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Experimental Study of Non-colloidal Mono and Polydisperse Suspension in Taylor-Couette Flow

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ABSTARCT

Monodisperse and polydisperse suspension flows form an extensive section of natural and technological flows. These flow structures can be categorized to sedimenting or neutrally buoyant suspensions considering the density ratio between particle phase to dispersion phase. Biological systems, food processing, ceramic injection, dynamic filtration and air conditioning are examples of areas that such flows arise. Various complicated interparticle interactions and their inevitable influence on and from the continuous phase result in some interesting phenomena which are challenging to justify. This research studies axial instabilities of suspension flow in a partially filled Taylor-Couette setup. Previous observations show that when a monodisperse suspension undergoes a rotational shear motion in a partially filled horizontal Couette cell, particles leave their initial uniform distribution and migrate to regions with lower shear rate. This migration helps formation of ring-shape axial concentrated bands. This study examines the noncolloidal neutrally buoyant suspensions of hard spherical particles with average diameters of 150, 360, 850 micron. Using UCON oil (poly ethylene glycol-ran-glycol) as suspending fluid, monodisperse and polydisperse suspensions in partially filled Stokesian Couette-Taylor flow were studied. The results show strong dependence of band number and profile on suspension concentration and filling level. Moreover interesting phenomena in polydisperse suspensions such as different band shape and weak dependence of band formation time on size of constituents were observed.

INTRODUCTION

The linear stability of fully-filled circular Couette flow of Newtonian fluid in an annulus between a rotating inner cylinder and a concentric, fixed outer cylinder has been studied theoretically and experimentally. The instability appears as pairs of counter-rotating, toroidal vortices stacked in an annulus. Chandrasekhar [1], DiPrima et al. [2], Kataoka [3], and Koschmeider [4] accomplished the first analytical studies in a narrow gap disturbed by axisymmetric perturbations. They provide extensive summaries of the abundant researches on this topic since the path-breaking work of Taylor [5]. However, the stability of Taylor vortex flow is altered when solid particle is added to the system. Typical approach in such circumstances has been to treat the suspension as a fluid with effective properties which change with particle concentration in suspension.

Nearly all researches on the stability of cylindrical Couette flow have been done for Newtonian fluids. In the

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case of non-Newtonian fluid, stability of a viscoelastic fluid in Taylor–Couette flow has been investigated by Larson [6]. Using a simple viscoelastic constitutive equation, Khayat [7] found that the flow is destabilized as the fluid elasticity is increased. However, experimental results indicate both stabilizing and destabilizing effects of viscoelasticity, depending upon the polymer solution used. Fewer studies have addressed a suspension as a complex fluid in cylindrical Couette flow. Nsom [8] carried out a stability analysis for a suspension of rigid fibers using rheological coefficients in the stress tensor to account for the non-Newtonian effects. Results indicate that increasing the concentration of fibers increases the stability of the system. Yuan and Ronis [9] considered the stability of colloidal crystals in cylindrical Couette flow using a Stokes drag interaction between the particles and the fluid. Although the Taylor instability is suppressed as the colloidal crystal lattices become more rigid, other lattice instabilities appear. Dominguez-Lerma et al. [10] detected a non-periodically time-dependent non-uniformity in the size of the vortices when a low concentration of flakes was used to visualize Taylor–Couette flow in vertical apparatus, but they did not state how the flakes affected the critical Taylor number. Ali et al. [11], found that at a given radius ratio, the theoretical critical Taylor number at which Taylor vortices first appear decreases as the particle concentration increases. They also showed that, increasing the ratio of particle density to fluid density above one decreases the stability. In addition, the axial wave number is the same for a suspension as it is for a pure fluid.

Particle-laden shear flows are important in a wide variety of applications including hydraulic fracturing technology, processing of solid-rocket propellants, ceramics and reinforced polymer composites, and the transport of slurries. Successful use of suspensions in engineering processes often requires that a flowing suspension be supplied at a specified location with a prescribed particle concentration. As applications grow increasingly, complex design specifications become more crucial and adjustments must be made to reach the desired specifications. Ultimately, the behavior of the flowing suspension must be better understood in order to effectively control particle concentrations throughout an application process.

