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Comparison of different pressure waveforms for heat transfer performance of oscillating flow in a circular cylinder

M. Abdulhameed [a,*], Dumitru Vieru [b], Sharidan Shafie [c]

[a] School of Science and Technology, The Federal Polytechnic, Bauchi, P.M.B. 0231, Off Dass Road, Bauchi, Nigeria
[b] Department of Theoretical Mechanics, Technical University of Iasi, Iasi R-6600, Romania
[c] Department of Mathematical Sciences, Faculty of Science, Universiti Teknologi 81310, Skudai, Malaysia

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ABSTRACT

In the present investigation, an oscillating motion of unsteady Burger's fluid in a circular cylinder was modeled with different pressure waveforms. Three different waveforms are considered: the case of a trapezoidal, triangular and sinusoidal waveform. Analytical solutions of velocity and temperature distribution are obtained for an oscillating laminar flow, which can be used to analyze the effects of flow type on the heat transfer performance. The limiting cases have been considered to examine the heat transfer performance of four different non-Newtonian fluids. Results show that the heat transfer of the oscillating flow depends on the fluid material parameter, Prandtl number, amplitude oscillating waveform and radial coordinate. The trapezoidal and sinusoidal waveforms of oscillating motion can result in a higher heat transfer performance.
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1. Introduction

Ruckmongathan [1] showed that besides the multisteps, other waveforms like trapezoidal and triangular exist in electronics for reducing power dissipation in liquid crystal displays. Most of the electronic components and systems continue reduction in size while growing in energy density resulting in the need for more efficient thermal management. Oscillating heat cylinder occurs in many electronic devices, and most of the interest in this subject is the ability to establish extra-high effective thermal and manage high energy rich in heat fluxes [2–6]. Yu et al. [7] developed an analytical solution to determine pulsating laminar heat convection in a circular tube with constant heat flux. The results show that both the temperature profile and the Nusselt number fluctuate periodically about the solution for steady laminar convection, with the fluctuation amplitude depending on the dimensionless pulsation frequency, the amplitude of the pressure, and the Prandtl number. Wang and Zhang [8] analyzed convection heat transfer of pulsing turbulent flow in a pipe with constant wall temperature and high velocity oscillating amplitudes. Their results showed that the heat transfer enhancement is principally impacted by Womersley number and velocity oscillation amplitude. Pendyala et al. [9] conducted experimental studies on the oscillation flow and heat transfer in a vertical tube with a constant amplitude. The results indicated that the influence of an externally imposed periodic oscillation on the heat transfer is stronger at lower flow rates. Akdag and Ozguc [10] analyzed experimentally the heat transfer flow with constant heat flux and oscillating flow inside a vertical annular liquid column. The results demonstrated that heat transfer increases with increasing both the amplitude of the oscillation and frequency. Liu et al. [11] solved the energy equation of circular micro-channels, which considers axial heat conduction, velocity slip, temperature jump, viscous dissipation and thermal entrance effect. The design criterion for whether the axial heat conduction and viscous dissipation should be considered in engineering is given by studying their contributions to average Nusselt number.

Yin and Ma [12] reported the analytical result on an oscillating capillary tube in Newtonian laminar pulsating flows driven by a sinusoidal waveform. Their results show that the oscillating frequency, amplitude, and Prandtl number, are significant factors affecting the heat transfer performance of an oscillating flow in a capillary tube. Yin and Ma [13] investigated Newtonian flow in a tube driven by a triangular pressure waveform and showed how the oscillating flow could result in a different heat transfer coefficient with the corresponding result of a sinusoidal pressure waveform. Abdulhameed et al. [14] proposed the mathematical modeling of unsteady second grade fluid flowing in a capillary tube with sinusoidal pressure waveform and non-homogenous boundary conditions. Exact analytical solutions for the velocity profiles have been obtained in explicit forms

* Corresponding author. Tel.: +234 8033524805; fax: +234 077541393.
E-mail address: moallahyidi@gmail.com (M. Abdulhameed).
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using finite Hankel transform. The solutions are written as the sum of the steady and transient solutions for small and large times. For large value of times, the starting solution reduces to the well-known periodic solution that coincides with the corresponding solution of a Newtonian fluid. Khalid et al. [15] studied the problem of unsteady MHD free convection flow of Casson fluid past over an oscillating vertical plate embedded in a porous medium. The governing equations were solved using the Laplace transform technique and exact solutions for velocity and energy are obtained. Gul et al. [16] analyzed the problem of unsteady thin film flow of a second grade fluid over a vertical oscillating belt. The governing equation for velocity field was solved analytically using Adomian decomposition method (ADM) and Optimal asymptotic method (OHAM).

