INTERMITTENT FLOW IN STIRRED YIELD STRESS FLUIDS SLOWS DOWN CHAOTIC MIXING

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Summary Chaotic advection at low Reynolds number mixes fluids via stretching and folding of fluid particles. We investigate chaotic advection of yield stress fluids when mixed using a protocol designed to enhance topologically-complex motion. We quantify the scalar field of dye concentration and its structure. The boundary of the chaotic region is characterized by a lobe-shaped intermittently flowing region which dominates the mixing dynamics.

INTRODUCTION

Mixing at low Reynolds numbers is observed in many physical systems. For example, mixing of molten glass, delicate pharmaceutical suspensions, and slow geophysical processes are all dominated by viscosity. In the absence of turbulence, mixing occurs through repeated stretching and folding of the fluid until the folded layers of fluid are of the scale of the diffusion length. This type of mixing is termed chaotic advection [1]. Much research has focused on experimental and analytical descriptions of chaotic advection in Newtonian systems, however many physical systems have non-Newtonian properties. The research described in this paper is an experimental analysis of chaotic advection using yield-stress fluids via a protocol designed to enhance topological chaos.

Background

Chaotic advection came into the fluid mechanics literature in the early 1980s. Since then, numerous papers have been published detailing the results of chaotic advection in a variety of mixing scenarios. The topology of the stirring protocol is very important to the resulting efficacy of mixing. For example, it has been shown that increasing the area of topological chaos via multiple stirring rods can dramatically increase mixing efficiency when pseudo-Anosov motions are used (resulting in a “braiding” of the fluid elements as opposed to a more straightforward circular mixing) [2]. Wall conditions are also important. A no-slip condition at the vessel wall has been shown to slow down the entire mixing process for Newtonian fluids and in general, the regions of slowest stretching control the rate of mixing [3]. Additionally, recent publications have shown that the yield-stress value of non-Newtonian fluids influences the mixing properties. However, these works focus on simple mixing protocols, such as impeller systems or cavity flows [4,5]. The work presented in this paper uses an egg-beater style mixing protocol that enhances topologically-complex motion of the fluid to further investigate chaotic mixing in yield stress fluid systems. We quantify the time-dependent scalar field of the dye concentration in the chaotic region and investigate the region’s structure.

EXPERIMENTAL APPARATUS

An experimental apparatus was designed to study chaotic mixing. It consists of a mixing vessel 14 cm in diameter, 11 cm deep, into which four mixing rods are inserted. The rods are moved as pairs, each pair rotating around an offset axis. Also, the vessel walls are rotated. The mixing motions of the rods and the vessel wall are shown schematically in Figure 1a. Since the substrate is a yield stress fluid, the fluid near the walls is only sheared when one of the stirring rods comes close to the wall. By rotating the vessel, more of the fluid at the edges comes into close contact with the mixing rods, improving the homogeneity of stretching. Images of the apparatus are in Figures 1b and 1c.

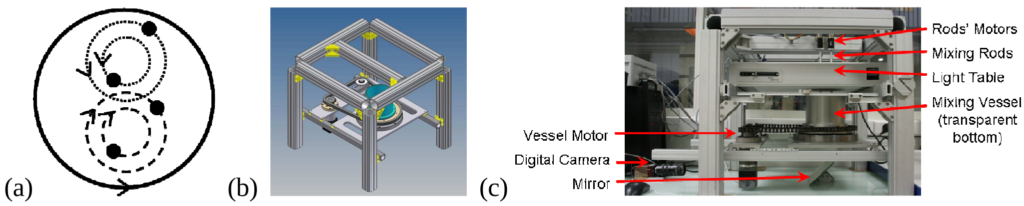

Figure 1: (a) Mixing protocol. (b-c) Experimental apparatus.

