Summary for Experiments

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Experiment-1. Rotating experiments with high & low viscous Triton mixture under low filling level and relatively low rotating speed

1-1. Overview

During the past few years, some interesting flow patterns have been observed within a rotating horizontal cylinder filled with particle-free liquid, or some suspensions composed of high-viscosity fluids and particles. Through experiments in partially filled horizontal Couette device, Tirumkudulu revealed a kind of instability in the flow of suspensions containing narrow-sized neutral-buoyant particles in a very viscous Newtonian liquid where the suspension under shear segregates into regions of high and low particle concentration along the length of cylinder pipe. In 1999, Tirumkudulu, Mileo and Acrivos did similar experiments but in a horizontal cylinder with a different geometry. The cylinder pipe was partially filled with the same suspension and rotated about its horizontal axis. They found that, within a proper range of parameter space, the initially uniform suspension was divided into cylindrical bands of high particle concentration separated by regions of pure liquid. In order to investigate this interesting phenomenon, we conducted a series of similar experiments with several Triton-mixture samples with both high and low viscosity.

1-2. Set-up and Experimental materials

This experiment was conducted in a cylinder pipe made of glass. The cylinder was supported horizontally and driven by a motor to maintain a uniform-speed rotation. The rotating speed could be well controlled within the range of 0.2~50.0 rpm. We chose two kinds of cylinder pipes for our experiment. They were in the same inner radius ($R = 1.396$ cm) but in different effective lengths ($l_1 = 15$ cm, $l_2 = 30$ cm). The longer one was comparable to that in Acrivos' experiment, which was $l = 30$ cm and $R = 1.27$ cm.

We chose a kind of Triton mixture to be the fluid in our experiment, and this fluid was prepared from a certain combination of Triton X-100, $ZnCl_2$ and water. The viscosity of Triton mixture is sensitive to the change of temperature. Therefore, a constant temperature (68 ± 2.0°F) had to be maintained throughout most of our experiments. Generally, with different combination ratio of three components, this mixture liquid can have a viscosity in the range of 50~8000 cp and a density in the range of 1.1~1.5 g/cm^3.

The particle is a kind of polymer. The average diameter of the particle is 0.046 cm, and its density is 1.034 g/cm^3 (<1.1~1.5 g/cm^3). Therefore, in almost all of our experiments, the blue particles were lighter than the Triton-mixture liquid, which was helpful for the particles to stay at the surface of liquid. This is different with Acrivos' paper, because he chose neutral-buoyant particle in his experiments and the density of particle is almost the same to that of liquid. We mixed the particles and Triton-mixture liquid to get suspension. Before experiments, particles were colored blue for visibility.

1-3. Experimental Analysis

1-3-1. Experiment description and parameter analysis

We initially put the uniform suspension of liquid and particles into the cylinder pipe. The filling level of suspension is very low and in the range of 3%~20%. Then we rotate the cylinder with a low rotating speed of 1.0~15.0 rpm for the high-viscous Triton mixture or a comparatively high speed of 30.0~80.0 rpm for the low-viscous one. During the following few hours, the distribution of liquid and particles will change and reach a steady state gradually. Within a proper range of parameter space, we observed that the suspension under shear segregated into regions of high and low particle concentration along the length of the cylinder. Sometimes the high particle concentration bands were separated by regions full of pure liquid. Especially in the experiment with high-viscous Triton mixture, the particle bands separation can be easily observed.

We also conducted similar experiment in relatively high filling level. Bands separation happened as well but it's a little different with low-filling level ones. There were many particles staying in the fluid sections between particle bands. Slight transverse movement of these particle could be observed in this experiment.

There were several key parameters we had to pay attention to in our experiments. They are described below.

The Reynolds number $R_e = (\Omega h_a^2)/\nu$, where Ω is the angular velocity of the cylinder pipe (in rad/s), h_a the mean thickness of the film, and ν the kinematic viscosity of the fluid. The range of Reynolds number in our experiments is always less than 10^{-2}. It's very small, so the inertial effects were generally negligible.

The filling level F, which is defined as the ratio of the initial length of mixture liquid in static state L_e to the effective length of cylinder pipe L. For the longer pipe with a length of $L = 30$ cm, the corresponding filling level is fixed at $F = L_e / L = 0.0614$.

The dimensionless parameter β, which is from the stand lubrication analysis, is defined by $\beta = F\sqrt{gR/\Omega\nu}$ and will be discussed in detail in the following section 1-3-3.

1-3-2. Film thickness (Average thickness h_a and minimum thickness $h_{\min}$)

When we conducted this experiment, we also paid attention to the profile of film thickness. The filling level F and another dimensionless parameter β are two dominant parameters for the profile of film thickness. With different filling level F and β, there would be different profile of film thickness.

When β was decreased to be a small value, there was no any sharp variation in thickness on the cross-section of rotating cylinder pipe. And in the case of small β, the features of thickness profile is almost not influenced by the filling level F. In Acrivos' experiment, the critical value of β is $\beta_c = 1.4$, which means that a homogeneous and continuous film can exist at a steady state if $\beta \le 1.4$. And when β is greater than the critical value β_c, the thickness profiles were often observed to having a sharp variation over a restricted range of the angle θ. Because it's difficult to investigate the cross-sections of cylinder in our experiment, we didn't measure the critical value of β and just picked up Acrivos' result for reference.

Dr. Joseph brought forward a method for the calculation of thickness profiles within coating flow and partially filled rimming flow. He thought the shape of free surface follows from the statement that the volume flux Q is a constant. According to definition, the volume flux Q is:

$$Q = \int_0^D V dy = \Omega R h - \frac{g}{\nu} \cdot \frac{1}{3} h^3 \cos\theta = \Omega R h_0 - \frac{g}{\nu} \cdot \frac{1}{3} h_0^3 \qquad \text{(A*)}$$

Where $h = h(\theta)$ is the film thickness, R the radius of cylinder pipe, $r = r(\theta) = R - h(\theta)$ (Figure 1-1), and h_0 is the film thickness at zero angle (i.e. $h_0 = h(\theta = 0)$).

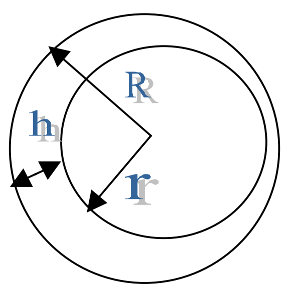


Figure 1-1. Sample for the relationship between cylinder pipe, liquid surface and thickness

Equation (A*) is a cubic equation for the film thickness $h = h(\theta)$. Generally, there will be three roots, probably including some complex root(s) in some cases. The number of complex root can be up to 2. Matlab can be effective to compute these roots for cubic equation. Anyway, it's difficult to determine which root we should take, and therefore the film thickness can not be easily determined. It's a problem we need to do some further investigation.

The average flow-rate can be determined by:

$$\overline{Q} = \frac{V_{cylinder} \cdot F}{L \cdot \Delta t} = \frac{V_{cylinder} \cdot F}{L \cdot 2\pi / \Omega} = \frac{V_{cylinder} \cdot F\Omega}{L \cdot 2\pi}. \qquad \text{(B*)}$$

Let $Q = \overline{Q}$ and then substitute into equation (A*), we got:

$$\frac{V_{cylinder} \cdot F\Omega}{L \cdot 2\pi} = \Omega R h(\theta) - \frac{g}{\nu} \cdot \frac{1}{3} h^3(\theta) \cdot \cos\theta \qquad \text{(C*)}$$

From equation (C*), we can calculate the film thickness $h = h(\theta)$ for different filling level F and rotating speed Ω.

Corresponding with a specified filling level F, the average film thickness h_a can be easily determined by $h_a = R - r_a$ (see Figure 1-1), where r_a can be obtained from $F = [\pi(R^2 - r_a^2)l]/[\pi R^2 l]$. Simplifying the above equations, we got $h_a = (1 - \sqrt{1-F})R$, which means that we just need to know the filling level F and the radius of cylinder R when compute the average film thickness.

As we know, the film thickness is not a constant at different angle θ no matter how much the β is. Therefore, there must be a minimum value of thickness $h_{\min}$ corresponding with a specified combination of control parameters. In order to study the comparability between the size of particle d_p and the minimum thickness $h_{\min}$, we also got some data especially for $h_{\min}$ by Joseph's method, see Table 1-1.

Actually, we can also investigate the film thickness $h(\theta)$ by the dimensionless film thickness profile $\eta(\theta)$, which is defined as $\eta(\theta) = h(\theta)/(\Omega R \nu / g)^{1/2}$.

