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Numerical simulation of thermal chaotic mixing in multiple rods rotating mixer

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ABSTRACT

In this research work, a numerical simulation is carried out to study the performance of coupled mixing and heating generated by chaotic advection in a mixer comprising rotating rods uphold inside a cylindrical tank. The effect of the number of the rotating rods on both the chaotic advection and the thermal efficiency of the mixer is presented. It is found that the use of non-continuous wall rotations is necessary to ameliorate the heat transfer by chaotic mixing. The increase in the number of rod within the mixer can also promote the thermal performance of the mixer.

1. Introduction

The chaotic mixing or the chaotic advection, that is defined as the arbitrary trajectory of a fluid particle convected by time-periodic flow with a fixed velocity field, has been investigated extensively in the literature because of its great importance in various industrial purposes including food engineering polymer processing, or chemical and biochemical engineering [1–5]. In these industrial applications, the mixing is generally carried out in laminar flow regime where the fluids considered are significantly viscous or are shear sensitive [6]. Good fluid mixing can be achieved in turbulent flows, but the inconvenience is the higher shear stress, which increases the pressure drop and thus energy consumption will be very high. However, it becomes difficult to enhance heat transfer in cases where turbulence cannot be generated in the flow due to high viscosity. One possibility for heating these kind of fluids (possessing high Prandtl number) under laminar flow conditions is by using the annular heat exchanger. In this application, the fluid passes through an annular form between two concentric cylinders. The heat flows into the fluid by both the inner and outer boundaries. Chaotic advection can take place in two-dimensional periodic flows, for instance, like a flow between two eccentric cylinders moving at time-periodic velocities [7–9], and in either spatially periodic or time-periodic 3-D flows [10–14]. It is interesting to note that Geometrical perturbations can also cause chaotic advection [15,16].

Several research works have studied two-dimensional, time periodic flows and have proved that the evolution of partially mixed structures in a fluid can be characterized based on the stretching and stirring of fluid elements put into the flow [17,18]. The "journal bearing flow" representing 2-D flow analysis between two eccentric rotating cylindrical forms, is simplified since an analytical solution exists for the cases of regular angular velocities of both elements. This solution is reported in bipolar coordinates and in a

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Table 1
The stirring configurations.

Stirring configuration	Rod 1	Rod 2	Rod 3	Rod 4	Tank
2a	(+)	(+)			(+)
2b	(+)	(-)			(+)
2c	(-)	(-)			(+)
3a	(+)	(+)	(+)		(+)
3b	(+)	(+)	(-)		(+)
3c	(+)	(-)	(-)		(+)
3d	(-)	(-)	(-)		(+)
4a	(+)	(+)	(+)	(+)	(+)
4b	(+)	(+)	(+)	(-)	(+)
4c	(+)	(+)	(-)	(-)	(+)
4d	(+)	(-)	(-)	(-)	(+)
4e	(-)	(+)	(-)	(+)	(+)
4f	(-)	(-)	(-)	(-)	(+)

Table 2
Fluid properties.

Dynamic viscosity	1.5 Pa.s
Density	990 kg m^{-3}
Thermal conductivity	0.15 W m^{-1} K^{-1}
Specific heat capacity	1000 J kg^{-1} K^{-1}
Prandtl number	10,000

mixed Cartesian-polar non-orthogonal coordinate system [19,20]. Theoretical [21,22] and experimental [23,24] approaches of chaotic mixing in 2-D unsteady incompressible laminar flow have been investigated. A great part of these contributions have employed a model of the unsteady Couette flow between two eccentric cylinders, often called unsteady journal-bearing flow. Other studies have shed light on chaotic advection in flow between two confocal ellipses, which perimeters are rotating in a periodic manner and allowed a good chaotic mixing pattern [25]. Further developments based on the classical eccentric cylinder form (Journal Bearing Flow) which indicate a two-rod mixer, have been studied by many researchers [26–28]. This apparatus was constructed by Jana et al. [26]. For constant angular velocities of all cylinders, there are many more possible streamline portraits in this flow. The two-rod mixer is an interesting option to have a full chaotic flow without integrable zones delimited by the presence of Kolmogorov–Arnold–Moser tori. This geometry presents also similitudes with an idealization model presented by Aref composed of a blinking vortex [8].

Ghosh et al. [29] numerically studied the enhancement of cross-stream heat transfer by forced oscillations of Stokes flow in an eccentric annulus mixer. They investigated the counter-rotating case, assumed that the angular velocity of the inner cylinder has a sinusoidal profile versus the time, and found the existence of an optimum frequency for maximum transport enhancement. Saatdjian et al. [25] carried out similar flow geometry, by considering the annular zone between two concentric, confocal ellipses. It was indicated that for steady counter-rotation of the two ellipses, the recirculation zones could improve to 80% heat transfer mechanism over pure conduction at high Peclect numbers. This improvement has the potential to achieve up to 100% if one of the ellipses undergoes a suitable sinusoidal modulation of the angular velocity. In chaotic system that involves two rods mixer, El Omari et al. [30] investigated numerically the thermal efficiency in the case of high Prandtl number fluids. They found that, to maximize the efficiency, discontinuous modulations over time should be used which means that the rod rotation is interrupted when the tank is rotating and so on.

Recently, Bahiraeia and Hangi assessed hydrothermal characteristics of water–TiO_2 nanofluid in rectangular C-shaped chaotic channel by applying the two-phase Euler–Lagrange method [31]. A neural network model has been applied to the optimal convective heat transfer coefficients and pressure drops. Also, the same authors studied the energy efficiency and flow properties of a non-Newtonian nanofluid comprising TiO_2 nanoparticles in a chaotic geometry [32]. The main finding was that using nanofluid allowed better cooling and a Figure of Merit higher than 1 at low Reynolds number was reported.

This study is dedicated to the numerical investigation of chaotic advection and heat transfer enhancement by a laminar flow in different cylindrical mixers. The novelties of the current study are the followings:

– Tests have been carried out for two velocities profiles of the rods and the tank
– While previous investigations were limited to two rods, the present work investigates the case of multi rods and discusses the impact of increasing their number
– Different combinations of rotating directions have been as well studied.