The instability of suspension flows with neutrally buoyant particles in free surface flows have been widely observed experimentally. However in free-surface suspension flow generated by partial filling of a concentric-cylinder apparatus a remarkable phenomenon occurs. In particular, we note the occurrence of axial instabilities which result in formation of axial concentrated bands. These instabilities can be associated with particle-scale phenomena such as fluid surface tension on the particle surfaces and normal forces. Tirumkudulu et al. [12] and Timberlake and Morris [13] reported axial banding instabilities in partially filled Couette devices in shear flow, whereas Timberlake and Morris [14] saw ribbing-type instabilities in suspension films on an inclined plane. Tang et al. [15] observed viscous fingering in a radial Hele–Shaw cell of a neutrally buoyant suspension. Linear stability theory has been used to understand rimming flows in partially filled Couettes with free surfaces for neutrally buoyant particles [16], flow down an inclined-plane for non-neutrally buoyant particles [17], and flow in an inclined settler [18]. Linear stability in a fluidized bed at the dilute limit has been investigated by Hernandez [19], who determined that instabilities occur as suspensions reach higher concentration due to flow. Spectral simulations from this work showed Rayleigh–Taylor-like instabilities at the unstable conditions predicted from the linear analysis. Similar instabilities have been observed in inclined batch settlers where vortices appear at the suspension–pure fluid interface. These instabilities have been analyzed with analytical methods [20].

This study mainly focuses on segregation phenomenon in a free-surface flow generated by a partially filled suspension flow in a Couette apparatus with application in coating processes. We examine the dynamics of band formation for a range of filling levels and concentration ratios for mono- and poly-disperse suspensions. In addition results obtained from this study can be used as a case study for anisotropic shear rate distribution to assess the capability of suspension models.

EXPERIMENTAL SETUP AND PROCEDURE

Experimental Setup

The experimental apparatus of this study is constructed of an annulus with a rotating inner cylinder and a fixed outer cylinder commonly known as Taylor-Couette cell. The outer cylinder is made of a transparent Plexiglass tube 275 mm long with an inner diameter of 36.8 mm. Plexiglass transparent texture provides good visibility of the suspension motion. A filling hole was drilled on the top of cylinder to facilitate the filling of annulus with suspension. The annulus is closed at each end by Plexiglass caps into which sealed bearings are mounted, allowing the rotation of inner cylinder while the outer cylinder is fixed. An AC/DC gear motor was employed to produce the angular velocity of inner cylinder which could be varied from 1 to 25 rpm. Figure (1) shows the experimental setup.

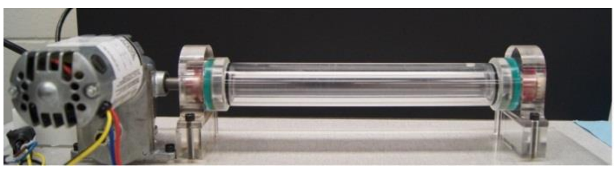


Figure 1. Experimental setup

Suspensions

Three particle types were used. Table 1 shows the physical properties of the particles. These particles mainly differ in diameter size and density. Type I and II are made of polystyrene while Type III is made of polyethylene. The continuous phase of all suspensions is UCON oil which is a commercial name for polyethylene glycol-ran-glycol with density of $\rho = 1.05\frac{kg}{m^3}$ and dynamic viscosity of $\mu = 3.78 Pa.s$.

Table 1. Particle types and specifications

Particle Type	Material	Density $\frac{kg}{m^3}$	Average Diameter $\bar{d}_P(\mu m)$
Type I	Polystyrene	1.03	150
Type II	Polystyrene	1.03	360
Type III	Polyethylene	1.00	850

For each type of particle, we made suspensions with three different particle volumetric concentrations, namely 2.5%, 5% and 10%. Density of Type I and II are very close to UCON oil, thus their mixture makes a neutrally buoyant suspension. Figure (2) shows suspension of type II particles after 24 hours at rest. Particles are uniformly suspended along the height of suspension. Figure (3) however, shows a suspension of type III after 30 minutes at rest. Evidently most particles are floated. There was only 2% difference between the density of UCON oil and type III of particles.