R	μ_f	ρ_f	ρ_p	d_p	Ω	F	β	h_a	Re	$h_{\min}$	$\frac{h_{\min}}{d_p}$
(cm)	(cp)	(g/cm^3)	(g/cm^3)	(cm)	(rpm)	-	-	(cm)	-	(cm)	-
1.396	4434	1.203	1.034	0.065	1.76	0.061	0.87	0.0432	$9.35*10^{-6}$	0.0403	0.620
1.396	4434	1.203	1.034	0.065	3.13	0.061	0.65	0.0432	$1.66*10^{-5}$	0.0412	0.634
1.396	4434	1.203	1.034	0.065	6.00	0.061	0.47	0.0432	$3.19*10^{-5}$	0.0418	0.643
1.396	4434	1.203	1.034	0.065	10.0	0.061	0.37	0.0432	$5.31*10^{-5}$	0.0421	0.648

Table 1-1. The minimum film thickness and corresponding other control parameters

1-3-3. The dimensionless β and its calculation

Just as mentioned above, β is an important dimensionless parameter for the appearance of particle bands separation in this experiment. It's also related to the properties of the thickness profile on the cross-section of cylinder pipe. β comes from the standard lubrication analysis. And it's defined as $\beta = F\sqrt{gR/\Omega\nu}$, where F is the filling fraction of fluid, g the acceleration due to gravity $g = (980 \text{cm/s}^2)$, R the radius of cylinder (cm), Ω the angular velocity of rotating cylinder (rad/s), ρ the density of fluid (g/cm^3), and ν the kinematic viscosity of fluid (cs). Notice that ν is given by μ/ρ where the dynamic viscosity μ is in poise (1 poise = 1g/cm.s).

We observed the bands separation similar to what's described in Acrivos' paper under different group of control parameters. Some relevant experiment data are shown in Table 1-2.

Acrivos' Experiment												
Results for experiment with high-viscous Triton mixture, low filling level and low rotating speed (large β cases)												
R_e	F	R_{pipe}	Ω_{pipe}	μ	ρ_l	ν	d_p	ρ_p	L_{pipe}	β	$h_{\min}$	$\frac{h_{\min}}{d_p}$
-	-	(cm)	(rpm)	(poise)	(g/cm^3)	(cm^2/s)	(cm)	(g/cm^3)	(cm)	-	(cm)	-
4.22*10^{-5}	0.150	1.270	1.40	40.00	1.172	34.13	0.046	1.172	30.0	2.36	0.0742	1.613
7.31*10^{-4}	0.125	5.000	2.80	49.00	1.172	41.81	0.046	1.172	30.0	2.50	0.2394	5.204

Joseph's Experiment												
Results for experiment with high-viscous Triton mixture, low filling level and low rotating speed (large β cases)												
R_e	F	R_{pipe}	Ω_{pipe}	μ	ρ_l	ν	d_p	ρ_p	L_{pipe}	β	$h_{\min}$	$\frac{h_{\min}}{d_p}$
-	-	(cm)	(rpm)	(poise)	(g/cm^3)	(cm^2/s)	(cm)	(g/cm^3)	(cm)	-	(cm)	-
4.97*10^{-5}	0.151	1.396	1.65	51.95	1.241	41.86	0.065	1.034	30.0	2.08	0.0853	1.312
7.47*10^{-5}	0.140	1.396	1.65	29.50	1.332	22.15	0.065	1.034	30.0	2.65	0.0735	1.131

$3.27*10^{-5}$	0.150	1.396	1.10	51.95	1.241	41.86	0.065	1.034	30.0	2.53	0.0799	1.229
				59.77	1.258				15.0			
Results for experiment with high-viscous Triton mixture, very low filling level and low rotating speed (small β cases)												
R_e	F	R_{pipe}	Ω_{pipe}	μ	ρ_l	ν	d_p	ρ_p	L_{pipe}	β	$h_{\min}$	$\frac{h_{\min}}{d_p}$
-	-	(cm)	(rpm)	(poise)	(g/cm^3)	(cm^2/s)	(cm)	(g/cm^3)	(cm)	-	(cm)	-
$3.23*10^{-4}$	0.145	1.396	10.9	48.50	1.212	40.02	0.065	1.034	15.0	0.79	0.0966	1.486
$9.35*10^{-6}$	0.061	1.396	1.76	44.34	1.203	36.86	0.065	1.034	30.0	0.87	0.0403	0.620
$1.66*10^{-5}$	0.061	1.396	3.13	44.34	1.203	36.86	0.065	1.034	30.0	0.65	0.0412	0.634
$3.19*10^{-5}$	0.061	1.396	6.00	44.34	1.203	36.86	0.065	1.034	30.0	0.47	0.0418	0.643
$5.31*10^{-5}$	0.061	1.396	10.0	44.34	1.203	36.86	0.065	1.034	30.0	0.37	0.0421	0.648
Results for experiment with very low-viscous Triton mixture, very low filling level and high rotating speed (small β cases)												
R_e	F	R_{pipe}	Ω_{pipe}	μ	ρ_l	ν	d_p	ρ_p	L_{pipe}	β	$h_{\min}$	$\frac{h_{\min}}{d_p}$
-	-	(cm)	(rpm)	(poise)	(g/cm^3)	(cm^2/s)	(cm)	(g/cm^3)	(cm)	-	(cm)	-
$2.70*10^{-3}$	0.046	1.396	38.71	2.377	1.498	1.587	0.065	1.034	30.0	0.67	0.0310	0.477
$3.56*10^{-3}$	0.046	1.396	51.10	2.377	1.498	1.587	0.065	1.034	30.0	0.58	0.0313	0.482

Table 1-2. Some parameters in the rotating cylinder experiments

Acrivos gave out a critical value of β for the analysis of film thickness, the values of β in his experiments were all greater than β_c. We did several experiments with $\beta < \beta_c$ for both high-viscous Triton mixture and low-viscous one. For experiment with low-viscous liquid and small β, the formation of bands separation becomes more difficult when compared with that in experiment with high-viscous ones, but we still can easily observe the particle clusters.

1-3-4. Filling level F and Rotating speed Ω

In most of experiments with high-viscous Triton mixture, we had to restrict the rotating speed to low values to get bands separation. Under low rotating speed, particles on the surface of thin fluid film are easy to get together to form clusters or bands. Even for those experiments with low-viscous Triton mixture, we also can't increase the rotating speed to a very high value, which will make it impossible to produce particle clusters. In our experiment, rotating speeds were all less than 60 rpm, therefore, the influence of secondary flow was always negligible. It is in a different mechanism when compared with another classic experiment described in Joseph's paper (1988).

Under low filling levels, the high-viscosity Triton mixture is easy to form a thin film at the inner wall of cylinder pipe. And the shape of film is influenced by the filling level to some extent, especially when $\beta > \beta_c$. This point has been discussed in section 1-3-2. Since the density of blue particle is smaller than that of Triton mixture in this experiment, it becomes possible that some blue particles stay at the inner film surface of Triton mixture fluid under a low rotating speed. When the rotating speed is increased, particles will be immerged into the fluid gradually because of large centrifugal force. For the experiments with low-viscous Triton mixture, the values of β were very small (0.58 and 0.67) and $\beta < \beta_c = 1.4$, so the influence of filling level on the shape of film thickness can be neglected.

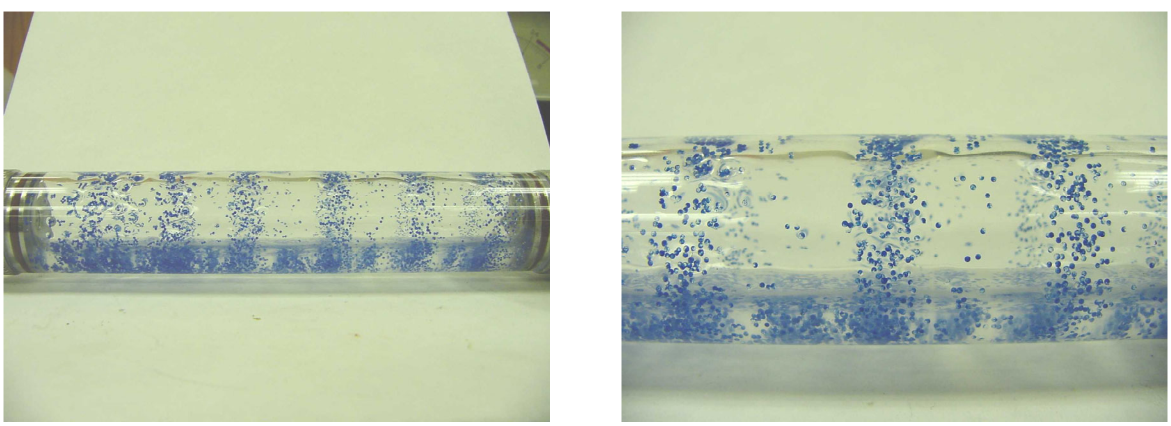


Figure 1-2. Rotating experiment with high viscous Triton mixture under a high filling level $F = 0.32$ and a low rotating speed $\Omega = 5.7$ rpm $\mu = 4850$ cp and $\beta = 2.11$

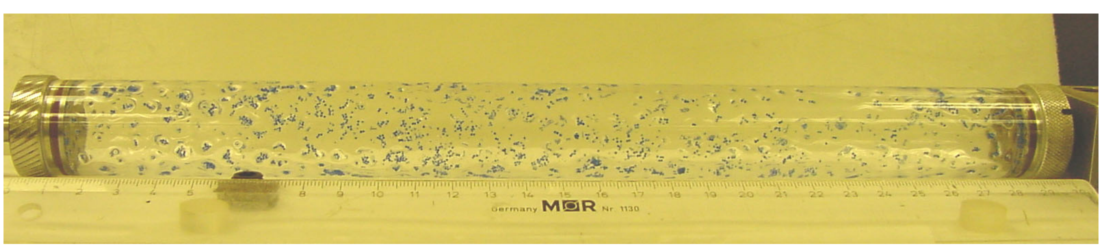
We also conducted similar experiment in relatively high filling level, and we observed particle bands separation as well. However, there were many particles staying in the fluid sections between particle bands, which is different to low-filling level experiment. Generally, it needed much more time to reach the steady bands separation, and the feature of bands separation is different to that of low-filling level ones. In this case, there's no fluid section free of particle. Particles exist anywhere together with Triton mixture, but the particle concentrations are much different here and there. There is slight secondary flow and transverse movement of particles can be seen between particle bands (Figure 1-2). Because of the high viscosity of fluid, some particles can move out of the bottom fluid and form the clusters or bands under the capillary force. With the increasing of filling level, bands separation becomes more and more difficult to happen because it's no longer very easy for particle to move out of bottom fluid and they are more likely to stay in the bottom fluid and do some slight random movement.

