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An improved vibration technique for enhancing temperature uniformity and heat transfer in viscous fluid flow

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HIGHLIGHTS

- Transverse vibration with a step rotation of orientation has many benefits.
- Wall heat transfer in viscous pipe flow is greatly enhanced.
- Much improved radial temperature uniformity is achieved.
- Thermal boundary layer grows rapidly along the pipe.
- Short processing pipes can be used for heating of viscous fluid flow.

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ABSTRACT

Radial heat transfer in viscous pipe flow is controlled by thermal conduction which leads to a wide radial temperature distribution and slow heating of the core region of the flow. This is highly undesirable in many industrial processes as it results in a grossly uneven distribution of fluid heat treatment. The use of static in-line mixers to promote radial mixing and, thus, heat transfer and temperature uniformity, engenders large pressure drops and the devices are generally prohibited in processes where hygiene is paramount as they are difficult to keep clean. We recently reported a Computational Fluid Dynamics (CFD) study which showed that the superimposing of transverse mechanical oscillations on the steady flow of a viscous fluid in a pipe with an isothermal wall, results in a large enhancement in wall heat transfer, as well as a considerably more uniform radial temperature distribution accompanied by rapid heating of the inner region of the flow. Such a transverse vibration also causes the thermal boundary layer to grow more rapidly and, thus, the temperature profile to develop very rapidly in the axial direction. In this article, we report on an enhanced vibration technique which combines transverse oscillations with a step rotation of oscillation orientation. The technique produces much more improved effects compared to transverse vibration alone, and it also excels in comparison with the well-known Kenics helical static mixer.

1. Introduction

When laminar fluid flow in a pipe is accompanied by radial heat transfer, the associated parabolic radial velocity profile leads to a wide radial temperature distribution as heat transfer is controlled by slow conduction. Such conditions pose a considerable challenge in a number of industrial processes, such as the processing of food products, polymer melts and pharmaceutical formulations, where the fluid to be heated (or cooled) is often viscous and temperature dependent. This problem has been recognised for a long time but effective technological solutions are still missing.

In the heating stage of continuous food sterilisation, for example, heat is transferred from the hot pipe wall to the fluid such that the fastest core region of the flow is the coldest, thus, resulting in an undesirable wide variation of product sterility and nutritional quality across the pipe which leads to poor product quality (Jung and Fryer, 1999). The challenge is, therefore, to be able to sterilise the fastest parts in the core region of the pipe without over-processing the slowest parts near the wall so that, ideally, all parts of the fluid should receive equal heat treatment. The optimisation of such thermal processes poses a challenging manufacturing problem. The overriding importance of safety often results in the food being exposed to a more severe process than is desirable from a quality aspect, resulting in poor sensory and nutritional attributes, especially with sensitive products. In the cooling stage of the process the problem is reversed and instead of

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rapid uniform cooling of the product, the central parts of the flow incur the slowest cooling rates, again leading to significant losses in product quality. These problems become even more complicated when more than one phase is present such as in solid-liquid flows.

To improve the uniformity of the temperature distribution, methods are needed to promote radial mixing in viscous fluid flow. Radial mixing can be enhanced by operating under turbulent flow conditions, but the high fluid viscosities encountered in practice make this proposition impractical and/or uneconomical. Various ways have been proposed to improve heat convection by adding internal screw-thread structures on the wall to disrupt the boundary layer (Shrirao et al., 2013), but such technological solutions are limited by their manufacturing complexity, cost, their high proneness to fouling and clogging, and the difficulty to keep them clean. Similarly, inserts or inline static mixers are used to promote radial fluid mixing and a number of designs exist (Hobbs and Muzzio, 1997; Saatdjian et al., 2012). In viscous flow, such devices can achieve a high degree of fluid mixing but usually at the expense of a high pressure drop. These inserts too are generally prohibited in hygienic processes because of the risk of contamination as their complex geometries also promote fouling and make them difficult to clean.

A number of studies have also demonstrated the effects of pulsating flow on the heat flux and Nusselt number in pipe flows (Gundogdu and Carpinlioglu, 1999). However, the effects on the radial temperature distribution in viscous fluids do not seem to have been reported.

