단축압출공정의 카오스 혼합에 대한 유동가시화

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Flow Visualization of Chaotic Mixing in a Single Screw Extrusion Process

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Introduction

In this study, we present experimental flow-visualization results and comparative numerical investigations on chaotic mixing in the Chaos Screw (CS) system. The objective of the study is to verify existence of dynamical structures by identifying their three-dimensional configurations and to see sequential growing and destruction of them according to the perturbation strength β. (Refer to Hwang & Kwon [1-2] for detailed description of the CS system, related theories and dynamics; see also Hwang et al.[3] for the extended form of this study.) An experimental apparatus will be described first and three-dimensional flow visualization results are to be shown. Then, periodic structures and the effect of perturbation on the dynamical structures of the CS system are explained using three-dimensional experimental deformation patterns. In the comparative numerical study, we indicate how the observed phenomena in the experiments can be verified and explained by the full three-dimensional numerical simulations. The numerical results show more detailed structures including weak small-scale resonance structures and variety of KAM tori structures.

Experiments

(i) Setup

In experiments, we designed and made a simulator that visualizes three-dimensional mixing patterns in the CS channel. Fig. 1 indicates schematic diagram of the simulator and a real picture of the experimental setup. The simulator is composed of four main parts; i) transparent grooved channel and core barrier parts with various perturbation values, ii) the motor-driven oblique slider with AC motor and chains, iii) two fluid reservoirs, a valve and a drain to maintain a constant flow rate, and iv) two CCD cameras and an image grabbing system.

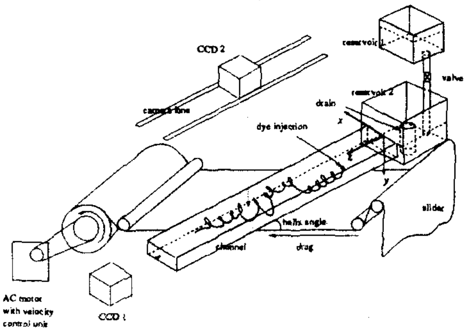

Fig. 1 Schematic diagram (left) and real setup (right) of experimental apparatus.

Working fluid is 1000cs silicone oil (Shinetsu Silicone Co., Japan), a high viscous Newtonian fluid. Viscosity μ is 0.974 Pa·sec and density is 0.967 g/cm^3. The dye material used in the experiment is also blue-colored 1000cs silicone oil (KE BL70) manufactured by the same company. Viscosity and density of dye are the same as the working fluid. Thus we expect neutrally buoyant distributive mixing patterns in the experiment. Using the characteristic velocity V_d and the characteristic length scale H, the Reynolds number Re in the experiment can be expressed and evaluated as $Re= \rho V_d H / \mu = 1.462$. The Reynolds number of $O(1)$ has been known as the best compromise to avoid both dye diffusion and inertial effect [4].

(ii) Resonance band of period 1/2

Identifying periodic structures from the deformation patterns is not an easy task especially in the three-dimensional systems, since they are superposed (subharmonic) motions. The resonance band is a representative periodic structure and, by its definition, is a banded region (an annulus in 3D) where most of the orbits have the same rational winding number. We say "most", because there can be some transports into or out of the resonance band. But these transports are very slow process and cannot be found in the relatively small finite-time (or finite-period) experiment. Hence, we can say that all the orbits in the resonance band have the same frequency in the experiment so that the deformation patterns in the region should be invariant at all the periods. Let us investigate experimental results shown in Fig. 2 where the corresponding value of perturbation strength is 0.025. The deformation patterns near the rotation center remain unchanged and are perfectly identical. One can say that the time-periodic structure found in the cross-sectional patterns must be a resonance band, because the deformation patterns remain unchanged only in the resonance band. Recall that, as time goes on, one never obtains the same deformation patterns in the nonlinear rotation at any period, because two neighboring stream surfaces always have different periods. The only possibility of having periodically invariant pattern is that there is a "linearly rotating" annulus that encloses the pattern, and this is definitely the resonance band.

(a) t=19+1/15 sec. (b) t=21+6/15 sec. (c) t=23+12/15 sec.

(d) t=26+3/15 sec. (e) t=28+8/15 sec. (f) t=30+14/15 sec.

Fig. 2 Continuous cross-sectional deformation patterns that indicate a periodic structure with period t=2.3 (approx.).

(iii) Effect of perturbation strength

One can expect smaller KAM torus and larger chaotic region to be present and resonance band to be destroyed, as the strength of perturbation increases. Cross-sectional deformation patterns under 6 distinct perturbation values β after 30 seconds are shown in Fig.3. It is evident that, as the perturbation increases, chaotic region expands its size and simultaneously the KAM torus shrinks. As mentioned earlier, KAM torus can be identified by the empty region in the right side of barrier and, at the same time, the colored region in the right side indicates chaotic region due to homoclinic tangle. The results are summarized in Figure 4.

(a) $\beta = 0$ (unpert.) (b) $\beta = 0.025$ (c) $\beta = 0.1$

(d) $\beta = 0.15$ (e) $\beta = 0.2$ (f) $\beta = 0.3$

Fig. 3 Cross-sectional deformation patterns that indicate the effect of perturbation strength β.

Numerical Study

Numerical investigations of chaotic dynamics in CS have been studied through Poincaré section methods. To obtain the Poincaré sections, we evaluated perturbed velocity fields and then integrated them with respect to time using the 4th order Runge-Kutta method [2]. We studied four small perturbed cases: (a) β=0.025, (b) β=0.1, (c) β=0.15 and (d) β=0.2. The values are selected for comparison to the experimental results.

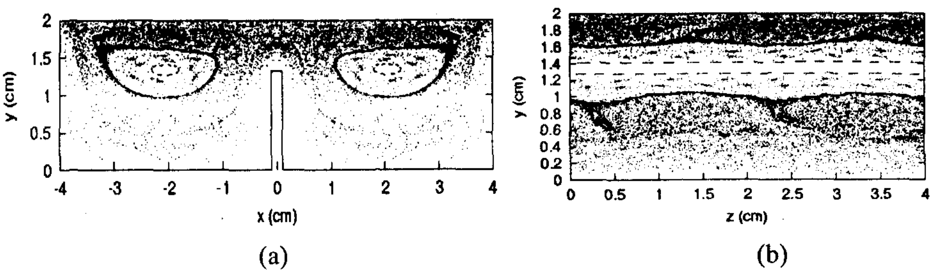

Fig. 4 Poincaré sections for β=0.1: (a) Cross-sectional Poincaré section; (b) Longitudinal Poincaré section

In Fig.4, the associated elliptic points of the period-1/2 resonance band are clearly shown. From the longitudinal Poincaré section (Fig.4b), the four elliptic dead spots are arranged in a completely periodic manner such that two dead spots above the KAM torus and the other two dead spots below the KAM torus. Taking any 2-centimeter-long unit in the longitudinal direction, one can obtain completely periodic structure: The unit has one elliptic point each above and below the largest KAM torus.

References

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