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Numerical investigation of heat transfer and flow inner tube with periodically cosine oscillation

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A R T I C L E I N F O

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A B S T R A C T

In the present study, both heat transfer and pressure drop was studied numerically for static round tube and cosine oscillating tube with finite volume method. The effect of dimensionless amplitude and frequency on heat transfer and pressure drop was also investigated for Reynolds number changing from 6170 to 14,000. Under the influence of cosine oscillation, the heat transfer and pressure drop is periodically changing and the frequency for heat transfer and pressure is half of that for cosine oscillation motion. Heat transfer was enhanced by cosine oscillation and increased by 1.9% compared to static tube for Re = 6140. Meanwhile, heat transfer increased by 35% as dimensionless amplitude increased from 1 to 10. While cosine rotation also caused larger pressure drop and the pressure drop for cosine oscillating tube is 3.01% that of static tube. The pressure drop is proportional to dimensionless amplitude and frequency. However, heat transfer first reduce and then increase with increase in frequency.

1. Introduction

A great deal of heat exchangers is applied in the industrial field, such as chemical engineering, energy engineering. In recent years, researchers are enthusiastic to enhance heat transfer inner tubes of heat-exchangers.

On the one hand, Rotating heat transfer wall can achieve a better heat transfer rate because of crated turbulence [1]. Morris and Rahmet-Abadi [2] carried out experiment to study heat transfer in a rotating round tube with three different types of internal ribs. And the experimental results showed that rotation motion increases three times of heat transfer compared with zero rotation. Li et al. [3] experimentally investigated thermal performance in a rotating U-turn smooth channel under turbulent conditions and they found that the Nu/Nu_0 increased to 4.3 on the trailing side in the inlet pass for case of rotation. Tao et al. [4] conducted an experimental study on thermal capacity and flow of smooth wedge-shaped channel with rotation. The obtained experimental results showed that Nusselt number was increased mainly by rotation motion with the cost of lager pressure drop. Wright et al. [5] designed six different types of ribs and studied the effect of these on heat transfer of rectangular duct in a rotating mode.

On the other hand, periodical vibration can enhance heat transfer according to previous findings. The numerical investigation of Bo et al. [6] found that heat transfer efficient can be enhanced by 20–400% in forced convection procedure and 30–2000% in natural convection procedure by vibration. Liu et al. [7]. performed an experiment to study heat transfer characteristics of tubular flow with sinusoidal vibration, which Reynolds numbers varied from 500 to 2100, and obtained a correlation of vibration frequency, vibration acceleration and Reynolds numbers. Karanth et al. [8] and Cheng et al. [9] both used non-inertial reference frame to study heat transfer form a transversely periodical oscillating cylinder and the results showed that heat transfer rate increased with the increasing of oscillating velocity and reached the maximum value near the lock-in regime. Ghazangarian and Nobari [10] studied heat transfer from a heated vibration cylinder in a cross flow numerically. The results indicated that heat transfer efficient was enhanced remarkably in the lock-in and lock-on regime. Yao et al. [11] investigated heat transfer performance of liquid hydrogen in a transverse tube with vibrating tube boundary based on numerical method and results demonstrated that vibration has a positive effect on convective heat flux while a negative effect on quenching heat flux and evaporative heat flux. Fu and Tong [12] carried out a numerical simulation to investigate the effect of transversely oscillating cylinder in a cross flow. The simulation results demonstrated that heat transfer was enhanced and approach a periodic. According to the investigations mentioned above the strengthening mechanism of vibration is mainly vortex generating and shedding.

Compared to experimental investigation, numerical investigation can save costs and get enough accurate results. At present, common numerical methods include Finite element method

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Nomenclature

A	amplitude, rad/s
A_0	tube cross-sectional area, m^2
A_m	dimensionless amplitude
c_{p_f}	specific heat capacity of fluid, J/(kg K)
d	diameter of the tube, mm
F	frequency, Hz
f	fraction factor
h	heat transfer coefficient, W/(m^2 K)
j	Colburn j-factor
$LMTD$	log-mean temperature difference, K
l	length of the tube, mm
Nu	transient Nusselt number
$\overline{Nu}$	average Nusselt number
ΔP	pressure drop between inlet and outlet, Pa
Pr	Prandtl number
Q	heat transfer quantity, W
q_m	fluid mass flow, kg/s
Re	Reynolds number
S	total heat transfer area, m^2
T_w	wall temperature, K
T_{in}	inlet water temperature, K
$\bar{T}_{in}$	average inlet water temperature, K
T_{out}	outlet water temperature, K
$\bar{T}_{out}$	average outlet water temperature, K
v	fluid inlet velocity, m/s

