EXPERIMENTAL AND NUMERICAL STUDY OF CHAOTIC MIXING IN A CURVED-SQUARE DUCT FLOW

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Abstract Chaotic mixing in a curved-square duct flow is studied experimentally and numerically. Two walls of the channel (inner and top walls) rotate around the center of curvature and a pressure gradient is imposed in the direction of the exit of the channel. There are two parameters dominating the flow, the Dean number De ($\propto$ the pressure gradient and the Reynolds number) and the Taylor number Tr ($\propto$ the angular velocity of the wall rotation). It is found that good mixing occurs for very low Dean numbers (low Reynolds numbers) if $De \leq 0.1\ |Tr|$ because Lagrangian chaos occurs for that case. The flow is studied both experimentally and numerically which agree with each other very well. The mechanism of chaotic mixing is investigated by observing the entanglement process of streamlines.

BACKGROUND AND OBJECTIVES OF THE STUDY

Recently, a great attention has been paid to the development of a micro-chemical-analysis device called μ TAS(Micro Total Analysis Systems) in the field of the engineering. This device, which consists of various micro-flow devices and sensors, functions in a series of operation such as mixture, reaction, separation and extraction. However, the flow is in the low Reynolds number region because of the micro-size of the channel, so that physical mixing by turbulence cannot be expected without a special artifice. Now a micromixer is needed to mix low Reynolds number flows efficiently. Stroock et al.[1] studied a micromixer generating secondary flows in a channel by carving a ditch on the channel wall surface. Kim et al. [2] also studied a micromixer using a similar method. Sato et al. [3] made a micromixer which generates stronger secondary flows by carving ditches on the three wall surfaces of the channel. It is been shown that these methods are effective when the flow velocity is fast, though the pressure loss becomes a serious problem in this case. On the other hand, a micromixer which uses the chaos of the flow was studied by Niu et al. [4] and Tabeling et al. [5]. It was shown that the flow is miscible within a relatively short channel distance from the inlet compared with that by the mixing using only secondary flows.

We then proposed a micromixer making use of the chaos of the secondary flow, specifically one in which the secondary flow becomes chaotic through a curved channel where two walls of the channel rotate [6]. In the present paper, we analyze the physical mechanism of the chaotic mixing in the rotating curved-duct flow by comparing experimental and numerical results. We produced a micromixer model of the curved channel several centimeters long with square cross-section of a few millimeters side as shown in Fig.1(a), (b). The secondary flow was measured using PIV (Particle Image Velocimetry) and LIF (Laser Induced Fluorescence) methods to examine secondary flow characteristics. We also performed three-dimensional numerical simulations for the exactly same configuration as the experimental system to study the mechanism of chaotic mixing and the occurrence of Lagrangian chaos [7].

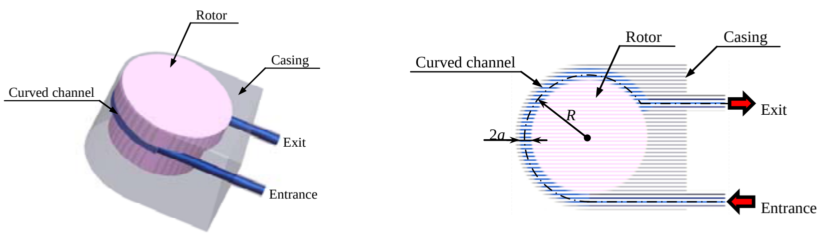

Figure 1. Experimental Setup
(a) Bird's eye view of the test section. (b) Top view of the test section.

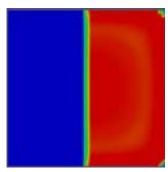

Figure 2. Two fluids at the entrance. Right side is the center of curvature of the duct and dyed by rhodamine B.