1-3-5. Analysis and Discussion

In this experiment, it always needed a long running time for the formation of steady particle concentration or bands separation. The rotating speeds were constant throughout the experiments. In sequence, we always first observed the formation of many small particle clusters, which were uniformly produced along the cylinder after a few minutes. With the development of running time, these particle clusters were in a tendency of collection and became larger and larger. And then gathered to be several comparatively large blocks along the cylinder pipe. These large blocks were often far from each other, so the influence of surface tension dropped down to a negligible extent and the large blocks didn't move towards each other again. Meanwhile, those particle blocks became thinner and longer gradually and some blocks merged again. At last, every block formed a circular particle band around the perimeter on the cross-section of cylinder pipe, which is called 'particle band' by us. So, we got bands separation at last and they were almost in uniform distribution along the cylinder. During the process, capillary force played an important role, especially in the beginning stages. After the formation of large blocks, the centrifugal force caused the blocks to be re-combined and changed to circular particle bands eventually. The concentration of particles in suspension were kept changing during the whole process of experiment, and the fluctuation of particle concentration should be an important factor for the formation of particle bands separation.

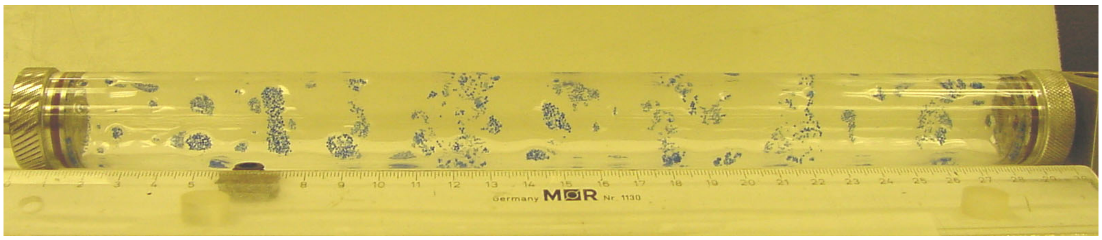
The sample process of this experiment is illustrated in Figure 1-3.

As discussed before, because the blue particles were lighter than Triton mixture, some particles were easy to stay at the inner surface of film. The capillary force caused the gathering of particles and therefore formed a lot of particle clusters.

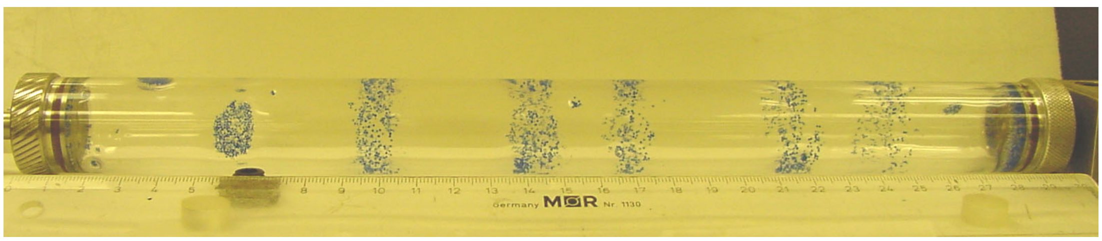


(a) Uniform distribution of particles at the beginning

(b) Particle clusters



(c) Particle blocks



(d) Particle bands

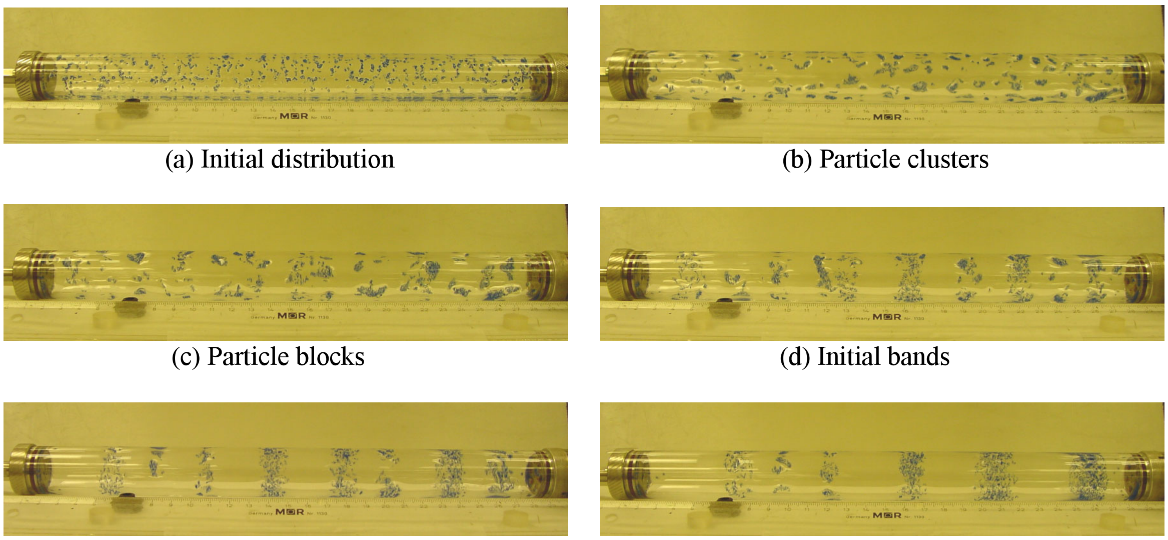
Figure 1-3. Illustration for the process of rotating experiment with high viscous Triton-mixture fluid under low rotating speed & low filling level ($\Omega = 6.0$ rpm, $F = 0.061$, $\beta = 0.47$, $\mu = 4434$ cp)

From experiment with Triton mixture liquid, experimental results show that if we set a low rotating speed, the larger the viscosity, the easier the formation of particle clusters or bands will be.

For the low-viscous Triton mixture, if we want to get bands separation, it's still possible but we have to decrease the filling level as well as increase the rotating speed at the same time. Anyway, such increase of rotating speed should be restricted in a small range. If the rotating speed is too large, it will be very difficult to form particle clusters and these particle clusters are unstable within high-speed rotation. The developing process of particle concentration for this case (Figure 1-4) is similar to that in the experiment with high-viscous Triton-mixture under low filling level & low rotating speed. In the experiment with low-viscosity liquid, we just got particle bands separation for small β cases (0.5~0.7), with corresponding relatively high rotating speeds.

However, decreasing the filling level F as well as increasing the rotating speed is not always effective for low-viscosity fluids, we repeated this experiment with Soybean Oil and Glycerin with relative high rotating speed (β=1.0~1.2), but there was no particle bands separation happened along the cylinder pipe. Anyway, we still observed small-sized particle clusters in these cases. In order to find an explanation, maybe we should consider some other physical properties of these liquids, such as surface tension or something else.

We didn't try the experiment with Soybean Oil or Glycerin for small β (such as $\beta = 0.5$). Maybe there will be similar phenomenon to that with low-viscous Triton mixture.



(a) Initial distribution (b) Particle clusters

(c) Particle blocks (d) Initial bands

(e) Developing bands (f) Final bands

Figure 1-4. Illustration for the process of rotating experiment with low viscous Triton-mixture fluid under relatively high rotating speed & low filling level ($\Omega = 51.1$ rpm, $F = 0.046$, $\beta = 0.58$, $\mu = 237.7$ cp)

For different rotating speeds and filling level, we also measured the average distance between the particle bands $\bar{l}$ and the running time t_w needed to reach steady states. Some relevant data are shown in the following Table 1-3.

From the data in Table 1-3, we found that, corresponding with the same filling level F, the larger the rotating speed Ω, the less time we will need for the formation of steady bands separation. On the other hand, if we maintain the rotating speed and change the filling level in its effective range, the higher filling level will correspond with the less time waiting for the bands separation.

Filling level F	Rotating speed Ω (rpm)	Waiting time for particle clusters t_{w1} (hour)	Waiting time for large blocks t_{w2} (hour)	Waiting time for bands appearance t_{w3} (hour)	Average distance between bands $\bar{l}$ (cm)
0.061	0.184	1.1	2.6	6.6	6.2
0.061	0.328	0.8	2.1	4.7	5.5
0.061	0.628	0.6	2.2	4.0	3.9
0.061	1.047	0.5	1.8	3.5	4.5
0.150					
0.150					
0.150					
0.150					

0.046	38.71	0.10	0.25	0.40	3.9
0.046	51.10	0.08	0.20	0.30	3.6

Table 1-3. Running time or Average distance between bands for different filling level and rotating speed

The influences of Ω and F can be embodied in the Reynolds number R_e and β ($\mathrm{Re} = (\Omega h_a^2)/\nu$, $\beta = F\sqrt{gR/\Omega\nu}$). Therefore, from the above experimental results, we can think that Reynolds number R_e and β were two dominant factors for how long time we would need to wait for the appearance of steady bands separation.