We recently reported a Computational Fluid Dynamics (CFD) study which showed that superimposing transverse mechanical oscillations on the steady flow of a viscous fluid in a pipe with an isothermal wall, results in a large enhancement in wall heat transfer, as well as a considerably more uniform radial temperature distribution accompanied by a substantial heating of the inner region of the flow (Eesa and Barigou, 2010; 2011). Transverse vibration also causes the thermal boundary layer to grow more rapidly and, thus, the temperature profile to develop very rapidly in the axial direction. It should be noted that this type of flow is different from the pulsatile (oscillatory) flow mentioned above.

In this article, we report on an enhanced vibration technique which combines transverse oscillations with a stepwise angular motion to achieve a high degree of radial fluid mixing, temperature uniformity and heat transfer. We use a validated CFD model to assess and compare the performance of this new method to our previous results using simple transverse vibration, as well as to the performance of the well-known Kenics helical static mixer, one of the best in this category of mixers.

2. CFD model

2.1. Fluid viscosity

The fluid used is an incompressible, temperature-dependent Newtonian fluid whose viscosity is assumed constant at a given temperature and is described by the well-known Arrhenius relationship:

$$\mu = k_0 exp\left(\frac{E_a}{R_g T}\right) \tag{1}$$

where k_0 is a pre-exponential factor, R_g is the ideal gas constant, T is temperature and E_a is the activation energy for viscosity. The constants k_0 and E_a are determined experimentally and their values for various fluids have been reported in the literature (e.g. Steffe, 1996). These parameters, as well as other physical properties (density ρ, specific heat capacity C_p, and thermal conductivity λ) were assumed constant and their values are given in Table 1.

2.2. Transverse oscillations

In our previously reported technique, transverse oscillations are imposed on the pipe wall in a direction perpendicular to the pipe axis, as illustrated in Fig. 1(a), and the wall displacement x is described by the function:

$$x = A\ \sin(\omega t) \tag{2}$$

where A is the amplitude of vibration, t is time and ω is the angular function of the frequency of vibration, f, such that $\omega = 2\pi f$. The linear transversal velocity of the pipe wall is then:

$$u = \frac{dx}{dt} = A\omega\ \cos(\omega t) \tag{3}$$

In the new enhanced technique being reported here, the pipe is continuously oscillated transversally but the orientation of oscillation is rotated instantly in a stepwise manner by an angle of 45 degrees about the pipe axis, as depicted in Fig. 1(b). The time interval, Δt, between change of orientation steps, needs to be optimised for a given set of flow conditions. For the conditions investigated in this work, a value of ~ 10 s was determined through numerical experimentation, thus, the frequency of the step rotation, Ω, is (and is expected to always be) very low compared with the frequency of lateral oscillations; for example, in this case Ω is ~ 0.1 Hz compared to $f = 50$ Hz.

In all the numerical experiments conducted, under steady state, the flow regime was always laminar with a Reynolds number ($Re = \rho \overline{w} D/\mu$) less than 100, where D is pipe diameter and $\overline{w}$ is mean axial velocity. When the pipe was vibrated, the vibration Reynolds number:

$$Re_v = \frac{\rho A \omega D}{\mu} \tag{4}$$

was always less than 1500, so flow remained laminar throughout, in all the unsteady-state cases studied.

2.3. Governing equations

The governing transport equations can be written in their general form (Bird et al., 1987), thus:

$$\text{Continuity}: \quad \nabla \cdot \boldsymbol{U} = 0 \tag{5}$$

$$\text{Momentum}: \quad \rho \frac{D\boldsymbol{U}}{Dt} = -\nabla p + \nabla^2 \mu \boldsymbol{U} + \rho \boldsymbol{g} \tag{6}$$

Table 1
Rheological parameters used.

k_0 (Pa s)	E_a (J mol^{-1})	R_g (J mol^{-1} K^{-1})	ρ (kg m^{-3})	C_p (J kg^{-1} K^{-1})	λ (W m^{-1} K^{-1})	μ (Pa s)	
						20 °C	140 °C
5.0×10^{-7}	35000	8.314	998	4180	0.668	0.868	0.0134