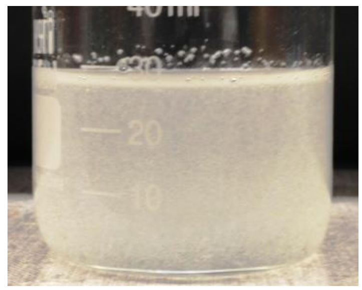


Figure 2. Suspension made with particle type II

Figure 3. Suspension made with particle type III

In summary, current study mainly concentrates on neutrally buoyant and slightly floating (close to neutrally buoyant) suspension at three different volumetric concentrations of 2.5%, 5% and 10%. Moreover, for comparison purposes, a polydisperse suspension was tested. It was a made of equal volumetric concentration of type II and type III particles.

Experimental method

In the beginning, mass of particles and required volume of fluid were measured. To measure the mass of particles, a scale with a tolerance of 0.1 gram was used. We have also utilized scaled beakers and pipette tubes with corresponding precision of 10 mL and 0.1 mL. Suspension was made and gently stirred to avoid entrapment of air bubbles. Then it was funneled into the annulus through filling hole carefully to avoid bubbles enter the suspension. Before conducting each test, the experimental device was checked for being leveled to assure the zero degree of inclination.

All the experiments reported in this paper are conducted at the fixed angular velocity of 19 rpm. At this low rotational velocity the fluid motion remained Stokesian (creeping flow). To measure the length of the bands and other physically important phenomena, a ruler was used.

To verify the validity of our tests, initially a 20% suspension of type II particles was made. The annulus was filled up to 50%. This type had similar physical properties to particles used by Timberlake and Morris [13]. They reported 8-10 bands for mentioned test conditions. Our test ended with 9 fully developed bands.

The run time of tests depended on type of suspension which was used. It varied from minutes to several hours as shown in table 2.

UCON oil has some volatile constituents, which their evaporation can change its density and disturb neutrally buoyant condition of suspension. The filling hole was covered with tape before starting the test to avoid this incident.

To check the repeatability of tests, first test in each category was repeated three times and the results including band numbers and time passed to for the bands to develop were compared. Number of bands and their development time deviate within a small range. Therefore tests were proved to be repeatable.

RESULTS AND DISCUSSION

Here we will report and discuss band dynamics including number of developed bands in each test, time required for the bands to evolve to a quasi-steady or steady state, and a brief discussion on their profile. Results will be presented in two categories of monodisperse and polydisperse suspensions. Tirumkudulu et al. [12] stated that a critical rotational rate exists which depends on both filling level and particle concentration beyond which the particle segregation occurs. In this study, all the experiments were conducted at constant rotational velocity of 19 rpm.

To the knowledge of authors, no definite and conclusive definition was presented in literature for a fully developed band. Hence number of bands or time interval measurements for a band development may vary due to definition used by the authors. In this study, band is defined as a region at which visible change of concentration of particles is evident with or without sharp contrast on its margins. In such regions, change of concentration comparing to adjacent regions should be distinguishable on both sides of bands.

Monodisperse suspensions

Table 2 shows the various monodisperse suspensions tested. Total number of 27 tests, including suspensions with three particle sizes with average diameters of 150, 360 and 850 micrometer were carried out. For each particle size, suspensions with three different concentrations of 2.5%, 5%, and 10% were made. Each concentration was tested at three filling levels of 50%, 75% and 95%.

Band formation time and number of bands

Table 2 presents number of bands and time required for their development according to introduced definition for a developed band.

As table 2 shows for a specific particle size, in most cases, increasing the filling level from 50% to 75% did not change the number of bands considerably. In some cases it decreased the number of bands such as $\phi = 0.025$ for particle type I, while it increased number of developed bands in other cases such as $\phi = 0.025$ for particle type II. However increasing the filling level to 95% in all cases increased band numbers.

In a similar concentration-wise analysis, one can deduce that at a constant filling level, increasing the concentration generally increased the number of bands. Another conclusion is the effect of particle size on the number of developed bands. Comparing suspensions with same filling level and particle concentration revealed that increasing particle diameter generally had a negligible effect on the number of developed bands.