1-4. Expanding topics

Corresponding to the rimming flow with high rotating speed, coating flow will be much different. However, what will happen if we coat the rotating cylinder with suspension composed of high-viscosity fluids and small-size particles? Will the re-distribution of particle concentration or the bands separation happen as well? It's another topic we need to pay attention to in the short future.

Experiment-2. Rotating experiments with high-viscosity fluids under high filling level and high rotating speed

2-1. Overview

In 1987, Joseph and Preziosi studied the run-off condition for coating and rimming flow. In their experiment, when the horizontal cylinder pipe was partially filled with particle-free liquid and kept running with a constant and high rotating speed, they observed an interesting phenomenon – In some parameter space, the air in running cylinder was separated into several axis-symmetrical air bubbles, which were uniformly distributed along the cylinder pipe (Figure 2-1). We were interested in the condition for the formation of air bubble separation. Therefore, a series of rimming flow experiments had been done with several kinds of comparatively high-viscous fluids. We also conducted similar experiment with suspension composed of these high-viscous fluids and some small-sized particles, and we put high premium on the particle's behavior in these experiments.

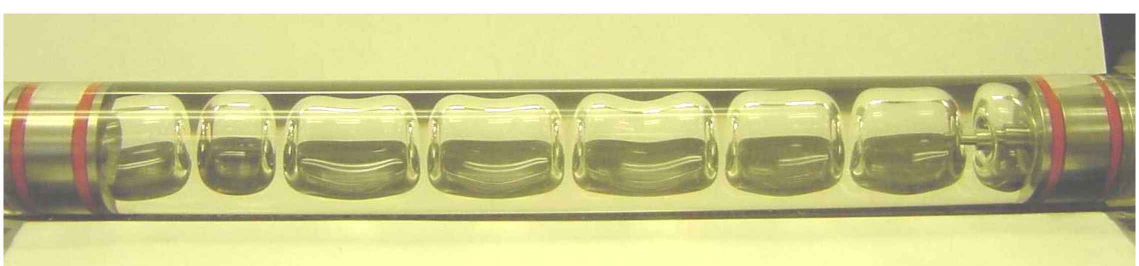


Figure 2-1. Air bubble separation in Soybean Oil ($\Omega = 600$rpm, $F = 0.6$)

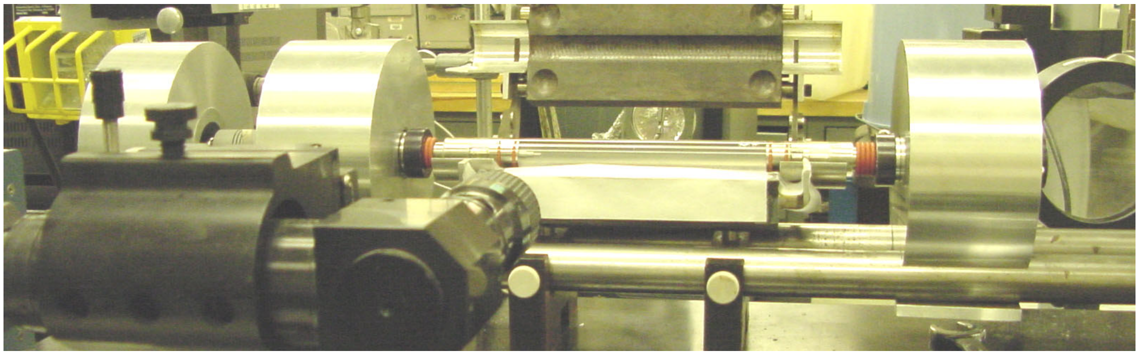


Figure 2-2. Set-up for rotating cylinder experiment with high speed

2-2. Set-up and experimental materials

The apparatus used in the experiment was a cylindrical glass container with inner radius of 0.64 cm, closed at the ends and with an end-to-end distance of 22.14 cm. There were two plugs at the ends of cylinder pipe and the positions of plugs were not fixed to the pipe, so the effective length of cylinder was not a constant and required to be measured each time. This apparatus was driven by a motor and could maintain a constant rotating speed in the range of 100~12000rpm. We had a CCD camera and a Video Synchronizer connected with the experiment apparatus to record the dynamic process and measure the surface tension (Figure 2-2).

Two kinds of particles were selected for this experiment. Their physical properties are shown in Table 2-1.

Type of particle	Polymer particle	16/30 AcFrac PR
Color	brown	yellow-brown
Average diameter $\bar{d}$ (cm)	0.065	0.088
Density ρ (g/cm^3)	1.24	1.64
hydrophobic / hydrophilic	hydrophobic	hydrophilic

Table 2-1. Some physical properties of experimental particle samples

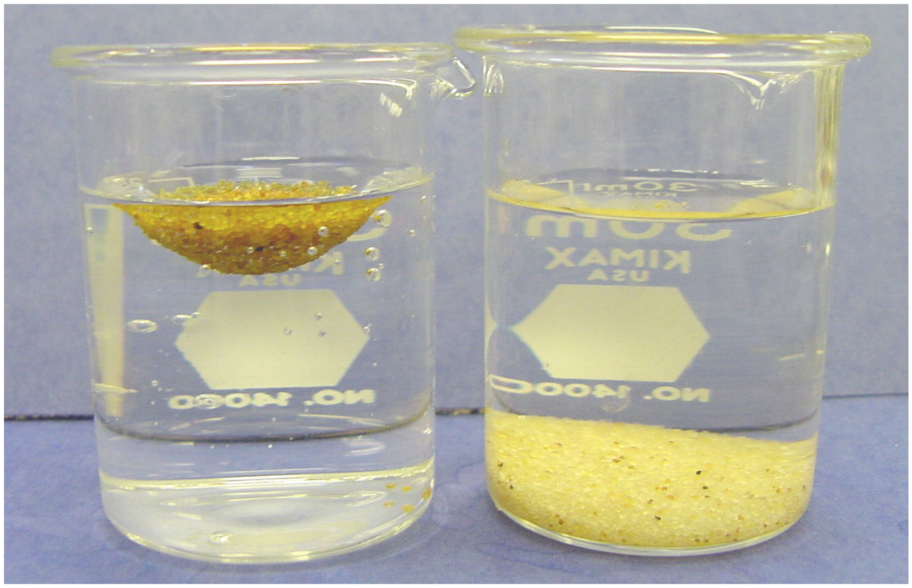


Figure 2-3. Comparison of hydrophobic and hydrophilic particle
(Left: Polymer particle; Right: 16/30 AcFrac PR particle)

The liquids used in this experiment were Soybean oil, Triton mixture and Glycerin. Corresponding physical properties of these liquids are given in Table 2-2.

Type of liquid	Soybean oil	Triton mixture	Glycerin
Viscosity μ (cp)	282	2950	1490
Density ρ (g/cm^3)	0.915	1.241	1.173
Surface Tension (mN/m)	24.285 (Ω=4290rpm)	33.152 (Ω=2610rpm)	41.458 (Ω=3230rpm)

Table 2-2. Some physical properties of experimental liquid samples

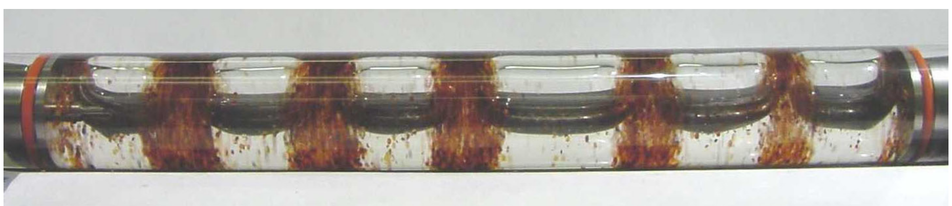
2-3. Experimental Analysis

2-3-1. Experiment description

When the cylinder pipe was partially filled with particle-free liquid and kept running, the feature of air bubble(s) in the pipe is mainly influenced by the type of liquid and the rotating speed Ω. In some cases, the initial single air bubble can be separated into several smaller bubbles. The number and the shapes of smaller air bubbles are much different for different type of liquid and rotating speed.

Accordingly, when we put suspension with small particles into the cylinder pipe and did this experiment under some control parameters close to those in particle-free liquid experiment, similar bubble separation happened as well and we also observed some interesting particle concentrations. We kept increasing the rotating speed Ω during the experiment. When the rotating speed was low, bubble separation didn't happen and particles were concentrated at the ends of the cylinder pipe. Then speeded up the rotating cylinder to 300~500 rpm, we observed the appearance of bubble separation and new particle concentration. Those particles kept staying at the narrow regions full of liquid between neighboring air bubbles and those bubbles looked like elliptic balls. When we continued to increase the rotating speed to 600~700 rpm, both air bubble separation and particle concentration were changed again. Some air bubbles were changed into the shape of peanut. Particles were forced to leave the regions between air bubbles and began to keep staying around air bubbles. However, particle concentration was not uniform along the bubble, and the lowest particle concentration approximately happened at the middle point of air bubble. Meanwhile, the regions between air bubbles were empty of particles and filled with pure fluid. See the sample process in Figure 2-3.

