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CFD study of heat transfer for oscillating flow in helically coiled tube heat-exchanger

Changzhao Pan[a,b], Yuan Zhou[a], Junjie Wang[a,*]

[a] Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

The heat transfer and pressure drop for oscillating flow in helically coiled tube heat-exchanger were numerically investigated based on the Navier–Stokes equations. The correlation of the average Nussel number and average friction factor were proposed considering the frequency and the inlet velocity. The oscillating flow heat transfer problems are influenced by many factors. Hence we need an easy way to reduce the numbers of simulation or experiment. Therefore, the method of uniform design was adopted and the feasibility of this method was verified. The field synergy principle was used to explain the heat transfer enhancement of oscillating flow in helically coiled tube heat-exchanger. The result shows that the smaller the volume average field synergy angle in the helically coiled tube, the better the rate of heat transfer.

1. Introduction

Helically coiled tube heat-exchanger is widely used in industry such as chemical plants, power generation plants, nuclear industry, food processing, cryogenic and medical equipment, etc. The steady flow in coiled tube has been studied by many researchers. Dean (1927, 1928) studied the curved channel flow and clarified the enhancement of heat transfer in curved channel. The centrifugal force in curved tube pushes the fluid particles toward the core region and produces a secondary flow field, which can enhance the heat transfer in the curved tube. The Dean number was used to characterize the flow of Newtonian fluids in helically coiled tube. The fluid flow and heat transfer in curved tube was firstly reviewed by Berger et al. (1983) and Shah and Joshi (1987). The latest review of helically coiled tube was presented by Naphon and Wongwises (2006). Prabhanjan et al. (2004), Nandakumar and Masliyah (1982) and Shah and Joshi (1987) used the boundary condition of constant wall temperature and constant heat flux to investigate the heat transfer coefficient of helically coiled tube. Experimental and numerical studies of the double pipe helically heat exchanger have been investigated by Rennie and Raghavan (2005, 2006a,b). Jayakumar et al. (2008) studied the fluid-to-fluid helically coiled tube heat exchanger by experimental and numerical method. Jayakumar et al. (2010) also brought out clearly the variation of local Nusselt number along the length and circumference of a helical tube. The hydrodynamics and heat transfer in tube-in-tube helical heat exchanger has been studied by Kumar et al. (2006).

The oscillatory flow in helically coiled tube heat exchanger is widely used in Stirling engines or cryocoolers such as VM cryocooler (Zhou, 1984; Kuosa et al., 2012; Simon and Seume, 1988). Oscillatory heat transfer in the helical coiled tube plays a key role in the heat driven cryocooler which works between three temperature resources. The intermediate resource of this type cryocooler will be kept a constant temperature by using liquid nitrogen or mix-refrigerants (Zhou, 1984; Zhou et al., 2012) to obtain the higher cooling power. Helical coiled tube heat exchanger is usually used because of its high performance in heat transfer. However, the heat transfer correlations of oscillating flow have not been published until recent years (Kuosa et al., 2012). Several literatures have studied the nature of oscillatory flows and presented the pressure drop and heat transfer coefficient in Stirling engine heat exchangers (Simon and Seume, 1988; Tew and Geng, 1992). Bouvier et al. (2005) described an experiment to study the oscillating flow inside a cylindrical tube and shown the difficulty of defining a dimensionless heat flux density to model local heat transfer in oscillating flow. Kuosa et al. (2012) studied the tubular heaters and coolers in Stirling engines. Guo et al. (2002) studied the transient convective heat transfer in a helical tube under pressure drop type oscillations, f = 0.05–0.003 Hz.

* Corresponding author. Tel.: +86 10 82543758; fax: +86 10 62564050.
E-mail addresses: wangjunjie@vip.sina.com, wangjunjie@mail.ipc.ac.cn, Pchangzhao@163.com (J. Wang).

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Nomenclature

A	area (m^2)
Cf	friction factor
c_p	specific heat ($J\,kg^{-1}$)
De	Dean number
f	frequency (Hz)
h	heat transfer coefficient ($W/m^2\,K$)
H	coil pitch (m)
n	unit vector along outward normal
m	the number of turns
Nu	Nusselt number
Pr	Prandtl number
q	heat flux (W/m^2)
r	pipe radius (m)
R_c	pitch circle radius (m)
Re	Reynolds number
t	cycle time (s)
T	temperature (K)
u	velocity (ms^{-1})
Va	Valensi number

Greek symbols

λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
ν	kinematic viscosity (m^2/s)
Δp	pressure drop (Pa)
μ	dynamic viscosity (Pa s)
Φ	dissipation function

