of $k$ due to turbulence ($kg^2$ $m^{-1}$ $s^{-3}$) |
| $Y_\omega$ | dissipation of $\omega$ due to turbulence (kg $m^{-3}$ $s^{-2}$) |
| $e$ | turbulent dissipation rate ($m^2$ $s^{-3}$) |
| $G_k$ | effective diffusivity of $k$ (kg $m^{-1}$ $s^{-1}$) |

*Greek symbols*

| | |
|---|---|
| $\Phi$ | energy dissipation due to viscosity (W $m^{-3}$) |
| $\Gamma_\omega$ | effective diffusivity of $\omega$ (kg $m^{-1}$ $s^{-1}$) |
| $\lambda$ | thermal conductivity (W m $k^{-1}$) |
| $\mu$ | viscosity (kg $m^{-1}$ $s^{-1}$) |
| $\mu_t$ | turbulent dynamic viscosity (kg $m^{-1}$ $s^{-1}$) |
| $\theta$ | phase angle (°) |
| $\rho$ | density (kg $m^{-3}$) |
| $\omega$ | specific dissipation rate ($s^{-1}$) or angular velocity (rad $s^{-1}$) |

*subscripts*

| | |
|---|---|
| 0 | comparison object |
| ave | average |
| i | tensor |
| m | mean |
| max | maximum |
| min | minimum |
| w | wall |

transient characteristics of the oscillatory flow and the associated thermodynamic process in the regenerator. Kanzaka et al. [14] analyzed the heat transfer coefficient of the cooler in a Stirling engine and presented a correlation of heat transfer coefficient of the working gas. Ibrahim et al. [17] calculated the overall heat transfer for the heat exchangers in a free piston Stirling engine to optimize critical design parameters. Additionally, the influence of operating parameters on heat transfer in other oscillatory flow machines including a thermoacoustic refrigeration system and pulse tube refrigerators were performed by Nsofor et al. [8] and Tang et al. [18], respectively.

In addition to the heat transfer characteristics, a few studies also examined pressure drop or friction coefficients of oscillatory flow in heat exchangers. Zhao et al. [19] investigated instantaneous and cycle-averaged friction coefficients in oscillatory tube flow. The results showed that the friction coefficients depended on the kinetic Reynolds number ($Re_\omega$) in conjunction with the dimensionless oscillation amplitude of fluid. Pan et al. [20] studied the heat transfer and pressure drop of oscillatory flow in a spirally coiled tube heat exchanger, and the heat transfer enhancement mechanism was interpreted by using the field synergy principle. Saberinejad et al. [21] studied the heat transfer of turbulent oscillatory flow in a tube filled with porous media. Two correlation equations were introduced for the maximum friction factor and space-cycle averaged Nusselt number ($Nu$) in terms of different parameters.

To date, the heat transfer and friction characteristic of oscillatory flow have been extensively studied. However, there is a paucity of studies on the enhancement of heat transfer of oscillatory flow although it is extremely significant to improve the performance of machines operating under oscillatory flow. Recently, variable approaches were utilized for heat transfer enhancement in heat exchanger, including surface-shaped heat exchangers [22–24], finned tubes [25,26], and inserts within tubes [27–30]. Most of the heat transfer enhancement methods in previous studies were based on unidirectional steady flow. However, studies on oscillatory flow are very limited. To the best knowledge of the authors, only Kato et al. [31] and Kuosa et al. [32] performed studies on heat transfer enhancement under oscillatory flow. Kato et al. [31] studied the heat transfer of channel-shaped heat exchangers and flat-shaped heat exchangers in a Stirling engine and found that the former 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. The results showed that the Carnot efficiency and the ratio of the shaft power and pumping loss were effectively enhanced.

In this study, the flow and heat transfer characteristics of oscillatory flow in the heater as well as the heat transfer enhancement were investigated by using a three-dimensional unsteady numerical simulation. The temperature, velocity, and pressure fields in a smooth tube and a two-head spirally corrugated tube were examined in the reciprocating oscillatory state with variable properties, pressure, and velocity. The mechanism of heat transfer enhancement in the spirally corrugated tube under oscillatory flow was studied, and its heat transfer enhancement capacity compared to that of a smooth tube was evaluated.

## 2. Physical and mathematical models

### 2.1. Physical model

Fig. 1 shows the physical model of the two-start spirally corrugated tubes. The geometric parameters are as follows: corrugation depth $e = 3$ mm, outside diameter $D = 16$ mm, hydraulic diameter $d = 13.3$ mm, and length $L = 400$ mm. The structure of the tube in the middle 200 mm is spiral corrugated in which the screw pith