The control parameters of the apparatus are the speed of the mixing rods, the speed of the vessel walls, and the fluid properties of the substrate. In the experiments, the yield stress fluid is Carbopol EZ-3. To study the efficacy of mixing, each experiment begins with injecting a large blob of coloured fluid into the same clear fluid in the mixing vessel. India ink is used to create the coloured blob. After injecting the coloured fluid, the experiment begins and the stirring rods and vessel walls begin to move. Images are captured via a digital camera once per cycle. The amount and variation of dye in

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a sample area of the mixing vessel are quantified as a function of mixing periods via image analysis using the Beer-Lambert method. Also, the presence of edge-effect lobes is investigated.

RESULTS

Starting from a sample with two different colour fluids, the mixing procedure mixes the two regions of the substrate to create areas of nearly homogeneous colouration. A time sequence of one experiment is shown in Figure 2.

Figure 2: A time sequence of mixing for 0.1% solution of Carbopol EZ-3, which has a measured yield stress of 2.5 Pa. The time between images is 4 periods.

As seen in Figure 2, chaotic advection is mixing via exponential stretching of the fluid. However, the stretching is heterogeneous. The fluid particles near the centre of the vessel are stretched frequently by the rods and the thickness of the layers quickly reaches the diffusion length. However, lobes of infrequently-stretched fluid are observed at the boundary of the chaotic region (Figure 3a). These lobes experience intermittent stretching because of the yield-stress properties of the fluid. In our geometry, the stress is lowest at the walls (as it would be in Couette flow). In the Newtonian case all of the fluid is sheared all of the time during stirring, although with various stresses. In the case of a yield stress fluid, the fluid close to the walls only flows when a rod passes nearby and imparts enough stress to overcome its yield criterion. Therefore, the majority of the time, the fluid near the wall is not stretched and inhomogeneities persist in this region. These inhomogeneities propagate through the whole chaotic region and lead to a very slow decay in the variance of the dye concentration, as shown in Figure 3b. This behaviour is not observed in Newtonian fluids of similar viscosity (Figure 3c). The number of lobes is well-predicted by a ratio of the period of the outer vessel wall to the period of the mixing rods (Figure 3d), further indicating the importance of the shear between the wall and the rods.

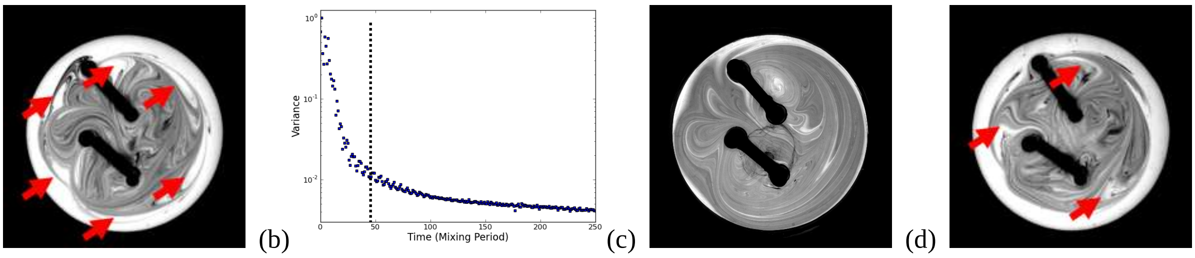
(a) 

Figure 3: Comparison of yield stress and Newtonian fluid mixing.(a) Yield stress fluid, 0.1% Carbopol EZ-3. Note presence of poorly-mixed lobed regions (red arrows). (b) Variance of dye concentration as a function of mixing period. The initial mixing (left of dashed line) indicates mixing of the bulk of fluid, however the slow decay to the right of the dashed line shows the influence of the slowly-mixing lobed regions. (c) Newtonian fluid, cane sugar syrup. Note the lack of lobed edges. (d)Period ratio of 3 results in 3 lobes in yield stress fluid.

CONCLUSIONS

The differences between Newtonian and non-Newtonian chaotic advection have important consequences for mixing technologies. This research has found that yield stress fluids have a larger the boundary layer and it is characterized by lobe-shaped unmixed sections, indicating that yield stress fluids do not mix as easily as Newtonian fluids via chaotic advection. These slow-stretching lobed regions slow down the entire mixing progress as they slowly propagate through the chaotic region. Research is ongoing to characterize the size of the lobes and decay rate of the concentration field as a function of yield stress.

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