(a) $\Omega = 200$ rpm



(b) $\Omega = 300$ rpm

(c) $\Omega = 600$ rpm

Figure 2-3. The influence of rotating speed Ω on particle's behavior
(Polymer particle in Soybean Oil, Filling level $F = 0.75$)

2-3-2. β and F

In our experiment, we found that if the rotating speed Ω was very low or very high, the initial single air bubble will still maintain the single state and can not be separated into several parts no matter how much the filling level F is. Generally, the proper range of Ω for bubble separation is 200~1200 rpm, which can be some different for different kind of liquid. On the other hand, if F is too small (<40%), bubble separation can not happen as well for any rotating speed (Table 2-3).

Soybean Oil (μ = 282 cp) (Note: 'N' means no bubble separation, and 'Y' means that bubble separation can be observed)					
	Ω = 100 rpm	Ω = 300 rpm	Ω = 600 rpm	Ω = 900 rpm	Ω = 1500 rpm
$F = 0.1$	N	N	N	N	N
$F = 0.2$	N	N	N	N	N
$F = 0.4$	N	N	N	Y	N
$F = 0.6$	N	N	Y	Y	N
$F = 0.8$	N	N	Y	N	N
$F = 0.9$	N	N	N	N	N
Triton Mixture liquid (μ = 2950 cp) (Note: 'N' means no bubble separation, and 'Y' means that bubble separation can be observed)					
	Ω = 100 rpm	Ω = 300 rpm	Ω = 600 rpm	Ω = 900 rpm	Ω = 1500 rpm
$F = 0.1$	N	N	N	N	N
$F = 0.2$	N	N	N	N	N
$F = 0.4$	N	N	Y	Y	N
$F = 0.6$	N	Y	Y	Y	N
$F = 0.8$	N	Y	Y	Y	N
$F = 0.9$	N	N	Y	N	N

Table 2-3. Influence of F and Ω for air bubble separation

The influence of rotating speed Ω can be shown by the dimensionless parameter β. Therefore, although it's in a different mechanism when compared with the experiment-1, β and F are still two significant dimensionless parameters for this experiment. As mentioned before, β is defined as $\beta = F\sqrt{gR/\Omega\nu}$, where F is the filling fraction of fluid, g the acceleration due to gravity ($g = 980$ cm/s^2), R the radius of cylinder (cm), Ω the angular velocity of rotating cylinder (rad/s), ρ the density of fluid (g/cm^3), and ν the kinematic viscosity of fluid (cs). Notice that ν is given by μ/ρ where the dynamic viscosity μ is in poise (1 poise = 1g/cm.s).

2-3-3. Critical curves

We conducted this experiment with three different kinds of liquids, including soybean oil, glycerin and a kind of Triton mixture mentioned in the first experiment. For all of these liquids, experiment results show that the separation can happen only if the filling level and rotating speed can satisfy some conditions. Generally, there exists a critical value of filling level for specified liquid and rotating speed. Only when the filling level is greater than the critical value, the bands separation can be observed. In order to investigate the relationship between critical filling level and rotating speed, a series of experiment has been done and some relevant results of measurement are shown in Table 2-4.

Kind of Liquid	Rotating Speed (rpm)	Length of Liquid (cm)	Total Length (cm)	Filling Level (%)	Bands Separation	Notes
Soybean Oil	450	3.825	4.865	78.62	Y	
Soybean Oil	450	4.585	5.915	77.51	Y	
Soybean Oil	450	3.825	5.270	72.58	Y	
Soybean Oil	450	3.825	5.400	70.83	Y	
Soybean Oil	450	3.825	5.465	69.99	Y	
Soybean Oil	450	3.760	5.565	67.57	Y	Critical
Soybean Oil	450	3.825	5.515	69.36	N	
Soybean Oil	450	3.760	5.600	67.14	N	
Soybean Oil	450	3.760	5.625	66.84	N	
Soybean Oil	500	3.290	4.345	75.72	Y	
Soybean Oil	500	3.025	4.075	74.23	Y	
Soybean Oil	500	3.290	4.450	73.93	Y	
Soybean Oil	500	3.290	4.545	72.39	Y	
Soybean Oil	500	3.665	5.075	72.22	Y	
Soybean Oil	500	3.290	4.595	71.60	Y	
Soybean Oil	500	2.900	4.055	71.52	Y	
Soybean Oil	500	3.665	5.230	70.08	Y	Critical
Soybean Oil	500	3.290	4.665	70.53	N	
Soybean Oil	500	3.290	4.705	69.93	N	
Soybean Oil	500	3.305	4.760	69.43	N	
Soybean Oil	500	3.665	5.295	69.22	N	
Soybean Oil	500	2.900	4.220	68.72	N	
Soybean Oil	500	2.900	4.850	59.79	N	
Soybean Oil	550	2.425	3.690	65.72	Y	
Soybean Oil	550	3.030	4.845	62.54	Y	
Soybean Oil	550	2.520	4.095	61.54	Y	
Soybean Oil	550	3.030	4.955	61.15	Y	
Soybean Oil	550	2.545	4.190	60.74	Y	
Soybean Oil	550	2.535	4.190	60.50	Y	
Soybean Oil	550	3.030	5.010	60.48	Y	
Soybean Oil	550	3.030	5.050	60.00	Y	Critical
Soybean Oil	550	2.425	3.855	62.91	N	
Soybean Oil	550	2.425	3.920	61.86	N	T>5hours
Soybean Oil	550	2.520	4.165	60.50	N	
Soybean Oil	550	2.535	4.215	60.14	N	
Soybean Oil	550	2.545	4.235	60.09	N	
Soybean Oil	550	3.030	5.070	59.76	N	
Soybean Oil	550	3.030	5.140	58.95	N	

Soybean Oil	600	2.790	4.260	65.49	Y	
Soybean Oil	600	3.165	4.980	63.55	Y	
Soybean Oil	600	3.060	5.600	54.64	Y	
Soybean Oil	600	3.315	5.815	57.01	Y	
Soybean Oil	600	3.315	5.890	56.28	Y	
Soybean Oil	600	3.315	5.960	55.62	Y	
Soybean Oil	600	3.060	5.520	55.43	Y	
Soybean Oil	600	3.060	5.530	55.33	Y	
Soybean Oil	600	3.315	6.050	54.79	Y	
Soybean Oil	600	3.185	5.850	54.44	Y	Critical
Soybean Oil	600	2.790	4.450	62.70	N	
Soybean Oil	600	3.060	5.640	54.26	N	
Soybean Oil	600	3.060	5.720	53.50	N	
Soybean Oil	600	3.185	5.995	53.13	N	
Soybean Oil	600	2.790	5.305	52.59	N	
Soybean Oil	600	2.245	4.680	47.97	N	
Soybean Oil	600	2.245	5.330	42.12	N	

Table 2-4. Experimental results for the critical curve of Soybean oil

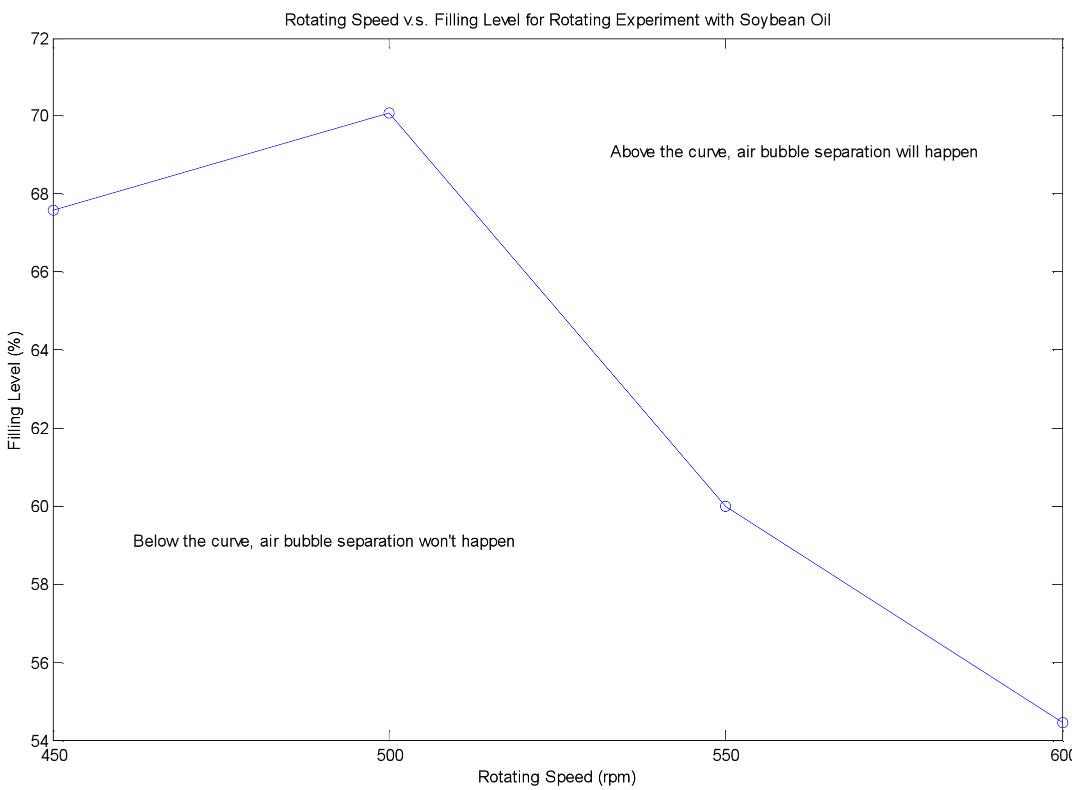


Figure 2-4. Critical value for bubble separation in Soybean oil with different Rotating speed and Filling level

The data in Table 2-4 can be concisely shown as Table 2-5.

