Particle segregation and flow in slurries: dependence on the interstitial fluid viscosity and angular velocity.

Scott Sievert[†]
Dr. Kimberly Hill*

Introduction:

A granular binary mixture of particles differing in size in a rotating drum will tend to segregate. The mechanism by which this happens occurs in the ‘flowing layer’ of the drum. As the particles flow through the flowing layer, the smaller particles are more likely to fall through holes created by the moving particles, so they segregate towards the bottom of the flow. Thus, the larger particles are more likely to be pushed to the top of the flowing layer.

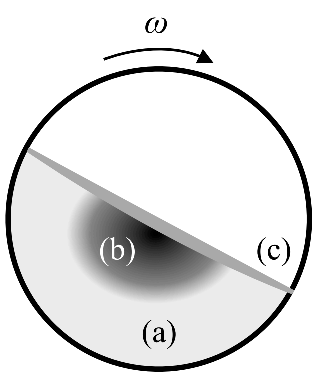

Figure 1: A circular drum rotating at an angular velocity ω, showing the half-moon pattern (a) represents large beads, (b) small beads, and (c) is the flowing layer.

When the particles ‘freeze,’ or come out of the flowing layer, the particles on the bottom of the flowing layer segregate towards the middle of the drum, and the particles on the top to the outside of the drum. Because the flowing layer is curved, the particles at the bottom of the layer freeze sooner (closer to the center) than the particles at the top. This is called radial segregation forms a ‘half-moon’ pattern.

When the drum is filled to about half full (51– 61% full [1]) something more interesting happens. The segregation pattern first forms the half-moon pattern, then forms stripes. These stripes form because small differences in volume fraction lead to different flowing layer velocities, and therefore, to stripes [3]. By the geometric argument proposed by Hill et. al, the stripe width is proportional to the depth of the flowing layer. It is known that a higher viscosity does increase the depth of the flowing layer [2], although this seems to be empirically observed.

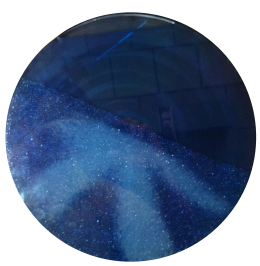
Figure 2. A typical stripe pattern, shown here after ~10 revolutions, in water at ω = 0.025 revolutions/s.

In this project, the effects of the viscosity interstitial fluid were investigated and speed of the drum rotation on the wavelength and width of the stripes were investigated. This has important applications in industry and chemical engineering.

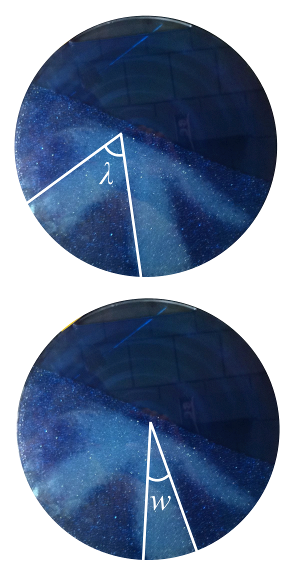

Figure 3: An example of measuring wavelength (top) and width (bottom)

Procedure:

Particles of two sizes (3mm blue glass beads and 1mm white glass beads) were placed in a quasi-two-dimensional rotating drum (r=14.5cm, depth = 8.0mm) and filled with an interstitial fluid (water and water-glycerin mixtures). 284 grams of 3mm and 234 grams of 1mm beads were placed in the drum, for a small:large ratio of 82.4% by mass. The drum was then

[†]College of Science & Engineering, U. of MN.
* Department of Civil Engineering, U of MN.

