EXPERIMENTS ON TURBULENCE MODULATION BY SURFACTANT ADDITIVES IN A PRECESSING SPHERE

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ABSTRACT

To investigate the physical mechanism of turbulence modulation due to a small amount of surfactant additives, which constitute thread-like micelles in a solution, we conduct well-controlled laboratory experiments. More concretely, using the precession of a vessel to drive the flow of a fluid confined within its spherical cavity (the radius, a, of which is 90 mm), we have constructed an experimental platform with high reproducibility of flow states being ensured. Using this platform, we conduct experiments on turbulence modulation in a dilute (50 ppm) solution of a cationic surfactant (cetyltrimethylammonium chloride; CTAC). When the Reynolds number, $Re = a^2\Omega_s/\nu = O(10^4)$, where Ω_s and ν are the magnitude of the spin angular velocity and the kinematic viscosity of the confined fluid, the turbulence intensity is, indeed, significantly reduced, but the turbulence modulation occurs locally in space. On the other hand, in this range of Re, the surfactant additive hardly affects the transition process from steady to unsteady flows. Namely, this turbulence modulation due to the surfactant additive appears under rather limited conditions. Therefore, these experimental observations will help us to reveal the physical mechanism of the turbulence modulation.

INTRODUCTION

A small amount of surfactant additives can drastically reduce turbulence intensity. This effect is well known (Zakin *et al.*, 1998), but its mechanism is not fully understood probably because systematic experiments on the effect are not necessarily easy to conduct due to its nontrivial dependence on various fluid parameters and flow conditions. Since the drag reduction by surfactant additives is particularly important in engineering applications, turbulence modulation due to surfactants has been extensively investigated for pipe flows (Gasljevic *et al.*, 2001; Hadri *et al.*, 2011), channel flows (Li *et al.*, 2005, 2008) and boundary layer flows (Tamano *et al.*, 2009). However, flow conditions of such open systems are generally difficult to control. Furthermore there remain unsolved problems such as sub-critical transitions to turbulence in these flows even for Newtonian fluids (Eckhardt *et al.*, 2007).

In this paper, we propose a new (closed) experimental platform to tackle this complex phenomenon (i.e. turbulence modulation by surfactant additives). More specifically, we use a precessing sphere (Fig. 1) where the word *precessing* denotes the rotation of the spin axis of a rotating object. It is well-known since the pioneering experiment by Malkus (1968) that weak precession of a vessel sustains strong turbulence of a fluid confined in its smooth cavity; see our recent experimental studies (Goto *et al.*, 2007, 2014*a*) and references therein for more details.

We emphasise that this flow system has the following advantages, if the confined fluid is Newtonian. (i) Only two dimensionless parameters,

$$Re = \frac{a^2\Omega_s}{\nu} \quad \text{(the Reynolds number)} \tag{1}$$

and

$$Po = \frac{\Omega_p}{\Omega_s} \quad \text{(the Poincaré number)}, \tag{2}$$

control the flow state. Here, a is the radius of the sphere, Ω_s and Ω_p are the magnitudes of the spin and precession angular velocities, respectively, and ν is the kinematic viscosity of the fluid. Since $\{Re, Po\}$ are easily controllable using precise motors and their controllers to drive the two rotations, this system possesses excellent flow reproducibility in the laboratory. (ii) Our experiments (Goto *et al.*, 2014*a*) have revealed details of flow dependence on $\{Re, Po\}$. For example, the most developed turbulence for a fixed Re is sustained when $Po \approx 0.1$ irrespective of Re. (iii) Since the boundary condition is simple, one can conduct direct numerical simulations (DNS) under the same condition as in the laboratory (Goto *et al.*, 2014*b*).

Thus, for Newtonian fluids, flow features in a precessing sphere (such as the critical parameters for turbulence sustainment, and the mean velocity and intensity of the sustained turbulence) are well established already. Then, the strategy and goal of the present study are the following: precisely investigating the effect of a small amount of surfactant additives on turbulence in a precessing sphere, we reveal the mechanism of the turbulence modulation due to surfactant additives.

EXPERIMENTS

It is easy to drive the precession of a vessel in the laboratory. We rotate a vessel with a spherical cavity (whose radius is 90 mm) filled with a fluid with a constant angular velocity $\boldsymbol{\Omega}_s$ on a turntable which also rotates with a constant angular velocity $\boldsymbol{\Omega}_p$ (see Fig. 2).