Table 2. Band formation time and number of bands

Average particle diameter $\bar{d}_P\,(\mu m)$	Particle concentration (%)	Filling level (%)	Number of bands	Band formation time (min)
150	2.5	50	2	1113
150	2.5	75	1	852
150	2.5	95	7	90
150	5	50	3	394
150	5	75	5	283
150	5	95	8	72
150	10	50	7	183
150	10	75	5	158
150	10	95	8	73
360	2.5	50	3	1080
360	2.5	75	4	840
360	2.5	95	7	80
360	5	50	4	310
360	5	75	3	155
360	5	95	9	70
360	10	50	6	63
360	10	75	6	45
360	10	95	8	30
850	2.5	50	2	368
850	2.5	75	3	290
850	2.5	95	7	39
850	5	50	4	161
850	5	75	6	154
850	5	95	12	10
850	10	50	7	61
850	10	75	8	29
850	10	95	9	8

Using the definition presented for a developed band, number of bands and their formation time were measured and reported in table 2.

Table 2 shows that for a fixed angular velocity, increasing the concentration at any filling level decreased the time required for the bands to develop. This decrease is more significant when concentration changed from $\phi = 0.025$ to $\phi = 0.05$. On the other hand, keeping the concentration constant and increasing the filling level remarkably decreased the development time of bands. This fact is more evident when filling level rose to 95%.

Effect of particle size on development time of bands is presented in table 2. Increasing the particle size decreased the time needed for the segregation of particles into band forms especially when the particle concentration was high i.e. $\phi = 0.1$.

In all tests performed in this paper, Reynolds number is calculated based on suspension properties:

$$Re = \frac{\rho \omega R_i d}{\mu} \tag{1}$$

where ρ and μ are the suspension density and dynamic viscosity, respectively. d is the gap between cylinders, ω is the rotational velocity of the inner cylinder and R_i is the inner cylinder radius. Reynolds number was always less than 1. Reynolds number based on the particle diameter was also much smaller than unity. This fact eliminated the influence of inertial forces. As the particle concentration increases the effective viscosity of suspension increases, which is in agreement with decreasing of development time and increasing of number of bands. The other dimensionless number which includes the effect of gravitational to viscous stresses is Grashof number:

$$G = \frac{g \Delta\rho R_i}{\mu\omega} \tag{2}$$

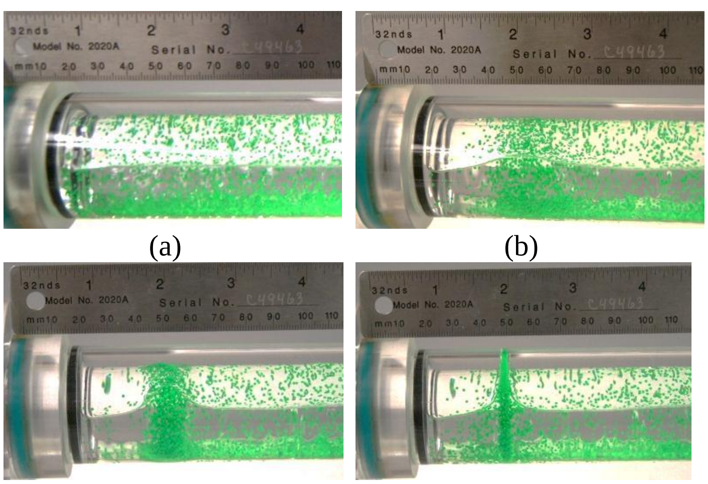
Where g is gravitational acceleration and $\Delta\rho$ is the density difference between particle and bulk fluid. In our test G<0.01 which indicates negligible effect of buoyancy force comparing to viscous force. Although there were other active forces in this flow like surface tension that could contribute to the flow regime.

Band profiles

Another challenging phenomena observed in present study were width and the shape of bands which changed in different tests.

