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ORIGINAL ARTICLE

Non-sinusoidal waveform effects on heat transfer performance in pulsating pipe flow

R. Roslan [a], M. Abdulhameed [b,*], I. Hashim [c,d], A.J. Chamkha [e]

[a] Centre for Research in Computational Mathematics, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
[b] School of Science and Technology, The Federal Polytechnic, Bauchi, P.M.B. 0231, Off Dass Road, Bauchi, Nigeria
[c] Center for Modelling & Data Analysis, School of Mathematical Sciences, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[d] Research Institute, Center for Modeling & Computer Simulation, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[e] Department of Mechanical Engineering, Prince Mohammad Bin Fahd University, P.O. Box 1664, Al Khobar 31952, Saudi Arabia

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Abstract In the present paper, an unsteady motion of fluid flow in a pulsating pipe is studied to determine the effect of non-sinusoidal waveforms on the heat transfer performance. Three non-sinusoidal waveforms, namely sawtooth, square and triangular waveforms have been considered. Explicit analytical expressions for a periodic laminar flow describing the flow and heat transfer at small and large times with sawtooth and square pressure waveforms have been derived using Bessel transform technique. The heat transfer performance of periodic flow at sawtooth and square pressure waveforms has been compared with the published result for triangular waveform [1]. The temperature performance for a triangular waveform pressure is very different from the sawtooth and square pressure waveforms.

1. Introduction

Periodic motion of fluid flow associated with heat transfer in a pipe with pulsating flow and constant heat flux occurs in many industrial processes and natural phenomena. Therefore, it has becomes the topic of many detailed, mostly analytical studies for different flow configurations. Most of the interest in this topic is due to its important in biological applications in relation to blood flow. Blood flow in human cardiovascular system is caused by the pumping action of the heart which produces a pulsatile pressure gradient throughout the system [2], and also in industrial applications in relation to heat exchange efficiency, such as the application in the production of plane glass where the glass sheet is pulled over a bath of molten while being cooled and solidified [3].

Moallemi and Jang [3] studied numerically the effect of the Prandtl number on the flow and heat transfer in a lid-driven square cavity. The numerical simulations showed that for higher values of Pr the effect of thermal buoyancy force on

* Corresponding author. Fax: +234 077541393.
E-mail address: moallahyidi@gmail.com (M. Abdulhameed).
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Nomenclature

a	constant defined by Eq. (28)
A	constant defined by Eq. (52)
b	constant defined by Eq. (29)
B	constant defined by Eq. (53)
c	constant defined by Eq. (30)
c_p	specific heat at constant pressure
C	constant defined by Eq. (54)
d	constant defined by Eq. (31)
D	constant defined by Eq. (55)
E	constant defined by Eq. (56)
F	eigenfunction
G_0	function defined by Eq. (57)
G_1	function defined by Eq. (58)
G_2	function defined by Eq. (59)
G_3	function defined by Eq. (60)
G_4	function defined by Eq. (61)
J_n	Bessel function of order n
k	thermal conductivity, W/mK
$k_0, \ldots, k_3$	real constants
Nu	Nusselt number
p	pressure, N/m^2
Pr	Prandtl number
q	heat flux, W/mm^2
r	radius, m
$\Re$	Reynolds number
t	time, s
u	velocity, m/s
z	axial position, m

Greek symbols

γ_0	sawtooth amplitude fluctuation, m
γ_1	square amplitude fluctuation, m
μ	dynamic viscosity, N-s/m^2
v	kinematic viscosity, N-s-m/kg
ρ	density, kg/m^3
Θ	temperature, K
ω	angular velocity, rad/s
λ	eigenvalue

Superscripts

$*$	dimensional conditions

Subscripts

a	mean value
bt	instantaneous bulk temperature
h	homogeneous part
m, n, q	order index
p	particular part
s	steady state
t	transient state
w	wall

the flow and heat transfer inside the cavity is more dominant. Richardson and Tyler [4] was among the earliest to compare the gradients of mean velocity resulting by alternating or continuous flow of air near the mouths of pipes of various sizes and cross sections. The results showed that the peak of mean velocity existed near the walls of the pipe in alternating flow, while this annular peak is absent in continuous flow. Zhao and Cheng [5], studied numerically laminar forced convection of an incompressible flow in a pipe subjected to constant wall temperature and reciprocating flow. They concluded that the average heat transfer rate is increased with an increase in Reynolds number, but decrease with the increases in the length to diameter ratio. Later, Moschandreou and Zamir [6], considered analytically the problem of velocity and heat transfer in pulsatile flow in a tube where heat is generated at a constant rate. Meanwhile, Guo and Sung [7], examined the effects of various form of Nusselt number in pulsating pipe flow and observed that the large pulsating amplitude ratio of flow rate caused reverse flow at the cross section in a pipe. Further, Hemida et al. [8], corrected the solution obtained by Moschandreou and Zamir [6] analytically for the thermally fully developed case subjected to constant wall heat flux. Hemida et al. [8] concluded that, as long as the problem considered is laminar and incompressible flow, the pulsation enhances heat transfer for nonlinear boundary conditions while degrades the time average Nusselt number for linear boundary conditions.

Yu et al. [9], studied analytically pulsating laminar convection in a circular tube subjected to constant heat flux and found that pulsation neither enhances or degrades heat transfer in a steady flow. Beyond laminar flow, Wang and Zhang [10], investigated numerically pulsating turbulent convection heat transfer with large pulsating amplitude in a pipe subjected to constant wall temperature. Their result showed that large velocity amplitude oscillation, flow reversal in the pulsating turbulent flow and an optimum Womersley number greatly enhance heat transfer. Pendyala et al. [11], studied experimentally the single-phase flow subjected to low frequency oscillations on the convective heat transfer in a vertical tube. Their result indicated that the heat transfer coefficient increased with oscillations in the laminar region. Akdag and Ozguc [12], studied experimentally the heat transfer from a surface subjected to oscillating flow in a vertical annular liquid channel. Similar to Pendyala et al. [11], the region of study is having a constant heat flux and found that the oscillating flow heat transfer increases with increasing both the amplitude and frequency of the oscillation.

Mehta and Khandekar [13], investigated numerically periodic pulsatile internal laminar flows in two configurations, circular axisymmetric tube and parallel plates in which the superimposed pulsations are axial and transverse, respectively. Shailendhra and AnjaliDevi [14], considered analytically the problem of heat transfer in the oscillatory flow of liquid metals between two infinite parallel horizontal plates, thermally insulated when a constant axial temperature gradient is superimposed on the fluid. They observed that sinusoidal oscillation of the fluid enhanced heat transfer and it is independent of the pattern of oscillations. Yin and Ma [15] performed an analytical study of an oscillatory effect on the heat transfer in a capillary tube and found another important factor that influences heat transfer values in an oscillating flow. Furthermore,