Minimum filling levels for Soybean Oil for Bubble separation				
Rotating Speed (rpm)	450	500	550	600
Minimum Filling level (%)	67.57	70.08	60.00	54.44

Table 2-5. Relationship between rotating speed and minimum filling level for Soybean Oil

The relationship between the critical filling level (minimum filling level) and rotating speed can be expressed as a curve which is shown as following Figure 2-4.

2-3-4. Liquid and Particle

Three kinds of liquids were used in this experiment. Although the changing tendencies were similar for the behaviors of particle and air bubble, there was still some difference between experiments with different types of liquids. ****** (Figure 2-5) Some relevant physical properties of these liquids can be found in Table 2-2 (section 2-2).

From the experiment results, we found that under the same conditions, air bubble within the particle-suspension is much easier to separate than that within particle-free liquid.

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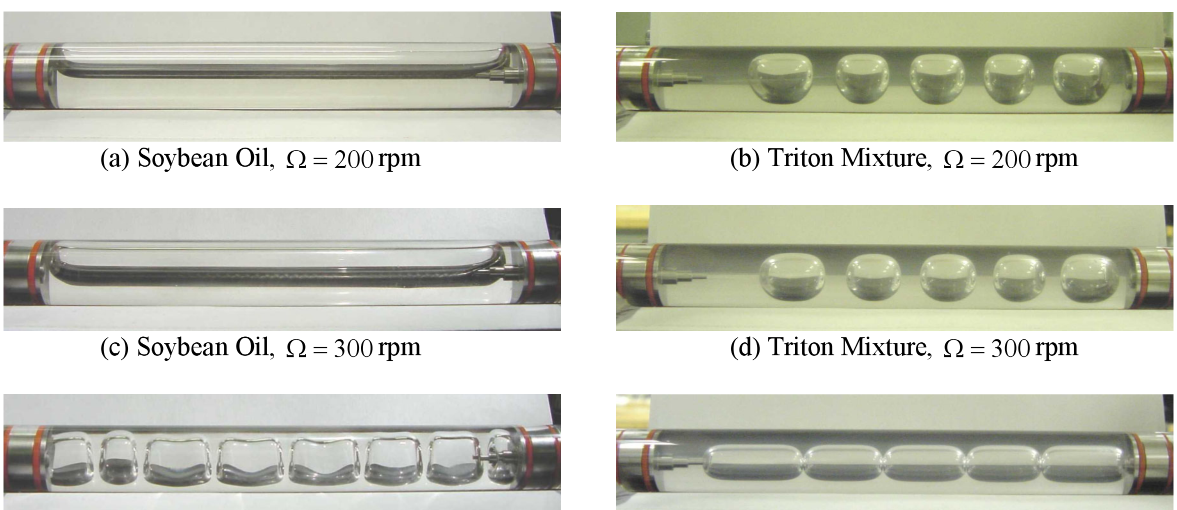


(a) Soybean Oil, $\Omega = 200$ rpm

(b) Triton Mixture, $\Omega = 200$ rpm

(c) Soybean Oil, $\Omega = 300$ rpm

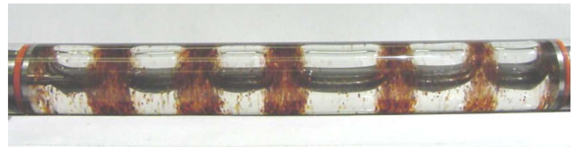
(d) Triton Mixture, $\Omega = 300$ rpm

(e) Soybean Oil, $\Omega = 600$ rpm

(f) Triton Mixture, $\Omega = 600$ rpm

Figure 2-5. Comparison of Soybean Oil and Triton Mixture under same conditions

(a) 16/30 AcFrac PR, $\Omega = 300$ rpm



(b) Polymer particle, $\Omega = 300$ rpm

(c) 16/30 AcFrac PR, $\Omega = 600$ rpm

(d) Polymer particle, $\Omega = 600$ rpm

Figure 2-6. Comparison of behaviors of different particles in Soybean Oil

2-3-5. Analysis and Discussion

Since the rotating speed is high, the effects of gravity are relatively small and negligible but the influence of centrifugal force becomes a main factor. Both hydrophobic and hydrophilic particles displayed similar properties in this experiment (Figure 2-6) because the initial hydrophobic particles were covered with liquid and seemed that they had been changed to 'hydrophilic'.

In this experiment, we observed that there were many small-sized transverse vortexes concentrated close to the ends of air bubbles. It can be seen clearly in the large size cylinder pipe with high rotating speed and comparatively lower filling level (Figure 2-7). The appearance of particle bands separation should be related to the large centrifugal force and the strong secondary flow to some extent.

For the experiment with particle-free fluids, the non-uniformity of pressure distribution is an important factor that should be responsible for the shapes of air bubbles. Thinking in terms of energy, the actual shapes of air bubbles are best for the fluids to maintain a steady state with the lowest energy.

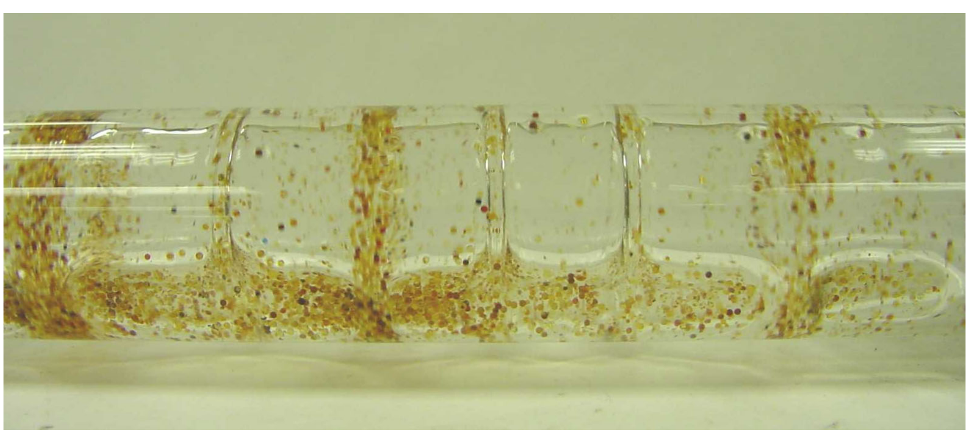


Figure 2-7. The transverse vortex in rotating experiment with polyox
(high rotating speed + low filling level)

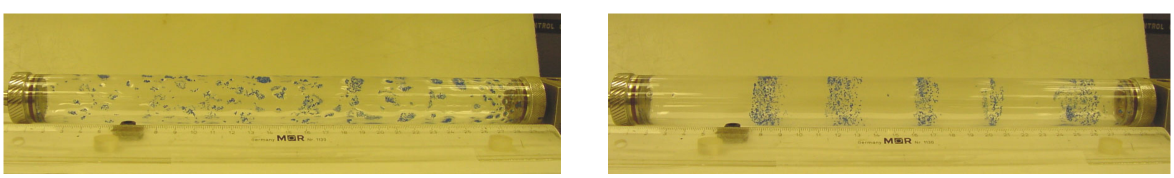
2-4. Expanding topics

In some additional experiments, we observed another kind of particle separation when the cylinder pipe was filled with suspension but the suspension contained two kinds of particles (Figure 2-8). The black particle is a kind of silicon particle and the brown one is a kind of polymer particle. Their diameters are comparable between each other. Obviously, the concentration of these particles was separated by fluid sections and uniformly distributed along the cylinder pipe. When we changed the filling level F, the particle concentration became much different (Figure 2-9). And we also observed air bubble separation. The formation of such kind of particle bands separation is very easy to produce even in very low viscous fluid such as water. It’s a dynamic problem in multiphase flow.

Experiment-3. Surface tension experiment

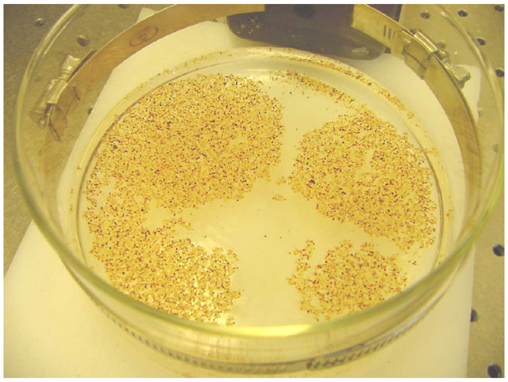
3-1. Overview

Generally, when we put some small particles into static water or some other liquids, these small particles will move towards each other because of influence of capillarity, especially for those hydrophobic particles. Such interesting phenomenon can be observed much easier if the viscosity of liquid and the density of particle are comparatively low. Actually, in both static and non-static liquid, particles always have a tendency to gather together as long as the surface tension can overcome the resistance caused by viscosity or some other factors. In the rotating cylinder experiment, particles in suspension change from the uniform-distribution state to a new state with clusters or bands separation (Figure 3-1). It is because the surface tension and centrifugal force can cause the fluctuation of particle concentration in some cases. And in the shaker experiment conducted in this spring, particles were forced to form different patterns with many particle blocks (Figure 3-2), which looks a little like to the Faraday Wave experiment. In a word, the surface tension plays an important role in all the above experiments and we’re interested in the mechanisms for different cases. In this experiment, we want to investigate some relevant features of particle concentration in the static and relatively high-viscous liquid such as Triton mixture and Glycerin.