Figure (4) depicts the evolution of a typical band from beginning to its fully developed form. First irregularities appeared on the interface of suspension. Such disturbances could be due to a subtle inhomogeneity in particle distribution. Such irregularities could disturb the interface in form of a bump. This bump could rise taller because of higher viscosity of its location, providing the bump was due to higher concentration of particles around it. As discussed in [14, 16, 20] particle migrate to regions where shear rate is lower. Higher viscosity of region under a wave crest decelerates the particles in its vicinity and creates a region of lower tangential velocity. If particles motion around a bump could be described according to this presumption, then there could be vortices that sweep the particles from intermittent regions between bands and accumulate them in regions with lower shear rate helping to evolution of bands. Such vortices were observed experimentally.

Different band profiles were observed in flow field at different filling levels. Generally they could be classified as hill shape bands with a soft curvature at the crest and gradually decreasing sides. Figure (5) shows sample of this band at filling level 50% and concentration of 2.5% for particle Type I. It was observed that such bands usually did not have clear margins with sharp contrast. Another band profile which was more prevalent at higher filling level was wedge-shape band with a ball-shape tip which is usually well defined and had distinguishable width. Figure (6) shows an example of such bands at filling level 50% and concentration of 5%. Third type which was common in 95% filling level is a continuous ring of particles which formed between two adjacent bubbles on the interface.



(a) (b) (c) (d)

Figure 4. Evolution of a band from a bump on interface (a) to a fully developed ring shape band (d)

At 95% filling level, the air was trapped in form of an elongated bubble on top of annulus. As the inner cylinder started rotating, the air capsule broke into smaller bubbles. The gap between these bubbles formed a necking path for particles to cross. Bands formed exactly at the same locations and the profile of bands was as figure (7). Width of bands decreased as the particle diameter increased. Figures (5)-(7) show bands with different widths for respective particle sizes of 150, 360 and 850 micron.

Seeking a correlation between band formation time, number of bands and flow properties will be postponed to future studies with richer relevant test data.

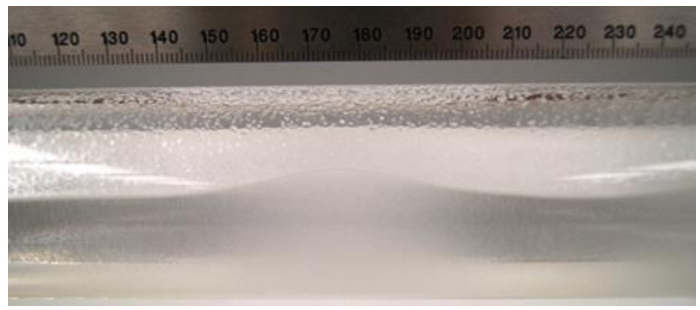


Figure 5. Hill-shape band at filling level 50% and concentration of 2.5% in suspension type I

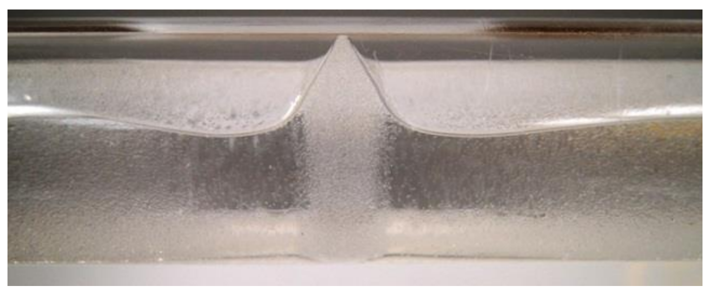


Figure 6. Wedge-shape band at filling level 50% and concentration of 5% in suspension type II

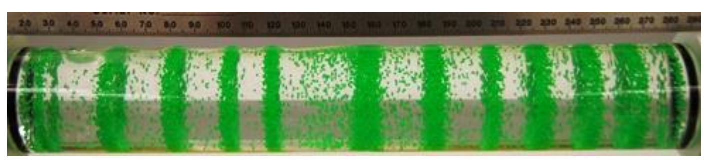


Figure 7. Side view of ring-shape band at filling level 95% and concentration of 5% for suspension type III

Polydisperse suspensions

For comparison purposes, a few polydisperse suspensions with combinations shown in table 3 were tested. However one cannot generalize conclusions made from these tests, they can be quite useful to highlight the main deviations of band formation dynamics of polydisperse suspension.

