AN IMPROVED TRANSVERSE VIBRATION TECHNIQUE FOR ENHANCING HEAT TRANSFER AND TEMPERATURE UNIFORMITY IN VISCOUS FLUID FLOW

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Introduction

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 paper, we report on an enhanced vibration technique which combines transverse oscillations with a step rotation of oscillation orientation. The improved performance of this new method is compared to that of the simple vibration technique reported in our previous work, as well as to the performance of the well-known Kenics helical static mixer.

Keywords: CFD; heat transfer enhancement; laminar flow; oscillations; temperature profile

Theory and method

(i) 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:

$$\mu = k_0 exp\left(\frac{E_\alpha}{R_g T}\right)$$

Table 1: Rheological parameters used in this study.

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

(ii) Transverse oscillation

The linear transversal velocity of the pipe wall considered here is:

$$u = A\omega cos(\omega t)$$

Three-dimensional simulations were set up and executed using the commercial software package ANSYS Workbench 14.5. The flow geometries were created and meshed using the software ICEM, while flow specification, solving and post-processing were all performed using CFX 14.5.

Results and conclusion

Forced transverse vibration superimposed on the steady laminar flow of a fluid in a pipe with an isothermal wall generates a vigorous swirling fluid motion represented by a strong vorticity field and complex spiralling fluid streamlines and trajectories. The method has been shown to have substantial benefits for heat transfer including a large (several folds) increase in wall heat transfer, a much more uniform radial temperature profile, a rapid development in the temperature profile along the pipe, rapid heating of the core region of the flow, and relatively short processing pipes.

Table 2: Comparison of the four different flow regimes studied (T_w =140 °C).

	Simple steady flow	Steady flow through Kenics static mixer	Flow with transverse oscillations	Flow with transverse oscillations and step rotation of vibration orientation
Mean temperature at exit $\overline{T}_{out}$ (°C)	61.3	108.1	116.8	126.5
Coefficient of radial temperature variation C_v (-)	0.49	0.026	0.069	0.021
Mean wall heat transfer coefficient h (W m^{-2} K^{-1})	297.8	935.3	1160.7	1544.7
Pressure drop Δp (Pa)	194.2	1500.7	264.2	241.9

A new enhanced technique has been introduced in this work which combines transverse vibration with a step rotation of oscillation orientation. This technique produces much improved effects compared to transverse vibration alone. It also excels in comparison with the well-known Kenics helical static mixer which has the disadvantages of being unsuitable for hygienic fluid processing and causes large pressure drops.

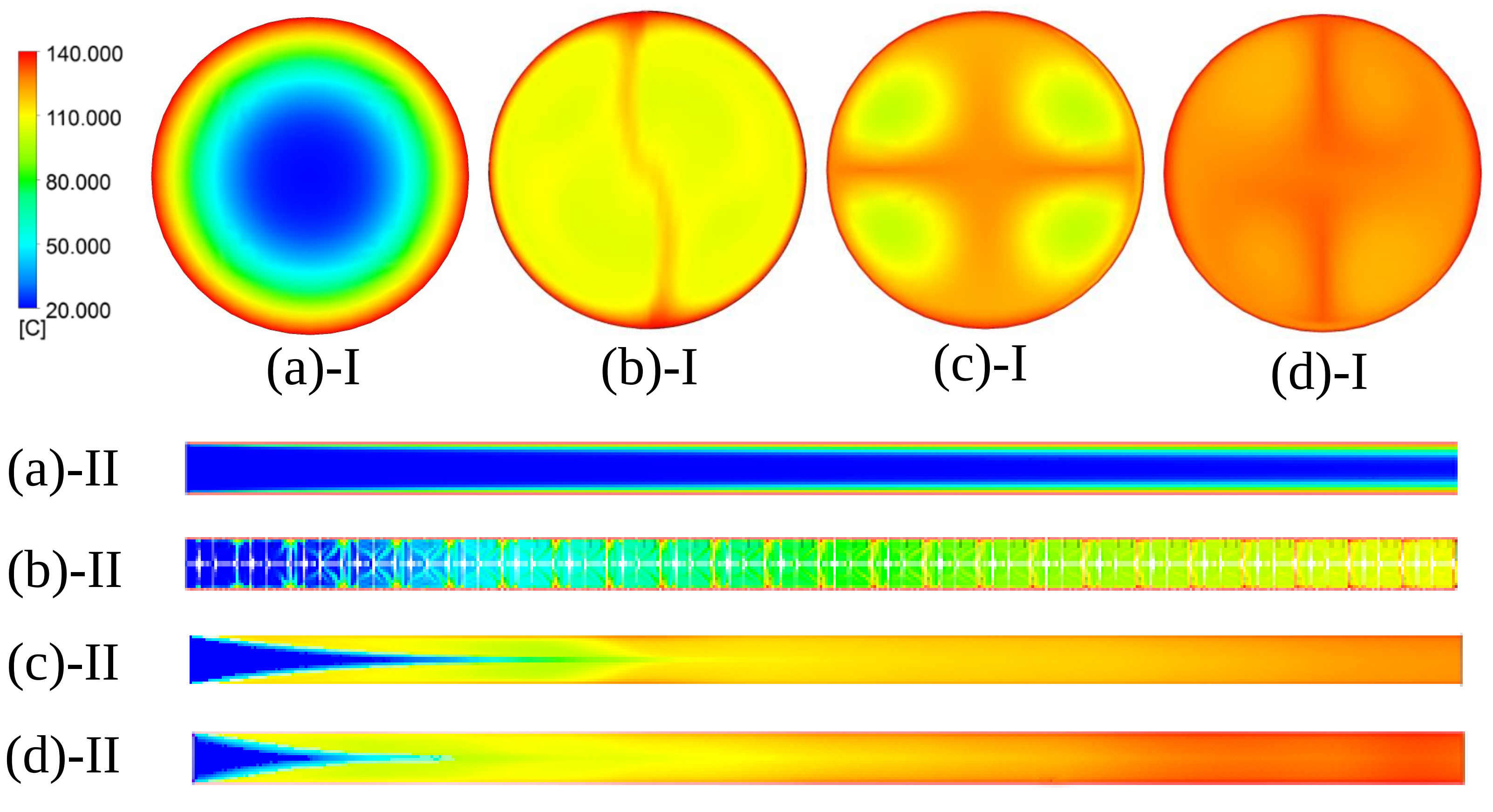

Figure 1: Comparison of I: temperature distribution at pipe exit; II: temperature development along pipe: T_{in} = 20°C; T_w = 140°C; D = 30 mm; L = 2400 mm; $\overline{w}$ = 4.0 cm s^{-1}; $\mu = k_0 \exp(E_a/R_gT)$ Pa s; ρ = 998 kg m^{-3}; C_p = 4180 J kg^{-1} K^{-1}; λ = 0.668 W m^{-1} K^{-1}: (a) simple steady flow; (b) steady flow through helical static mixer; (c) flow with transverse oscillations; (d) flow with transverse oscillations and step rotation of vibration orientation.

Nomenclature

μ	Viscosity for Newtonian fluid, Pa s
ρ	Density, kg m^{-3}
λ	Thermal conductivity, W m^{-1} K^{-1}
ω	Angular function of frequency of vibration, rad s^{-1}
A	Vibration amplitude, m
C_p	Specific heat capacity, J kg^{-1} K^{-1}
E_a	Activation energy for viscosity, J mol^{-1}
f	Vibration frequency, Hz
k_0	Pre-exponential factor, Pa s
R_g	Gas constant, J mol^{-1} K^{-1}
T_w	Wall temperature, °C