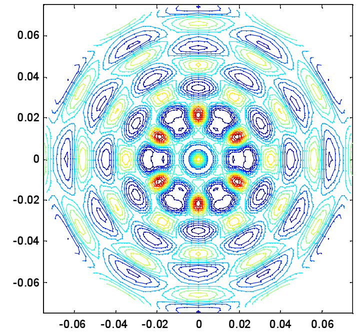


(a) Particle clusters (b) Bands separation

Figure 3-1.Particle cluster and bands separation in rotating experiment



(a) Particle blocks in shaker experiment



(b) Wave pattern in Faraday Wave experiment

Figure 3-2.Surface wave patterns in shaker experiment and Faraday Wave experiment

3-2. Set-up and experimental materials

This experiment was conducted in some shallow dishes made of glass. Sometimes we needed to use the light of projector. The digital camera could record a series of pictures as well as corresponding time. We selected four kinds of glass dishes with different inner diameters. They were $d_1 = 5$cm, $d_2 = 6$cm, $d_3 = 9$cm and $d_4 = 15$cm.

We conducted this experiment with three kinds of liquid including Glycerin, Soybean Oil and a comparatively low-viscous Triton mixture. Some physical parameters for these liquids are given in Table 3-1.

Type of liquid	Glycerin	Soybean Oil	Triton Mixture
Density ρ (g/cm^3)	1.173	0.915	1.241
Viscosity μ (cp)	1490	282	2950
Surface Tension (mN/m)	41.458 (Ω=3230rpm)	24.285 (Ω=4290rpm)	33.152 (Ω=2610rpm)

Table 3-1. Some physical parameters for experimental liquid samples

We chose two kinds of particles in our experiment, including a kind of large-sized plastic particle and a kind of small-sized polymer particle. See their physical properties in the following Table 3-2.

Type of particle	Polymer particle	Plastic particle	
Density ρ (g/cm^3)	1.034	1.170	
Diameter d (cm)	0.065	0.314	

Color	blue	white	
Material	polymer	plastic	

Table 3-2. Some physical parameters for experimental particle samples

An oil viscometer was used to measure the viscosity of liquid by $\nu = k\Delta t$, where the calibration coefficient $k = 2.3935$ cs/s, Δt is the time difference and ν the kinematic viscosity.

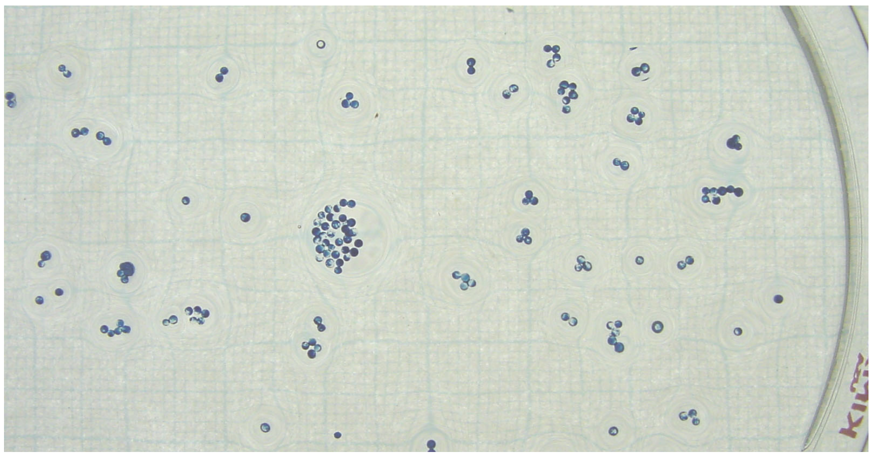


Figure 3-3. Collection of blue particles in shallow dish with Glycerin

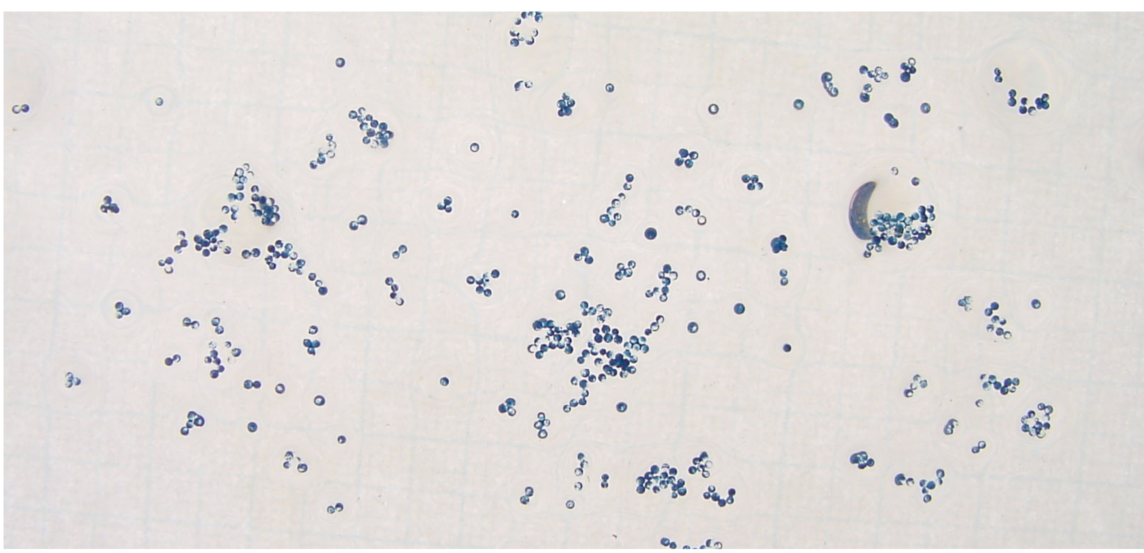


Figure 3-4. Collection of particles in turning over flat plate with Glycerin

3-3. Experimental Analysis

3-3-1. Experiment description

In this experiment, we focused on the properties of particle's behavior in different kinds of liquid. When we put some polymer particles into a glass dish with some liquid, they were divided into several particle clusters and moved towards each other in each cluster (Figure 3-3). For those comparatively high-viscous liquids, we tried to turn the shallow dish over after we put some particle in the surface of the thin liquid film on the bottom of dish, and we observed similar particle concentration as before. However, those particle clusters were not uniform in size probably because the bottom of dish was not flat. Then, we tried the turning over process with a flat glass plate, we also observed the particle blocks (Figure 3-4).

We also did some experiments with just two particles for three different kinds of liquids. These two particles tended to concentrate until they got together, so the distance between the surfaces of two particles experienced a changing process with the development of time (Figure 3-5). For liquids with different viscosity, the time scales were different. And the characteristics of the distance ~ time curves were not the same as well.

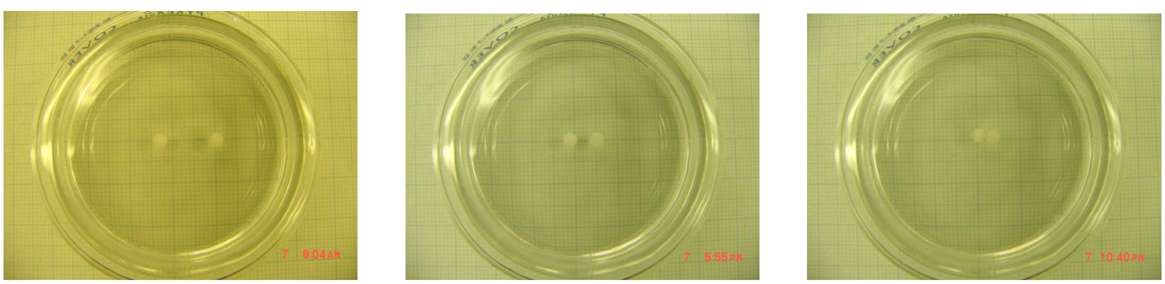


Figure 3-5. Illustration for the change of distance between two particle with the development of time

3-3-2. Instant Distance ~ Time curves

As discussed before, corresponding with different particles or liquids, the time scale and the changing tendency were different for the distance ~ time curves.

For large-sized plastic particles, the change of distance (between two particles) with time is shown in the following Figure 3-6. Both large-sized and small-sized particles can hardly get close between each other in high-viscous liquid because the influence of surface tension force is too small when viscosity is considered.

Similar measurement has been done for glycerin and soybean oil with the same-sized plastic particles. The experimental curve for Glycerin is given in Figure 3-7. Because the density of Soybean Oil is much smaller than that of particle in our experiment, particle can hardly stay at the surface of Soybean Oil for a relatively long time even the capillarity is considered. Particle sank to the bottom of dish each time, so we didn't get corresponding distance ~ time curve for Soybean Oil.