As mentioned above, the previous literature have focused on the Newtonian and second-grade fluids at a sinusoidal and triangular waveform effect on the heat transfer performance of oscillating flow in a capillary tube. The oscillating flow non-Newtonian Burgers' fluid at a trapezoidal, triangular and sinusoidal waveform has not been investigated before. It has been demonstrated that the oscillating heat tube using the thermally excited oscillating motion can significantly enhance the heat transfer performance (Yin and Ma [13]). The unanswered questions regarding trapezoidal, triangular and sinusoidal waveforms in Burgers' fluid made it necessary to study the effect of oscillating motion on the heat transfer performance of oscillating flow in a circular cylinder. In the current investigation, a Burgers' fluid of an oscillating flow with trapezoidal, triangular and sinusoidal waveforms is modeled using an infinite Fourier series. Using the constant heat flux boundary condition, analytical solutions of velocity and temperature distribution have been obtained. The effects of waveform frequency, waveform amplitude, and Pr number on the heat transfer performance of oscillating flow are analyzed. To demonstrate the unique feature of trapezoidal waveform effect, the sinusoidal waveform and triangular effect on the temperature of the oscillating flow are presented as well.

2. Governing equation of Burgers' fluid

Burgers' model has the ability in successfully capturing various non-Newtonian strange features, e.g. shear thinning/thickening and display of elastic effects. Therefore, it has been the subject of many investigations covering various facets [17–21].

The constitutive equations for an incompressible homogeneous Burgers' fluid are given by:

$$\mathbf{T}=-p\mathbf{I}+\mathbf{S},\quad \mathbf{S}+\lambda_1\frac{\delta\mathbf{S}}{\delta t}+\lambda_2\frac{\delta^2\mathbf{S}}{\delta t^2}=\mu\left[\mathbf{A}+\lambda_3\frac{\delta\mathbf{A}}{\delta t}\right], \tag{1}$$

where

$$\frac{\delta\mathbf{S}}{\delta t}=\frac{d\mathbf{S}}{dt}-\mathbf{LS}-\mathbf{SL}^T,\quad \frac{\delta\mathbf{A}}{\delta t}=\frac{d\mathbf{A}}{dt}-\mathbf{LA}-\mathbf{AL}^T. \tag{2}$$

where $\mathbf{T}$ is the Cauchy stress tensor, $-p\mathbf{I}$ is the indeterminate spherical stress, $\mathbf{S}$ is the extra-stress tensor, λ_1 is the relaxation time, λ_2 is the material constant of Burgers' fluid, $\frac{d}{dt}$ is the material time differentiation, $\mathbf{L}$ is the velocity gradient, T is the transpose operator, μ is the dynamic viscosity, $\mathbf{A}$ is the first Rivlin-Ericksen tensor and λ_3 is the retardation time.

The above model includes special cases, the Oldroid-B model (for $\lambda_2=0$), the Maxwell model (for $\lambda_2=\lambda_3=0$), the second-grade model (for $\lambda_1=\lambda_2=0$) and the linear viscous model (for $\lambda_1=\lambda_2=\lambda_3=0$).