In contrast, we had to overcome several hurdles for accurate measurements. We employ particle image velocimetry (PIV) and laser Doppler velocimetry (LDV), for both of which we must avoid the refraction of lights on the surface of an acrylic vessel. So we use a cylindrical vessel

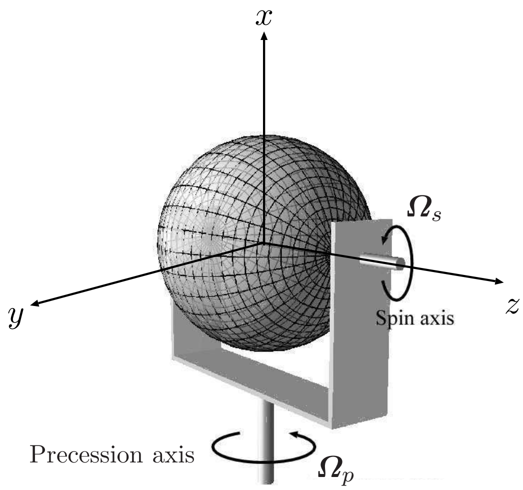

Figure 1. Precessing sphere. The spin and precession axes are at a right angle. The coordinate (x, y, z) is fixed in the precession frame, which rotates at a constant angular velocity, $\boldsymbol{\Omega}_p$.

with a flat bottom, through which measurements are conducted (Fig. 2). In addition, we place a laser devise for PIV and a signal analyser for LDV in the laboratory because they are too large to be installed on our turntable. Using the fact that the rotation axis of the turntable (the *x*-axis in Fig. 1) is the fixed line both in the rotating frame and the laboratory frame, the incident laser beam for PIV and the scattered light for LDV are communicated along this line (details of PIV measurements are described in Goto *et al.* 2014*a*). Thanks to these techniques, we are able to conduct accurate PIV and LDV measurements of flows in the precessing sphere.

We investigate turbulence modulation by a dilute (50 ppm) solution of a cationic surfactant (cetyltrimethylammonium chloride; CTAC). When this surfactant forms thread-like micelles, it can modulate turbulence. Therefore, the molar ratio *M* of counterions (here we use sodium salicylate) to the surfactants is an important factor, and we set $M = 2$. Since properties of the surfactant solution are sensitive to its temperature, we have installed a precise temperature controller for the space surrounding the apparatus so that the fluid temperature can be kept at 20.0 ± 0.1 degrees Celsius.

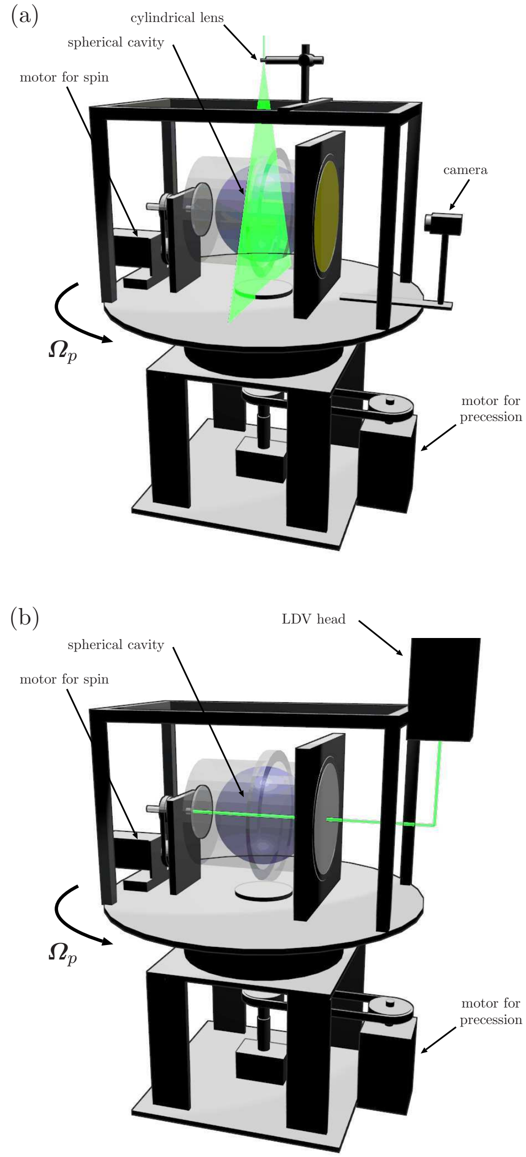

Figure 2. Experimental apparatus for (a) PIV and (b) LDV. The outer shape of the container is cylindrical so that we can make measurements through the bottom flat window. Note also that the camera for PIV and the LDV head are fixed on the turntable.

RESULTS

We conducted two kinds of series of experiments. One is the measurement of temporally averaged velocity field to investigate the space-locality of turbulence modulation by the surfactant additive. The other is the measurement of the time-series of velocity at a fixed point to investigate the effect of the surfactant additive on the transition from steady flows to turbulence.

