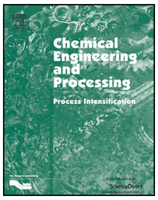
Chemical Engineering and Processing 74 (2013) 1–13

Contents lists available at ScienceDirect

Chemical Engineering and Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep



Mixing enhancement by pulsating chaotic advection

Mojtaba Jarrahi[a,b], Cathy Castelain[a], Hassan Peerhossaini[c,*]

[a] Thermofluids, Complex Flows and Energy Group, Laboratoire de Thermocinétique, UMR CNRS 6607, Nantes University, La Chantrerie, BP 50609, F-44306 Nantes, France
[b] Univ. Paris-Sud, LIMSI-CNRS UPR 3251, BP 133, 91403 Orsay Cedex, France
[c] Univ. Paris Diderot, Sorbonne Paris Cité, Institut des Energies de Demain (IED)-CNRS-FRE 3597, Paris, France

ARTICLE INFO

Article history:
Received 4 June 2012
Received in revised form 5 October 2013
Accepted 10 October 2013
Available online 21 October 2013

Keywords:
Mixing
Pulsating flow
Chaotic mixer
Secondary flow
Dean flow
Lyne instability

ABSTRACT

The purpose of this study is to investigate transverse mixing enhancement by superposition of periodic time dependence, in the form of pulsation, on a twisted pipe flow in which the fluid particles trajectories are spatially chaotic. The pulsation makes the secondary flow structure more complex, resulting in stronger velocity gradients that enhance stretching and folding, the main mechanisms of chaotic mixing. Here, the chaotic configuration is six alternating 90° curved pipes. The imposed pulsating conditions range as follows: steady Reynolds numbers $420 \le Re_{st} \le 1000$, velocity component ratios $1 \le (\beta = U_{\max,osc}/U_{m,st}) \le 4$ and frequency parameters $8.37 < (\alpha = r_0(\omega/\nu)^{0.5}) < 24.5$. The secondary velocity fields are measured by particle image velocimetry. The axial vorticity and transverse strain rate at the outlet of each curved pipe in pulsatile flow are compared with those of the steady flows. Analysis of these criteria for mixing assessment shows that $\beta \ge 2$ and $\alpha \le 15$ are favourable pulsating conditions for transverse mixing enhancement. Moreover, in some pulsation conditions, the cell centres visit a zone in the flow cross-section that is much larger than in the steady case, implying that pulsation also contributes to mixing homogenization.

1. Introduction

Mixing enhancement in laminar flows is significant in such industries as pharmacologicals, foods, polymer and chemicals. In these sectors, however, turbulent flows are rarely used despite their mixing advantages because the large stresses in a turbulent flow may affect the quality of the product (usually long, fragile molecular chains). In such situations mixing can be carried out only in laminar flows, and intensification of mixing in such flows requires new techniques.

Chaotic advection, introduced by Aref [1], analyzes the macroscopic transport of tracers in spatially chaotic trajectories generated by simple laminar velocity fields. It is the special geometry of the system that allows these chaotic trajectories to be produced. The chaotic nature of the streamlines in alternating Dean flow has the same cause: the geometrical perturbation of a steady Dean flow (flow in a curved pipe). This perturbation is introduced by successive changes in the orientation of the curvature plane. At each change in orientation, the centrifugal force is reoriented and thus the Dean cell positions are modified in such a way that cells are destroyed and reconstructed in a perpendicular plane. Since the Dean cells play the role of "agitators," their alternating displacement and reorientation contribute to better stirring and consequently better mixing. Moreover, the analysis of the residence time distribution has shown [2,3] that axial dispersion in the alternating Dean flow is more than 20% less than in a helicoidally coiled-pipe flow having the same number of bends. The decrease in axial dispersion, accompanied by an increase in transverse dispersion, is due to the generation of chaotic trajectories and contributes to mixing enhancement. Several studies have been carried out on mixing improvement and also heat-transfer enhancement in steady alternating Dean flows [4–8].

Much previous research on pulsating flow in curved pipes has been motivated by physiological applications [9–15]. Simon et al. [16] investigated the effects of pulsation on heat-transfer enhancement. In the present work, we are interested in the effects of pulsation on mixing improvement in alternating Dean flow. Timité et al. [17] demonstrated some of the potential of pulsating alternating Dean flow using laser-induced fluorescence (LIF) visualizations; although qualitative, these images revealed an important modification in the secondary flow structure due to the pulsation. Under certain pulsating conditions, the secondary flow becomes more complex, with the appearance of Lyne instability [18] or swirling structures. Moreover, Timité et al. [17] showed by a Lagrangian method that superposition of an oscillation on a steady alternating Dean flow reduces the non-stretching zones in the flow. This phenomenon was observed by following the tracer spreading at different bend outlets.

---

[*] Corresponding author. Tel.: +33 607 53 31 61.
E-mail address: hassan.peerhossaini@univ-paris-diderot.fr (H. Peerhossaini).

0255-2701/$ – see front matter
http://dx.doi.org/10.1016/j.cep.2013.10.003

Nomenclature

r_0	pipe cross-sectional radius
r_c	curvature radius
u	velocity in x direction
v	velocity in y direction
Re	Reynolds number, $Re = U_m(2r_0)/\upsilon$
Greek symbols	
α	Womersley number, $r_0(\omega/\upsilon)^{1/2}$
β	velocity component ratio
υ	kinematic viscosity
η	curvature ratio of curved pipe, r_0/r_c
ω	angular frequency
$\zeta(x, y)$	axial vorticity at position (x, y) in the curved pipe cross-section: $(\partial v/\partial x) - (\partial u/\partial y)$
$\left\lvert \zeta_P \right\rvert$	cross-sectional average value of absolute vorticity in a pulsatile flow
$\left\lvert \zeta_S \right\rvert$	cross-sectional average value of absolute vorticity in a steady flow
$\varepsilon(x, y)$	transverse strain rate at position (x, y) in the curved pipe cross-section: $1/2[(\partial v/\partial x) + (\partial u/\partial y)]$
$\lvert \varepsilon_P \rvert$	cross-sectional average value of absolute transverse strain rate in a pulsatile flow
$\lvert \varepsilon_S \rvert$	cross-sectional average value of absolute transverse strain rate in a steady flow
Subscripts	
P	pulsating flow
S	steady flow

This work aims to characterize experimentally the secondary flow and transverse mixing in pulsating alternating Dean flow. The paper is organized as follows: Section 2 describes the experimental setup and measurement techniques. The PIV measurements allow the detailed Eulerian analysis of the secondary flow presented in Section 3. It has been shown that the complex structures reported in one bend of a chaotic configuration [19–21] persist in successive bends but in a more convoluted shape. Complexity of flow topology is important for mixing because it can provide stronger vorticity and strain rates and thus better stirring. In order to better understand the effects of pulsation on the secondary flow patterns and transverse mixing in alternating Dean flow, the steady state is studied first, and then the displacements of the cells and variations in mixing are analyzed for different pulsating conditions. The pulsating conditions studied here range as follows: steady Reynolds numbers $420 \leq Re_{st} \leq 1000$, velocity component ratios $1 \leq (\beta = U_{max,osc}/U_{m,st}) \leq 4$ and frequency parameters $8.37 < (\alpha = r_0(\omega/\nu)0.5) < 24.5$. Concluding remarks, presented in Section 4, discuss the effects of pulsation on mixing enhancement in alternating Dean flow.

2. Experimental setup and measurement techniques

The velocity field of the pulsating flow U_P can be expressed as

$$U_P(t) = U_{mS} + U_{\max,\sin} \sin(\omega t) \tag{1}$$

where U_{mS} is the mean velocity of the steady flow and $U_{\max,\sin}$ is the velocity amplitude of the sinusoidal flow. If we define a dimensionless velocity component ratio as the ratio between these values:

$$\beta = \frac{U_{\max,\sin}}{U_{mS}} \tag{2}$$

Eq. (1) can be written as

$$U_P(t) = U_{mS}(1 + \beta \sin(\omega t)) \tag{3}$$

Another dimensionless parameter, the Womersley number, α, can be used to describe the angular velocity ω in Eq. (3). The Womersley number represents the inertial effects due to pulsating flow frequency in relation to viscous effects:

$$\alpha = r_0 \cdot \left(\frac{\omega}{\upsilon}\right)^{1/2} \tag{4}$$

where r_0 is the pipe radius and υ is the kinematic viscosity of the fluid.

Fig. 1 is a schematic diagram of the experimental setup. The working fluid used in the experiment is water. A pulsating flow can be obtained by superposition of a sinusoidal flow on a steady flow. A volumetric pump connected to a head tank of 300 l provides the steady flow, as measured by an electromagnetic flow meter. The sinusoidal flow is generated by a Scotch-yoke mechanism. The dimensionless frequency α, which depends on the angular velocity of the pulsation ω, and also the velocity component ratio β, which depends on the piston stroke and the angular velocity ω, are controlled in the Scotch-yoke mechanism. The angular velocity of the pulsation ω is adjusted by a motor-speed reducer that controls crank velocity. A piston of 0.04 m diameter is connected to the crank by a metal stem; its stroke is controlled by the crank in 20 mm steps up to a maximum of 200 mm. The reliability of this Scotch-yoke mechanism in producing a sinusoidal flow has been verified in previous work [17] by LDV measurements of the axial velocity.

The steady and sinusoidal flows join each other at the inlet of a 2.5 m straight tube of circular cross section ($2r_0 = 40$ mm). The sinusoidal flow, which is fully developed at the outlet of the straight tube, enters the test section. The test section is composed of six bends arranged in a chaotic configuration: the curvature plane of each bend makes a 90° angle with that of its neighbor. According to the numerical study of Jones et al. [22], a 90° angle is optimal for efficient stirring in steady alternating Dean flow. Each bend is a 90° curved pipe of circular cross-section with cross-section diameter $2r_0 = 40$ mm and curvature radius $r_c = 220$ mm. The long straight tube and the bends are made of 5-mm thick Plexiglas.

A T-shaped Plexiglas flow divider was installed downstream of the curved pipe and PIV measurements were conducted at the pipe outlet (the flow divider eliminates light-refraction effects). The outer walls of the flow divider are flat and mirror polished. The cylindrical inner tubes have the same diameter as the bend cross-section (40 mm). The particles used for seeding are silver-coated hollow glass spheres (diameter 10 μm). The PIV camera is perpendicular to the illuminated outlet section of the curved pipe (Fig. 1) and acquires images through an optical window made of 3 mm thick float glass with a multilayer antireflection coating on both sides. A 7 Hz camera equipped with a Nikon lens (AF-Micro-NIKKOR 60 mm) is used. A Nd YAG laser (50 mJ–532 nm) provides a 2 mm thick laser sheet. Each image shows a 68.3-mm-square visualization window (2048 × 2048) centred on the flow field in the curved pipe cross-section. Dynamic Studio software (version 2.30) is used for digital analysis of the pictures, particularly for the velocity computation. Adaptive correlation with interrogation zones of 64 × 64 pixels (50% area overlap) was used. The acquisition system is synchronized with the piston motion by an electronic power source that is controlled by a switching contact device. Each contact between the switch and the knob (which is on the crank periphery) sends a signal to the acquisition system. The acquisition then occurs after a delay time that is entered into the PIV control system and depends on the phase position ωt at which the velocity measurements are conducted. Four principal phase positions are studied here: $\omega t = 0°$, 90°, 180° and 270°. Each velocity field is obtained by