Subscripts

A	amplitude
f	working gas
w	wall
in	tube inlet
max	maximum
osc	oscillatory flow

Superscript

–	average

Most of the investigations involved either helical coiled tube or oscillating flow. However, the oscillating flow in the helical coiled tube requires a comprehensive study. This article is dedicated to obtain the correlations of heat transfer and pressure drop for oscillating flow in the helical coiled tube by using CFD method. Large numbers of simulation are needed in order to obtain the interaction of velocity and the frequency f, which both influence the flow characteristics in this case. The other factors, such as pitch and the number of turns, will increase the numbers of simulation significantly. Therefore, it needs an easy way to reduce the times of simulation or experiments in multi factors heat transfer problems. The uniform design method is an experimental design method and can reduce the times of simulation or experiments significantly. The present work used this method to study the heat transfer and verified its feasibility. And then, the enhancement mechanism of oscillating flow in the helical coiled tube was investigated by the viewpoint of field synergy principle (Guo et al., 1998, 2005).

2. Dimensionless similarity criterions

The schematic of helically coiled tube used in this paper is shown in Fig. 1. The simulation is mainly used in VM cryocooler. In this cryocooler, the empty volume should be reduced to obtain the larger

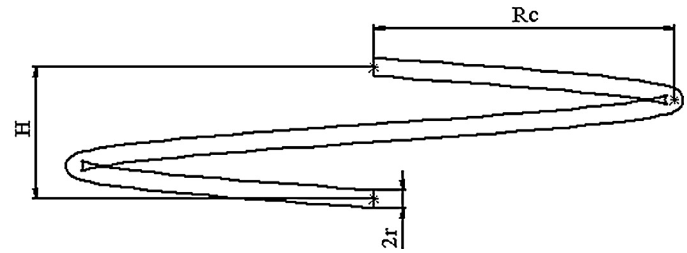

Fig. 1. The schematic of helically coiled tube.

cooling power (Zhou, 1984; Rule and Qvale, 1969). So the diameter of tube should be small enough. According to the structure of Zhou's (1984) cryocooler, the diameter of the tube is chosen $2r = 3$ mm, and the diameter of the coil is $2R_c = 103$ mm, the coil pitch is $H = 22$ mm. A dimensionless parameter can be used to characterize the flow of Newtonian fluids in helically coiled tube, which can be expressed in Dean number (Dean, 1928; Jayakumar et al., 2008):

$$De = Re\sqrt{\frac{r}{R_c}} \tag{1}$$

where, Re is the Reynolds number.

In oscillatory flows, Reynolds number can be characterized as (Gül and Akpinar, 2007):

$$Re_{\max} = \frac{u_A \cdot 2r}{\nu} \tag{2}$$

where, u_A the amplitude of the velocity in oscillatory flow, $2r$ is the characteristic length of pipe, and ν is the kinematic viscosity.

Similar to Reynolds number, Valensi number is another dimensionless number that is important in oscillatory flows. The Valensi number, Va is defined as,

$$Va = \frac{2\pi f \cdot (2r)^2}{\nu} \tag{3}$$

where f is frequency, so the Va number reflects the frequency of oscillatory flows.

The average Nusselt number and friction factor are defined as follows:

$$\overline{Nu}_{osc} = \frac{\bar{h} \cdot 2r}{\lambda} \tag{4}$$

$$C_f = \frac{2 \cdot 2r \cdot \Delta\bar{p}}{\rho u_A^2 L} \tag{5}$$

where λ is thermal conductivity, ρ is density, $\bar{h}$ is average heat transfer coefficient, which can be evaluated by:

$$\bar{h} = \frac{1/t\int_0^t q dt}{1/t\int_0^t (T_f - T_w)dt} \tag{6}$$

where q is heat flux, t is cycle time, T_f is the temperature of working gas, T_w is the temperature of the tube. $\Delta\bar{p}$ is average pressure drop, which can be calculated by:

$$\Delta\bar{p} = \frac{1}{t}\int_0^t \Delta p dt \tag{7}$$

L is the length of the coiled tube, which can be calculated by:

$$L = m\sqrt{H^2 + (2\pi R_C)^2} \tag{8}$$

where m is the number of turns, H is the coil pitch, the case of this simulation is $m = 1$, so $L = 315$ mm. According to Latzko's (1921) research, the entrance length of tube can be obtain by

$$\left(\frac{x}{D}\right)_{entry} = 0.623Re^{0.25} \tag{9}$$