Mean velocity field

First, we show results on the modulation of the most developed turbulence sustained at the Poincaré number, $Po = 0.1$. We measured turbulent velocity fields on the equatorial plane using PIV to evaluate its temporal average over about 100 spin periods. Results for the three different values of the Reynolds numbers ($Re = 2.0 \times 10^4$, 4.0×10^4 and 8.0×10^4) are shown in Fig. 3.

Figure 3 shows that, although the surfactant solution is very dilute (50 ppm), the mean velocity is significantly reduced in a central region of the sphere. We can also see in Fig. 4 that the turbulence intensity, which is defined by the rms value of a velocity component normalised by the wall velocity, $a\Omega_s$, on the equatorial plane, is also drastically reduced in the central region. It is also remarkable in Fig. 3 that the turbulence reduction occurs irrespective of *Re*, but the region of reduced turbulence expands with the increase of *Re*.

Interestingly, however, the turbulence examined in

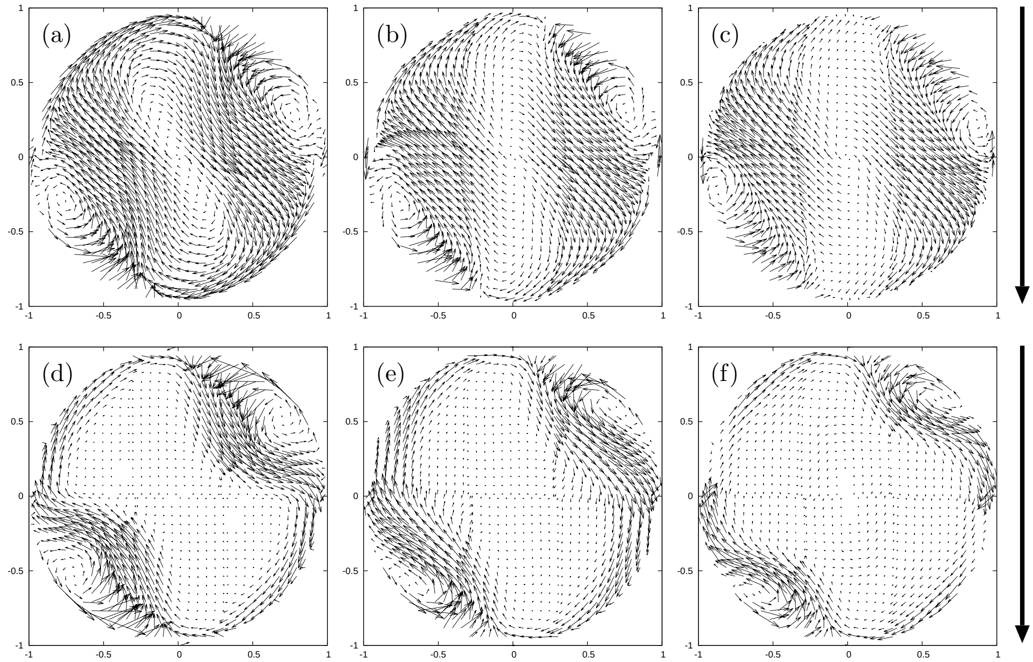

Figure 3. Temporally averaged velocity field on the equatorial plane. Three cases with different values of the Reynolds number [(a)(d) $Re = 2.0 \times 10^4$, (b)(e) 4.0×10^4 and (c)(f) 8.0×10^4] are examined for a fixed Poincaré number at $Po = 0.1$. Results for (a)(b)(c) water and (e)(f)(g) the CTAC solution (50 ppm). The thick arrow indicates the wall speed on the equatorial plane.

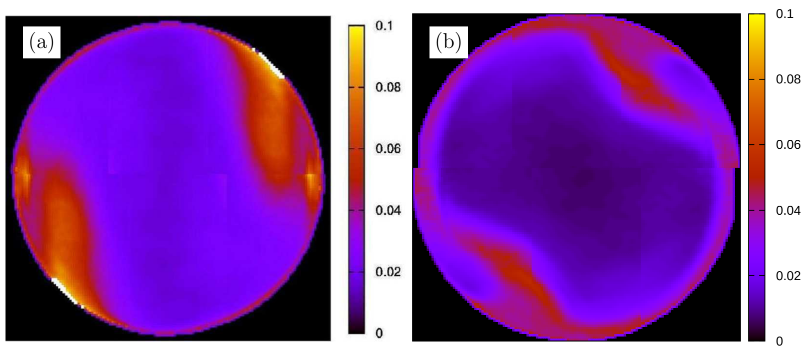

Figure 4. Turbulence intensity, which is defined by the rms value of y-component velocity normalised by $a\Omega_s$, for the case that $Re = 8.0 \times 10^4$ and $Po = 0.1$. Results for (a) water and (b) surfactant (CTAC 50 ppm) solution.