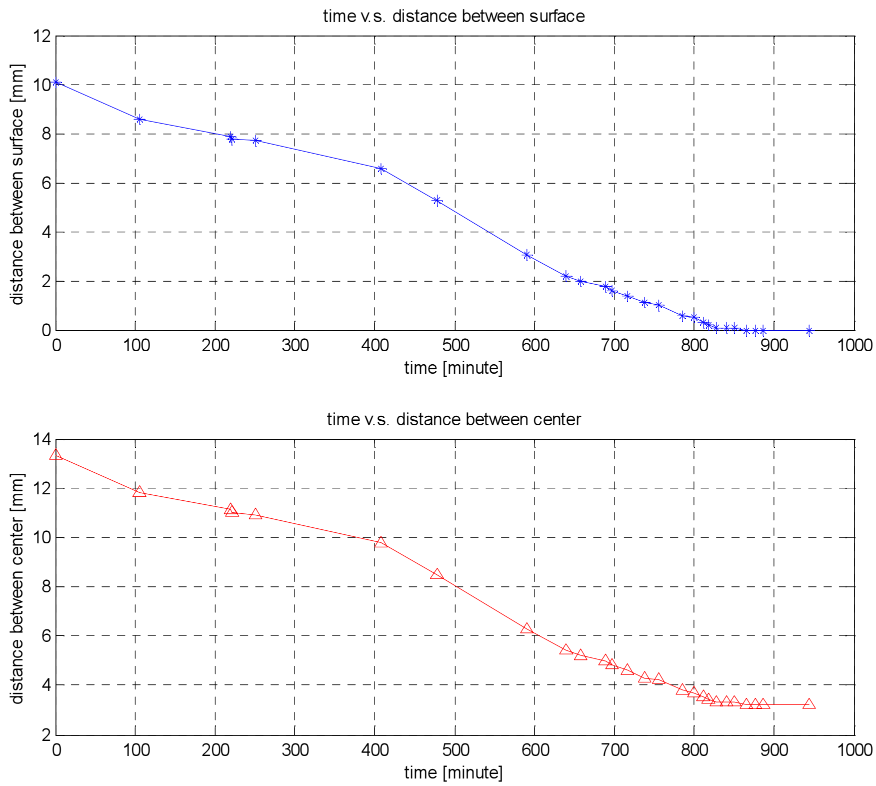


Figure 3-6. Change of distance between two particles v.s. Time
(Low-viscous Triton mixture liquid with $\rho_L = 1.241$ g/cm^3, large-sized plastic particle with $\rho_P = 1.170$ g/cm^3)

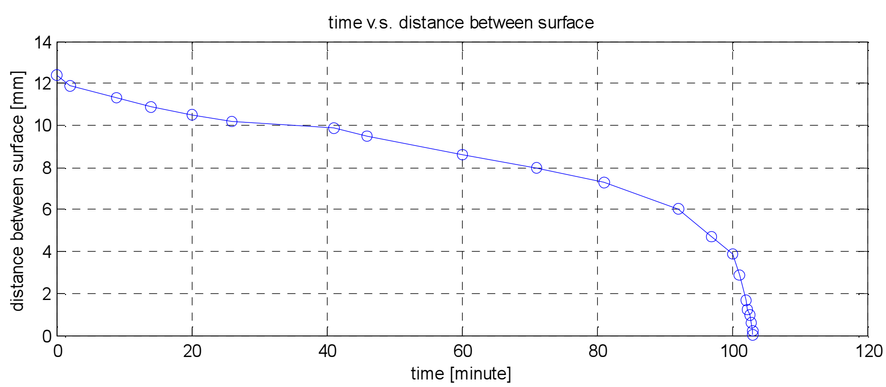


Figure 3-7. Change of distance between the surfaces of two particles v.s. Time
(Glycerin, large-sized plastic particle)

For the small-sized blue particles, it's difficult to measure the distance ~ time curve even in low viscous liquid because these small particles were so easy to be influenced by casual factors. Therefore, the results we got for small-sized particles were much different although experiments were conducted under the same conditions.

3-3-3. Viscosity and surface tension

There is no doubt that the viscosity of liquid plays an important role in particle's behavior. The experiment phenomenon stated in section 3-3-2 will happen only if surface tension force can overcome the viscosity resistance caused by the internal friction between molecules of liquid.

Surface tension is the force at the surface of a liquid due to adhesive forces of the liquid molecules for the walls of the container and the attractive forces of the molecules of liquid for each other. One way to think of surface tension is in terms of energy. The larger the surface, the more energy there is. To minimize energy, most fluids assume the shape with the smallest surface area. So the dispersedly distributed particles in liquid are often unstable, and will get together to minimize the surface of liquid.

Generally, the higher the viscosity, the lower speed the particles will move at. But the higher viscosity will correspond with the lower moving speed of particles. Furthermore, the size of particle is another important factor for particle's behavior. Smaller-sized particle will have a higher moving speed when compared with larger-sized particles.

Some relevant physical properties for experimental samples can be found in Table 3-1 (see section 3-2).

We repeated this experiment for higher-viscosity Triton mixture liquid (μ=5977cp). However, the two large-sized plastic particles didn't move at all no matter how close they were initially placed between each other. This is because the surface tension was not large enough to overcome the viscosity resistance.

3-3-4. Analysis and discussion

In both of the clustering experiment and the measurement of distance ~ time curves, the properties of particle's behavior were all dominantly influenced by surface tension and viscosity of liquid, which caused the concentration and re-distribution of particles on the surface of liquid. Both the polymer particle and the plastic particle were hydrophobic to Glycerin and Triton mixture.

To make the movement of particle easier and faster, the liquid was required to have the comparatively lower viscosity and higher surface tension. Particles, especially the large-sized particles, can hardly move in the high viscous liquid. The behavior of small-sized particles was unstable and non-repeatable because it's very easy to be influenced by external factors.

The time scale is not the only difference in the distance ~ time curves for liquids with different viscosity. Their changing tendencies were also different to some extent, especially when compared with that performed in water (see Figure 3-8).

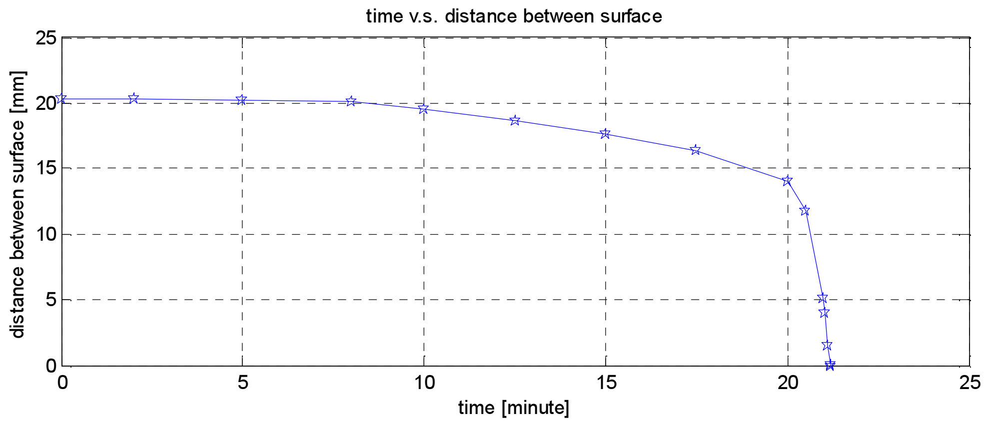


Figure 3-9. Change of distance between the surfaces of two particles v.s. Time
(Water with $\rho_L = 1.000$ g/cm^3, large-sized plastic particle with $\rho_P = 1.170$ g/cm^3)

3-4. Expanding topics

Internet Access: List of links for experimental figures

http://www.aem.umn.edu/research/particles/rotcylinder/highspeed/soybeanoil/

http://www.aem.umn.edu/research/particles/rotcylinder/highspeed/tritonmixture/

http://www.aem.umn.edu/research/particles/rotcylinder/lowspeed/highviscous/

http://www.aem.umn.edu/research/particles/rotcylinder/lowspeed/lowviscous/

http://www.aem.umn.edu/research/particles/properties/philic_phobic/

http://www.aem.umn.edu/research/particles/instability/polyox/

http://www.aem.umn.edu/research/particles/surfacetension/cluster/

Outline of the Summary for Experiments

Haoping Yang (June, 2002)

Experiment-1. Rotating experiments with high & low viscous Triton mixture under low filling level and relatively low rotating speed

1-1. Overview
1-2. Set-up and experimental materials
1-3. Experimental Analysis
    1-3-1. Experiment description and parameters analysis
    1-3-2. Film thickness (h_a and h_{min})
    1-3-3. The dimensionless β (and its calculation)
    1-3-4. Filling level F and Rotating speed Ω
    1-3-5. Analysis and Discussion
1-4. Expanding topics

Experiment-2. Rotating experiments with high-viscosity fluids under high filling level and high rotating speed

2-1. Overview
2-2. Set-up and experimental materials
2-3. Experimental Analysis
    2-3-1. Experiment description
    2-3-2. β and filling level F
    2-3-3. Critical curves
    2-3-4. Liquid and particle
    2-3-5. Analysis and Discussion
2-4. Expanding topics

Experiment-3. Surface tension experiment

3-1. Overview
3-2. Set-up and experimental materials
3-3. Experimental Analysis
    3-3-1. Experiment description
    3-3-2. Instant Distance-Time curves
    3-3-3. Viscosity and surface tension
    3-3-4. Analysis and discussion
3-4. Expanding topics

Internet Access: List of links for experimental figures + Brief introduction