Table 3. Band formation time and number of bands

Particle Types	Particle type II conce-ntration (%)	Particle type III conce-ntration (%)	Suspen-sion filling level (%)	Numbe r of bands	Band formation time (min)
II and III	2.5	2.5	50	5	1164
	2.5	2.5	75	5	130
	2.5	2.5	95	10	725

For these three tests angular velocity was kept constant at 19 rpm. Also the dispersion phase was UCON oil as previous tests.

Band formation time and number of bands

Table 3 shows number of bands and required time for the bands to develop. Particle concentration was kept constant in these tests and the effect of filling level was examined. It was seen that changing the filling level from 50% to 75% did not change the number of bands which was consistent with previous monodisperse tests. In addition increasing the filling level from 50% to 75% decreased the developing time significantly but it increased from 75% to 95%.

All the bands started initially with a region richer in green particles which had larger size. This observation fortified the presumption that resultant force which is applied to larger particles was greater than resultant force on smaller particles, and caused them to segregate faster.

Comparing the polydisperse suspension with monodisperse suspensions having equal type II and III concentrations, revealed that number of bands in polydisperse tests was higher than both tests of monodisperse suspensions with same filling level and particle concentration. Time needed for the bands to develop was more in polydisperse tests.

Band profiles

Distribution of particles along the width of a band was mainly determined by particles size. In these three tests, band profiles were mainly wedge-shape (Fig. 8). Only in 95% filling level, all the bands were ring-shape with a necking region between the bubbles.

In a specific test, width of the bands varied according to concentration of each type of particles. Smaller particles felt smaller forces and spread more widely comparing to larger particles. Figure (8) shows a developed band. It is clear that white particles spread in a wider length while green particles lined up more compactly. Another interesting observation was type of bands. However the initial distribution of particles in suspension was reasonably homogeneous, in test with 95% filling level, some bands developed with solely white particles or green particles. Majority of bands are formed by both particles.

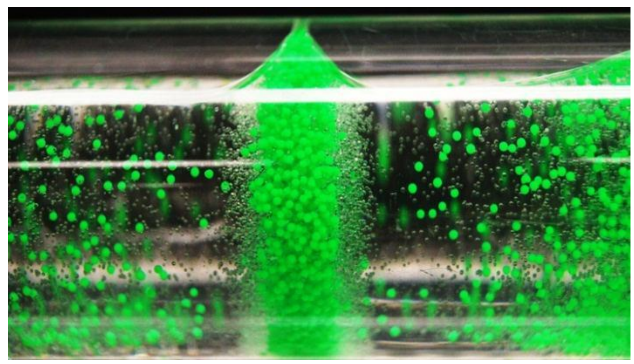


Figure 8. Comparison of width of white and green particles in a mixed band

Conclusion

A Taylor-Couette cell was used to study the effects of particle concentration and filling level on banding dynamics of different suspensions. Suspensions varied significantly in their particle size and combinations. 27 tests were conducted on monodisperse suspensions with different average diameters of 150, 360, and 850 micron. For each particle size, three suspensions with concentrations of 2.5%, 5% and 10% were tested at filling levels of 50%, 75%, and 95%. Also 3 tests of a specific polydisperse suspension were conducted at three different filling levels. In all tests, angular velocity was constant at 19 rpm. A validation test was performed and compared with previous study done by Timberlake and Morris [13]. Number of bands and their formation time were measured. Experimental data showed that increasing the filling level from 50% to 75% did not change the number of bands significantly however; it reduces the formation time notably. Further increase of filling level to 95%, increases the number of bands considerably and reduced the formation time remarkably. Increasing the concentration generally reduces the developing time and number of bands. Width of bands also decreased with increasing of filling level. It was observed that three dominant band profiles occurred, namely, hill-shape, wedge-shape, and ring-shape bands. In addition, three polydisperse tests were conducted which showed higher number of bands for polydisperse suspension comparing to monodisperse suspension with same concentration and filling levels.

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