Figs. 3 and 4 is hardly affected in the near wall region. In particular, the vortices observed in the left-bottom and right-top regions of Fig. 3 are almost unchanged. According to our DNS (Goto *et al.*, 2014*a,b*) of a Newtonian fluid, these large-scale vortices (which compose a ring-like structure in three-dimensional space) are the source of the strong turbulence sustained for this parameter ($Po = 0.1$). It is therefore intriguing that even though these large-scale vortices are unaltered, turbulence in a central region of the sphere is drastically reduced. This spatial locality of turbulence modulation must be a key for the understanding of its physical mechanism.

Incidentally, the value of Re for the flow of the surfactant solution is estimated using the value of the kinematic viscosity of water at the same temperature. Although the kinematic viscosity of the surfactant solution is actually larger than that of the water, the inhomogeneous turbulence modulation observed in Fig. 3 cannot be explained only by a uniform increase of the viscosity.

Transition to turbulence

Second, we investigate the transition from steady to turbulent flows by using LDV. A forte of this system is that weak precession drives turbulence in a smooth cavity. For example, at $Re = O(10^4)$, the flow of a confined Newtonian fluid becomes turbulent when $Po \gtrsim 0.01$. To examine whether or not this feature is changed by the surfactant additive, we measured the time-series of the y-component velocity (see Fig. 1 for the definition of coordinates) at a point in the sphere, and evaluated its power spectrum, $S(\omega)$, for a fixed Po and increasing Re. The first Hopf bifurcation is

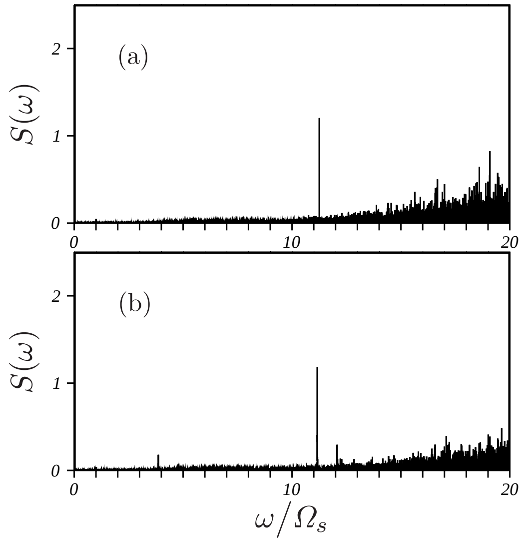

Figure 5. Power spectrum at the first Hopf bifurcation in the transition regime for $Po = 0.01$. (a) Water at $Re = 1.7 \times 10^4$. (b) Surfactant solution (CTAC, 50 ppm) at $Re = 2.0 \times 10^4$. Recall that Re of the surfactant solution is evaluated by using the value of ν of water at the same temperature.

observed at almost the same *Re* both for water [Fig. 5(a)] and for the surfactant solution [Fig. 5(b)]. Furthermore, the most unstable mode is also similar with the angular frequency being about $11\Omega_s$. We have also examined other values of *Po* to conclude that the surfactant additive does not change significantly structures of the steady flow and its instability in the low-*Po* range.

CONCLUSION

By using the precession of a spherical cavity (whose radius is 90 mm) and PIV/LDV techniques, we constructed a new experimental platform to tackle the unsolved issue of the turbulence modulation by surfactant additives. To demonstrate the utility of this platform, we examined the effect of dilute surfactant solutions (CTAC, 50 ppm) on the turbulence. The PIV analyses show that turbulence intensity is drastically reduced in a central region, but the coherent large-scale vortical structures near the boundary are unchanged; whereas the LDV analyses show that the surfactant additive does not change the instability leading to turbulence.

These experimental results imply that turbulence modulation due to the surfactant additive occurs under rather limited conditions. We expect that these findings are useful to develop a first-step argument on the physical mechanism (in terms of the shear-thinning viscosity, elastic effects, so-called shear-induced structures, extensional viscosity, etc.) of the turbulence modulation by the surfactant additives.

We are now further conducting systematic experiments for various parameters so that we can present, at the conference, overall results on the turbulence modulation in the precessing sphere. In addition, by the help of DNS, we shall discuss the physics which may explain the observed phenomena.

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