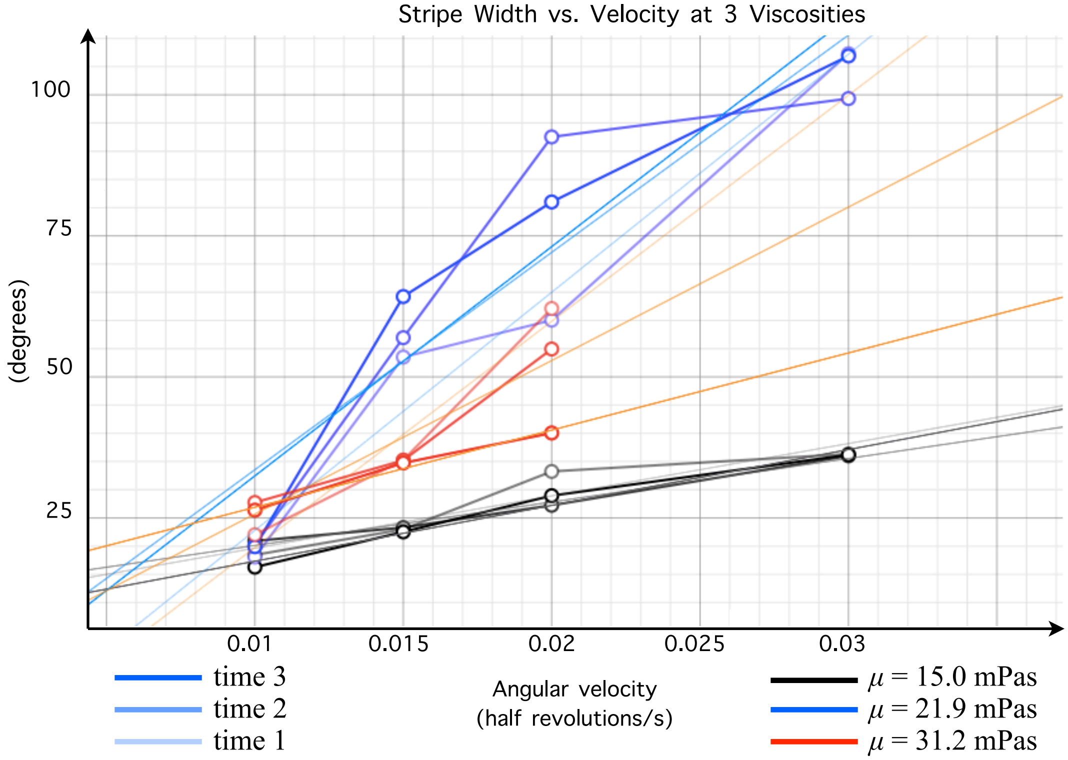

Figure 4: Here, the effect of interstitial fluid viscosity on stripe width is shown. Three different viscosities are shown for each velocity. At each velocity, the width at three different times are shown. T1 denotes the first time, and so on. The widths at any particular run can be read vertically.

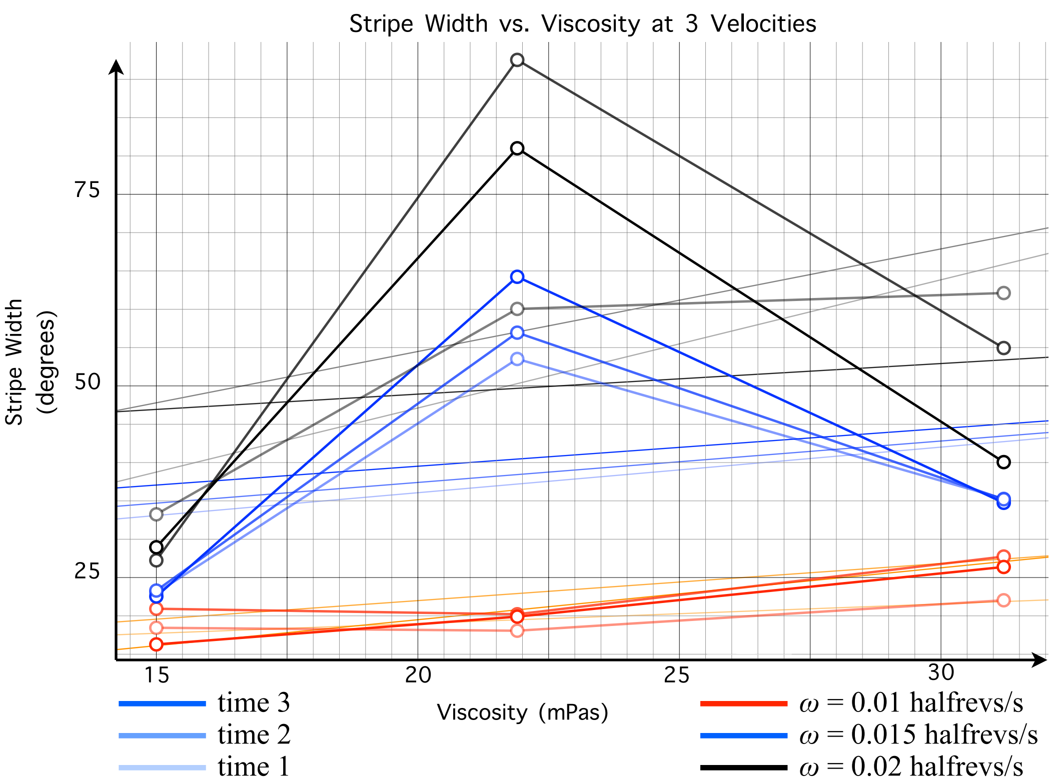

Figure 5: Following the same graphing scheme as Figure 4, stripe width vs. viscosity is shown at three different velocities.