The flow is incompressible and the surface tension effect is not considered

$$\nabla\mathbf{u}=0,\quad \rho\frac{d\mathbf{u}}{dt}=\mathrm{div}\mathbf{T},\quad \rho c_p\left(\frac{\partial\Theta}{\partial t}+\mathbf{u}\cdot\nabla\Theta\right)=k\nabla^2\Theta. \tag{3}$$

where the velocity and temperature fields are assumed to be of the form:

$$\mathbf{u}=u(r,t)\mathbf{a}_z,\quad \Theta=\Theta(z,r,t). \tag{4}$$

Under the above considerations, Eq. (3) gives the following dimensional governing equations

$$\rho\left(1+\lambda_1\frac{\partial}{\partial t}+\lambda_2\frac{\partial^2}{\partial t^2}\right)\frac{\partial u}{\partial t}=\left(1+\lambda_1\frac{\partial}{\partial t}+\lambda_2\frac{\partial^2}{\partial t^2}\right)\left(-\frac{\partial p}{\partial z}\right)+\mu\left(1+\lambda_3\frac{\partial}{\partial t}\right)\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}\right), \tag{5}$$

$$\rho c_p\left(\frac{\partial\Theta}{\partial t}+u\frac{\partial\Theta}{\partial z}\right)=k\left(\frac{\partial^2\Theta}{\partial r^2}+\frac{1}{r}\frac{\partial\Theta}{\partial r}\right). \tag{6}$$

The boundary conditions corresponding to Eqs. (5) and (6) are

$$\frac{\partial u}{\partial r}=0\quad\text{and}\quad\frac{\partial\Theta}{\partial r}=0\quad\text{at}\quad r=0, \tag{7}$$

$$u=0\quad\text{and}\quad k\frac{\partial\Theta}{\partial r}=q_w\quad\text{at}\quad r=r_0. \tag{8}$$

3. Trapezoidal pressure waveform

The oscillating Burgers' flow shown in Fig. 1 is driven by pressure difference with a trapezoidal waveform as in Fig. 2 of amplitude γ and frequency ω, i.e.

$$-\frac{\partial p}{\partial z}=\gamma\frac{32}{\pi^2}\sum_{n=1}^{\infty}\left[\frac{\sin\left(\frac{\pi}{8}(2n-1)\right)}{(2n-1)^2}\right]\sin((2n-1)\omega t). \tag{9}$$

Here, we need to solve Eqs. (5) and (6) subject to Eqs. (7) and (8) in the case where pressure gradient is given by Eq. (9).

Consider the following nondimensional quantities

$$u^*=\frac{u}{u_m},\quad t^*=\frac{\upsilon t}{r_0^2},\quad r^*=\frac{r}{r_0},\quad \lambda_1^*=\frac{\upsilon\lambda_1}{r_0^2},\quad \lambda_2^*=\frac{\upsilon^2\lambda_2}{r_0^4},$$
$$\lambda_3^*=\frac{\upsilon\lambda_3}{r_0^2},\quad z^*=\frac{4z}{r_0\,\mathrm{Pr}\,\mathrm{Re}_m},\quad \Theta^*=\frac{k(\Theta-\Theta_0)}{r_0 q_w}, \tag{10}$$
$$\mathrm{Pr}=\frac{\mu c_p}{k},\quad \mathrm{Re}_m=\frac{2u_m r_0}{\upsilon}.$$

Using Eq. (10) in Eqs. (5) and (6), the dimensionless momentum and energy equations (after dropping the * notation):

$$\left(1+\lambda_1\frac{\partial}{\partial t}+\lambda_2\frac{\partial^2}{\partial t^2}\right)\frac{\partial u}{\partial t}=\left(1+\lambda_1\frac{\partial}{\partial t}+\lambda_2\frac{\partial^2}{\partial t^2}\right)\left(-\frac{\partial p}{\partial z}\right)+\left(1+\lambda_3\frac{\partial}{\partial t}\right)\left(\frac{\partial^2 u(r,t)}{\partial r^2}+\frac{1}{r}\frac{\partial u(r,t)}{\partial r}\right), \tag{11}$$

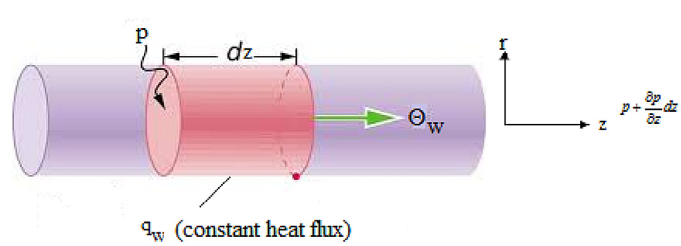

Fig. 1. The physical model configuration.

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