RESULTS

The test section consists of two parts, i.e., the rotor and the casing as shown in Fig.1. The channel is formed of the casing and the rotor where the upper wall and right (inner) wall of the channel rotate. The experiment was carried out in the range of *De* from 0 to 10 and *Tr* = 0, 3 and -3. Two working fluids (70wt% of glycerol aqueous solution and 70wt% of glycerol aqueous solution dissolving rhodamine B at the 2.5 ppm concentration) flow into the curved channel, the test section. At the entrance of the curved section, two fluids are completely separated side by side (Fig.2). In Fig.3(a), the flow is viewed by LIF in the cross-section at 180 degree downstream from the entrance for *De* = 0.3 and *Tr* = 3, where the two walls rotate in the same direction as the mean flow. The bar light and shade display on the right-hand side shows concentration of the glycerol aqueous solution including rhodamine B. It is seen that there is very little area of concentration 0% (glycerol aqueous solution) or 100% (glycerol aqueous solution including rhodamine B) where two fluids are not mixed, and two fluids are mixed very well. We performed three-dimensional numerical simulations for the same configuration as the experiment. Fig.3(b) shows the result of the numerical simulation for *De* = 0.3 and *Tr* = 3 at the same position of the experimental visualization. Red color shows the region with high rhodamine B and blue color that with low rhodamine B. Fig.3(b) is very similar to Fig.3(a) and thus the simulation is found to be accurate. By an extensive experimetal and numerical study over *De* and *Tr*, it is found that very good mixing is achieved for $De \leq 0.1 |Tr|$. It should be remarked that the two walls rotate in the opposite direction to the mean flow for *Tr* < 0. If *De* increases, the area of good mixing reduces rapidly.

In order to study the physical mechanism of the mixing, we traced fluid particles regularly put at the entrance where fluid particles are aligned on the three vertical (parallel to the axis of rotation) lines by the numerical simulation. Fig.3(c) shows the trances of fluid particles on the same cross-section as Fig.2 for a long time. It is found that fluid particles spread over the nearly whole cross-section. Numerical simulations show that this is associated with the entanglement process of streamlines and Lagrangian chaos occurs for this case. It is interesting that the experimental results show the secondary flow manifests weak unsteadiness when Lagrangian chaos occurs.

Finally we calculated the mixing efficiency of the fluid, *M*,which is defined as

$$M = 1 - \frac{1}{\overline{C}}\sqrt{\frac{\Sigma(C_i - 0.5)^2}{N}} \quad , \qquad \overline{C} = \frac{\Sigma C_i}{N} ,$$

where C_i is the volume fraction at the *i* th nodal point and *N* is the total number of the grids [8]. If no mixing occurs, *M* = 0, while *M* = 1 for the case of perfect mixing. Numerical results show that *M* attains 0.4 for *De* = 0.3 and *Tr* = 3. In conclusion, it is found that the present system can achieve good mixing for the very low Reynolds number fluid.

(a) (b) (c)

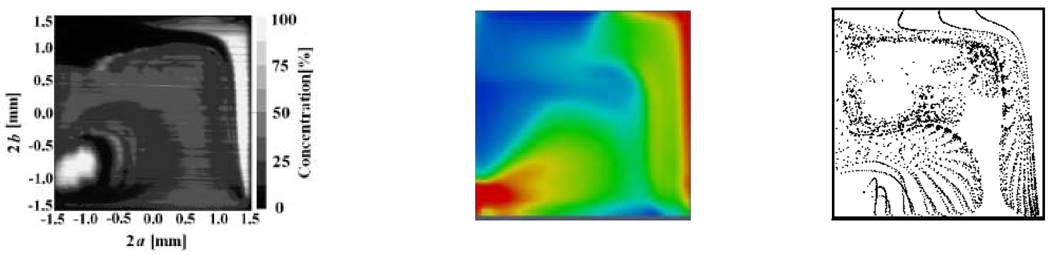

Figure 2. Mixing of two fluids in the cross-section of the curved duct
at 180 degree downstream from the entrance for *De* = 0.3 and *Tr* = 3.
The concentration distribution in the cross-section by (a) Experiment (LIF) and (b) Numerical simulation.
(c) Traces of the fluid particles regularly put at the entrance.

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