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Heat transfer of pulsating laminar flow in pipes with wall thermal inertia

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ABSTRACT

The effects of wall thermal inertia on heat transfer of pulsating laminar flow with constant power density within the pipe wall are investigated theoretically. The energy equation of the fully developed flow and heat transfer is solved by separation of variables and Green's function. The effects of the pulsation amplitude and frequency, the Prandtl number and the wall heat capacity on heat transfer features characterized by temperature, heat flux and Nusselt number are analyzed. The results show that the oscillation of wall heat flux increases along with the wall thermal inertia, while the oscillation of temperature and Nusselt number is suppressed by the wall thermal inertia. The influence of pulsation on the average Nusselt number is also obtained. The pulsating laminar flow can reduce the average Nusselt number. The Nusselt number reduction of pipe flow are a little more remarkable than that of flow between parallel plates, which is mainly caused by differences in hydraulic and thermal performances of the channels.

1. Introduction

Pulsating flows have a significant impact on heat and mass transfer in Stirling engines, electronics cooling, nuclear reactors, gas turbines and arterial blood flow [1–7]. Flow characteristics of pulsating flows in different channels have received extensive attention [8–16]. Theoretical analysis is in accordance with both experimental data and numerical studies. In contrast to hydraulic studies, the conclusions drawn from previous researches on heat transfer in pulsating flow, including experimental investigations, numerical simulations and theoretical analysis, are often inconsistent and sometimes even in contradictions.

The experimental data [17–23] on heat transfer in pulsating laminar flow in pipes showed that pulsation could either decrease or increase Nusselt number. In several works [17–20], it is said that for pulsating flow with low frequency and large pulsation amplitude, the heat transfer rate increases. Al-Haddad [21] concluded that the Nusselt number hardly changes when the product of Reynolds number and dimensionless frequency is less than 2.1×10^5 and the Nusselt number increases notably when the product is larger. Habib et al. [22] performed experimental studies on laminar pulsating air flow with constant heat flux. The heat transfer is augmented at particulars zones of the pulsation frequency. The augmentation is as high as 30% at Reynold number of 1366 and pulsation frequency of 1.4 Hz. Habib et al. [22] also found a reduction in relative mean Nusselt number up to 40% for pulsation frequency range of 4.1–17 Hz and for Reynolds numbers range of 780–1987. Mamayev [23] found the pulsating heat transfer is attenuated when Reynolds number is less than 2000, and the effect fades out with the increase of pulsation frequency. However, Mackley's results [24] showed that pulsation has no influence on bare tube.

Simulations by Chattopadhyay and coworkers [25–27] showed that pulsation does not affect time-averaged heat transfer in pipe flow although the Nusselt number distribution varies with time in the near-entry region, but sinusoidal velocity can provide improved heat transfer performance in wavy channels. Guo and Sung [28] numerically studied pulsating flow in a pipe with constant heat flux. They concluded that heat transfer enhancement is observed with small amplitude in a certain zone of pulsation frequency or with large amplitude. Guo and Sung [28] also pointed out that for the same spatial and temporal temperature distribution, different definitions of average Nusselt number will lead to contradictory conclusions.

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Nomenclature

General symbols

a	area of cross section
c	fluid specific capacity
c_A	wall heat capacity
C	constant
e	Euler number
f(r)	function defined in Eq. (13)
g(r)	function defined in Eq. (4)
G	Green's function
i	imaginary unit
J	Bessel functions of the first kind
k	conductivity
K	parameter defined in Eq. (14)
Nu	Nusselt number
p	pressure gradient
Pr	Prandtl number
q	heat flux
r	radial coordinate
r''	variable of Green's function
R	radius
Re	Reynolds number
t	time
t_0	pulsation period
T	temperature
u	velocity
x	axial coordinate
Y	Bessel functions of the second kind

Greek letters

γ	dimensionless pulsation amplitude of pressure gradient
Γ	dimensionless pulsation parameter
δ	Dirac delta function
η	ratio defined by Eq. (6)
ν	kinematic viscosity
π	mathematical constant
ρ	density
ω	pulsation frequency

Subscripts

av	average
b	bulk
in	inlet
p	pressure gradient
ref	reference
s	steady
t	time dependent
u	velocity
w	wall

Superscript

*	dimensional parameter

Operator

$\Re$	real part of complex

Kita et al. [29], Yu et al. [30], Nield and Kuznetsov [31], Yan et al. [32] analytically studied pulsating flow in fully developed region with constant wall temperature or constant wall heat flux. They obtained that Nusselt number fluctuates periodically around the value of steady flow. Furthermore, Yu et al. [30] and Yan et al. [32] concluded that the average Nusselt number is the same as the steady one. Faghri et al. [33] and Sorour et al. [34] theoretically analyzed low frequency pulsating flow and obtained Nusselt number which increases along with the ratio of conductivity to Prandtl number. The pulsating heat transfer rate was higher than the steady flow. Yin and Ma [35] concluded that the oscillating flow can result in significant heat transfer enhancement. Yin and Ma [36] also investigated oscillating flow driven by triangular pressure waveform and concluded that the oscillating motion enhances heat transfer under low oscillating frequency or small oscillating amplitude, but the effect disappears when the oscillating frequency is high enough. The analytical solutions of Hemida et al. [37] and Yuan et al. [38] proved that pulsation can decrease the average Nusselt number. The results of Hemida et al. [37] also showed that wall thermal inertia can damp out pulsation effects.

From the literature review, it is found that studies on pulsating heat transfer frequently lead to contradictory results. Some of them are caused by different definitions of the average Nusselt number; some of them are not. Thus, effort should be made to eliminate the confusion. What's more, most previous studies are limited to constant wall temperature or constant heat flux conditions. However, theoretical studies on the effects of wall heat inertia on heat transfer are expected as wall thermal inertia can affect the thermodynamic and safety performance of heat exchangers working under pulsating condition. Hence we conducted this research to investigate pulsating heat transfer considering the influence of wall thermal inertia.

2. Governing equations

2.1. Velocity profile

Velocity profile of circular pipe flow under pulsating condition has been studied by many researches [29,30,34]. In this section, a brief introduction of velocity distribution for fully developed laminar flow of an incompressible Newtonian fluid is illustrated.

$$\begin{cases} \dfrac{\partial u^*}{\partial t^*} = -\dfrac{1}{\rho} p_s\left[1+\gamma\cos\left(\omega^* t^*\right)\right] + \nu\left(\dfrac{\partial^2 u^*}{\partial r^{*2}} + \dfrac{1}{r^*}\dfrac{\partial u^*}{\partial r^*}\right) \\ r^* = R^* :\ u^* = 0 \end{cases} \tag{1}$$

where u^*, ρ, p_s and ν are the velocity, density, pressure gradient and kinematic viscosity, respectively. γ and ω^* denote the relative amplitude and frequency of the oscillatory pressure gradient, respectively. R^* is the pipe radius.

It should be note that second-order effects such as the variation of thermo-physical properties are neglected. To get a non-dimensional form equation, the following dimensionless quantities are introduced.

$$r = \frac{r^*}{R^*},\ \omega = \frac{\omega^* R^{*2}}{\nu},\ t = \frac{\nu t^*}{R^{*2}},\ u = \frac{u^*}{u^*_{s,av}} \tag{2}$$

where $u^*_{s,av} = -R^{*2} p_s / 8\rho\nu$ represents the cross-sectional average velocity corresponding to steady flow driven by p_s. The dimensionless form of Eq. (1) is: