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Mass transfer and mixing by pulsatile three-dimensional chaotic flow in alternating curved pipes

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ABSTRACT

We present an experimental and numerical study of three-dimensional pulsatile flow in a twisted pipe in order to show the effects of chaotic advection on mixing in this flow configuration. The numerical study is done by CFD code with a pulsatile velocity field imposed as an inlet condition. The experimental setup is composed principally of a "Scotch-yoke" pulsatile flow generator and a twisted duct. The twisted duct consists of six 90° bends of circular cross-section; the plane of curvature of each bend is at 90° to that of its neighbors. The secondary flow, generated by centrifugal force, the pulsating velocity field and also due to the change in curvature plane, leads to irregular fluid particle trajectories. Velocity measurements were made for a range of stationary Reynolds numbers ($300 \leqslant Re_{st} \leqslant 1200$) and frequency parameters ($1 \leqslant \alpha < 20$) and for two velocity-amplitude ratios (β); agreement between the numerical and experimental results is satisfactory. In the first bend, for certain control parameter values, the secondary flow becomes more complex due to the pulsation, and in some cases Lyne instability and a siphon phenomenon appear. However, in the other bends, one passes from four cells (Lyne instability) in the first bend with two cells in the other bends. The numerical and experimental study revealed modifications in the trajectories' evolution due to pulsation. The superposition of an oscillating flow on a stationary curved-pipe flow, in some cases, causes the destruction of the trapping zones (KAM structures). The number of regular zones that disappear with an increase in the number of bends decrease with pulsation frequency and velocity-amplitude ratio. Both these phenomena contribute to the mixing and mass transfer enhancement in the flow.

1. Introduction

This work is motivated by the interest in mixing enhancement by flow manipulation. Previous work on spatial manipulation of Dean vortices showed significant mixing and heat transfer enhancement by chaotic advection. In the present work we combine spatial and temporal flow manipulation for increasing this enhancement beyond chaotic advection.

The study of periodic flows began in earnest in 1950 with much work in blood flow applications. The first analytical studies for a fully developed flow regime in circular tubes determined the characteristic parameters controlling a pulsated flow of velocity pulsation ω [1–3]: the Womersley parameter α, also called the frequency parameter, the oscillating Reynolds number based on the maximum oscillating velocity amplitude Re_{osc}, the stationary Reynolds number Re_{st} based on the stationary mean velocity, the maximum Reynolds number $Re_p = Re_{st} + Re_{osc}$, the ratio β, characterizing the balance between steady and oscillating components of the pulsated flow, and the oscillating velocity amplitude, defined in a flow cross section. These works were mainly focussed on the effects of pulsation on the flow in single curved pipes; the effects of *rotation of the curvature plane of a succession of curved pipes* (which is the main focus of this paper) were not considered. In periodic flows, the interaction between viscous and inertial effects produces a velocity profile that deviates significantly from the parabolic shape of steady flow [1,4,5]. Ohmi et al. [6] have classified the different regimes in pulsatile flow versus the influence of the nondimensional frequency parameter α. In 2001, Çarpinlioğlu and Gündoğdu [7] provided an extensive review of work on pulsating flows from 1928 to 2000.

In steady laminar flow, the presence of duct curvature generates a secondary flow in the form of a pair of counter-rotating symmetrical vortices called Dean cells. Steady fully developed laminar Newtonian curved flows of circular cross-section have been studied extensively; some review of previous work is presented in Berger et al. [8]. Dean flow [9,10] is thus the fluid flow in a curved duct, and the corresponding control parameter is the Dean number *Dn*. Beyond a critical Dean number another pair of counter-rotating vortices appears, called hereafter Dean vortices. These vortices are due to the Dean instability, which belongs to the large family of

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Nomenclature

A_0	initial tracer area
$C(\vec{x}_i, t)$	scalar in the mesh i
$\overline{C(\vec{x}, t)}$	average value of the scalar in the section
$C_D(\vec{x}, t)$	mixing degree
d	maximum transverse transport due to molecular diffusion
D_h	hydraulic diameter
D_m	molecular diffusion coefficient
Dn	Dean number, $Dn = \frac{U_m D_h}{\nu}\sqrt{\frac{D_h}{Rc}}$
r	radial coordinate
r_o	pipe radius
R_c	curvature radius
Re	Reynolds number, $U_m D_h/\nu$
t	time
U	axial velocity
x, y, z	coordinates

Greek symbols

α	Womersley number, $r_o(\omega/\nu)^{1/2}$
β	velocity-amplitude ratio = $(U_{\max,osc}/U_{st})$
γ	Lyapunov exponent
τ_d	diffusion time scale
Φ	angular position
η	nondimensional curvature ratio of curved pipe, r_o/R_c
ν	kinematic viscosity
ω	angular frequency

Subscripts

m	mean
max	maximal
osc	oscillation component
st	steady component

centrifugal instabilities. Lyne [11] was the first to highlight the complexity of the fully developed laminar oscillatory flow in curved pipes. He demonstrated the appearance of a new vortex pair over and above those observed in the steady case. These results were confirmed theoretically by Zalosh and Nelson [12] and experimentally by Bertelsen [13]. Rabadi et al. [14], in an analytical study of pulsatile flows in curved pipes with strong curvature radius ratio, observed that the amplitude of the shearing forces decreases with increasing frequency. Moreover, considerable variation in secondary flow intensity occurs at small oscillation frequencies during a pulsation cycle.

Through experimental measurements of the axial and secondary velocities in a 180° curved pipe, Talbot and Gong [15] highlighted the existence of reverse flows at the inside wall during the deceleration phase. The reverse flows and the appearance of the vortex were emphasized in a numerical study by Toshihiro et al. [16], who observed that the secondary flow is characterized by more than two vortex pairs. Chang and Tarbell [17] found, however, that the secondary flow has only one vortex pair at the beginning of the deceleration half-phase; here the secondary flow becomes complex and a new vortex pair appears near the outside wall and then disappears with the start of the last third of the deceleration phase, only to reappear at the end of the acceleration process. More recently, Hamakiotes and Berger [18,19], studying the effect of the Reynolds number on pulsatile flow in uniformly curved pipes, found that the secondary flow becomes much more complex with increasing average stationary Reynolds number. Timité et al. [20], in an experimental and numerical study of pulsatile flow in a curved pipe, present visualizations by laser-induced fluorescence, velocity measurements and the numerical results that permit analysis of the swirling secondary flow structures developing along the bend during the pulsation phase. These measurements were made for a range of stationary Reynolds number ($300 \leqslant Re_{st} \leqslant 1200$), frequency parameter ($1 \leqslant \alpha < 20$), and two velocity-component ratios. For a high amplitude parameter β, the secondary flow structure is modified by a Lyne instability and a siphon effect during the deceleration phase. By siphon effect we mean an apparent suction type effect which occurs during the flow deceleration phase. The intensity of the secondary flow decreases as the frequency parameter α increases during the acceleration phase. During the deceleration phase, under the effect of reverse flow, the secondary flow intensity increases with the appearance of Lyne flow. All things considered, then, pulsatile flows in uniformly curved pipe are far more complex than those in a straight tube or steady Dean flows. The fluid motions resulting from the pulsations have been found to depend on the characteristic oscillation parameters.

The generation of *spatially chaotic* behavior from deterministic flow by simple geometrical perturbations has attracted much attention in recent years [21–23]. The interest arises both from the very curious fundamental peculiarities of this *Lagrangian chaos* and from its potential application in mixing [24–27] and heat transfer [28–30]. The necessary conditions for the existence of laminar steady three-dimensional flows with chaotic streamlines were pointed out by Arnold [31]. The blinking-vortex system [21] emulates a "closed" highly idealized two-dimensional chaotic flow. However, it has inspired the construction of a more realistic three-dimensional steady chaotic open flow [22,23]. Here the rectilinear vortex filaments of the blinking-vortex flow are replaced by a pair of streamwise vortices in a duct flow (Dean cells) and the temporal periodicity of the vortices is replaced by the spatial oscillation of a geometrical parameter that is the orientation of the curvature plane. The flow constructed in this way is a laminar twisted-duct flow made up of a series of bends; the plane of curvature of each bend makes an angle with the curvature plane of the neighboring bends. Parametric studies by Jones et al. [22] in twisted pipe flow have shown the domain of the rotation angle of the curvature plane for which the Poincaré maps show extended chaotic regions. A comprehensive review of the state of the art of chaotic advection can be found in Ottino [25].

Following the study of the steady flow in the twisted pipe and the demonstration of mixing and heat-transfer enhancement by Castelain et al. [32], the purpose of this work is to study experimentally and numerically the laminar pulsatile flow in twisted pipe. The paper is organized as follows: Section 2 describes experimental facilities, procedures and the numerical simulation methodology. Section 3 describes the experimental and numerical velocity fields and flow visualizations in which the frequency parameter, the velocity components ratio and the stationary Reynolds number are varied. Section 4 is devoted to results on Lagrangian properties of the flow and the influence of the pulsation, and Section 5 gives some concluding remarks.

2. Experimental facilities, procedures and description of the numerical method

2.1. Water tunnel facility

Steady flow is generated to the test section by a volumetric pump and its flow rate is measured by three parallel calibrated