Greek symbols

ε	turbulence energy dissipation rate
λ	thermal conductivity, W/(m K)
ρ	fluid density, kg/m^3
μ	dynamic viscosity, Pa s
τ	flow time, s
ω	angular velocity, rad/s

Subscripts

in	tube inlet
out	tube outlet
w	tube wall

(FEM) [13–16], Lattice-Boltzman method (LBM) [17–19] and Finite volume method (FVM) [20–22]. FVM is more suitable for the calculation of fluid flow and signal-phase heat transfer in the current study compared to other methods. FVM is based on the conservation equation in the integral form and integrate on the control volume. Discrete equations derived from FVM can guarantee conservation and have good adaptability. In general, FVM can be applied to irregular grid and parallel computation. FVM includes five steps: grid generation, discretization of convection items, discretization of boundary conditions, pressure-velocity coupled and solution of discrete equations.

According to previous works, rotation and periodical vibration both can enhance heat transfer. But most study of rotation is unidirectional. In the current study, the effect of cosine rotation, cosine vibration in other words, on heat transfer inner tube was investigated with FVM. This article provides a certain reference for heat transfer enhancement methods.

2. Model

2.1. Physical model

The heat transfer characteristics and flow of smooth tube with periodically cosine rotation was investigated in the present study. Because three-dimensional model is more consistent with real model than two-dimensional model. So, the three-dimensional structure of smooth tube was modeled in the present work. A schematic view of the transverse numerical model is shown in Fig. 1. And the detailed parameters were shown in Table 1.

Turbulent flow was adopted in the present study and three different Reynolds numbers, $Re = 6170$, $Re = 10200$ and $Re = 14000$ (the corresponding inlet velocity is 0.3 m/s, 0.5 m/s and 0.7 m/s respectively), was considered. Water-liquid is adapted as working fluid, and aluminum is adopted as wall material.

The boundary conditions of numerical model are defined as followed:

(a) The inlet conditions: Velocity inlet, inlet temperature T_{in} = 293.15 K, intensity and hydraulic diameter are adopted as specification method and turbulent intensity I = 5%, hydraulic diameter d = 0.02 m.
(b) The outlet conditions: Pressure outlet (P_0 = 101.325 kPa), intensity and hydraulic diameter are adopted as specification method and turbulent intensity I = 5%, hydraulic diameter d = 0.02 m.
(c) The wall conditions: The wall temperature is constant and uniform T_w = 323.15 K, no slip condition is adopted as shear condition.

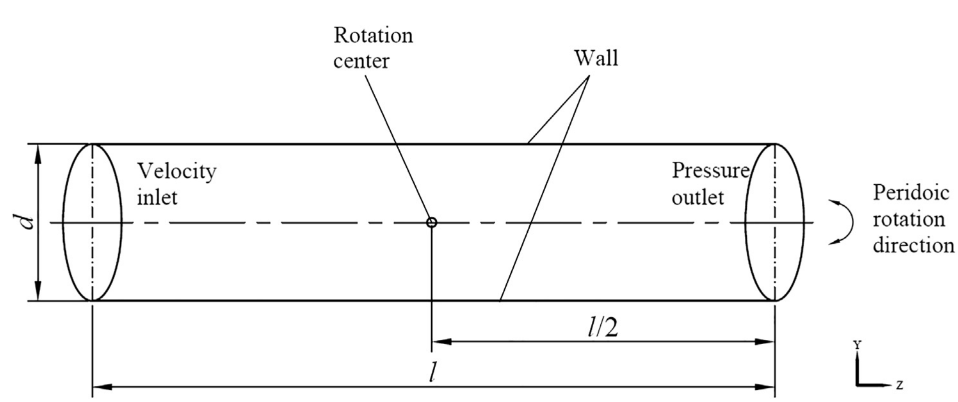

Fig. 1. Geometric structure of the model.