spun using a stepper-motor (Compumotor) and recorded by a computer-controlled CCD camera (Cohu). The camera recorded a new frame every half-rotation. The drum was spun for ≥100 revolutions.

In each data run, the desired viscosity was achieved by adding glycerin or water to the drum using a small hole and a syringe, spinning the drum at a high velocity to to thoroughly mix it, then measuring a small sample (~17mL) with a digital viscometer (Brookfield). Typically, the particles were not taken out of the drum.

<u>Qualitative Description:</u>

At first, when the drum first starts spinning, the half-moon pattern forms very quickly, within a rotation. Since the half-moon pattern is unstable when the drum is filled just above 50%, it deteriorates into stripes. These stripes typically first touch the outside of the drum by 10-20 rotations. Then, the stripes stabilize over the next 40-50 rotations then

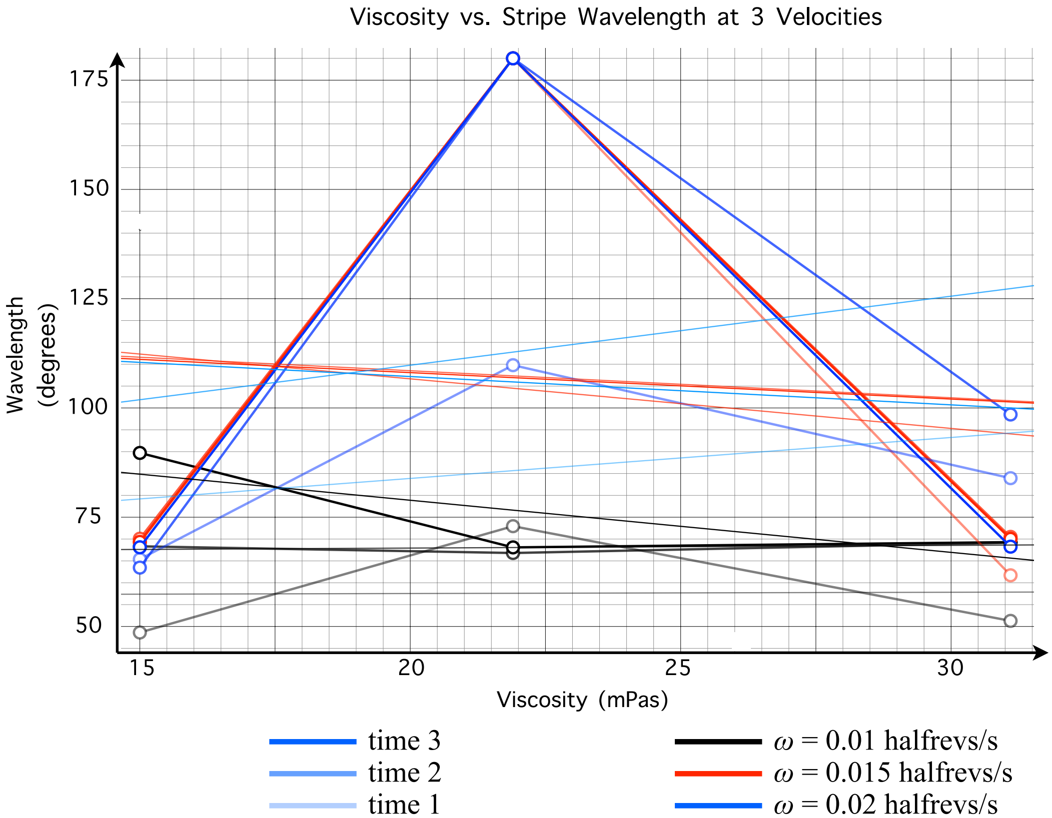

Figure 6: Here, the effect of drum angular velocity on stripe wavelength is shown. Three different velocities are shown for each viscosity. At each velocity, the width at three different times are shown. T1 denotes the first time, and so on. The wavelengths at any particular run can be read vertically.

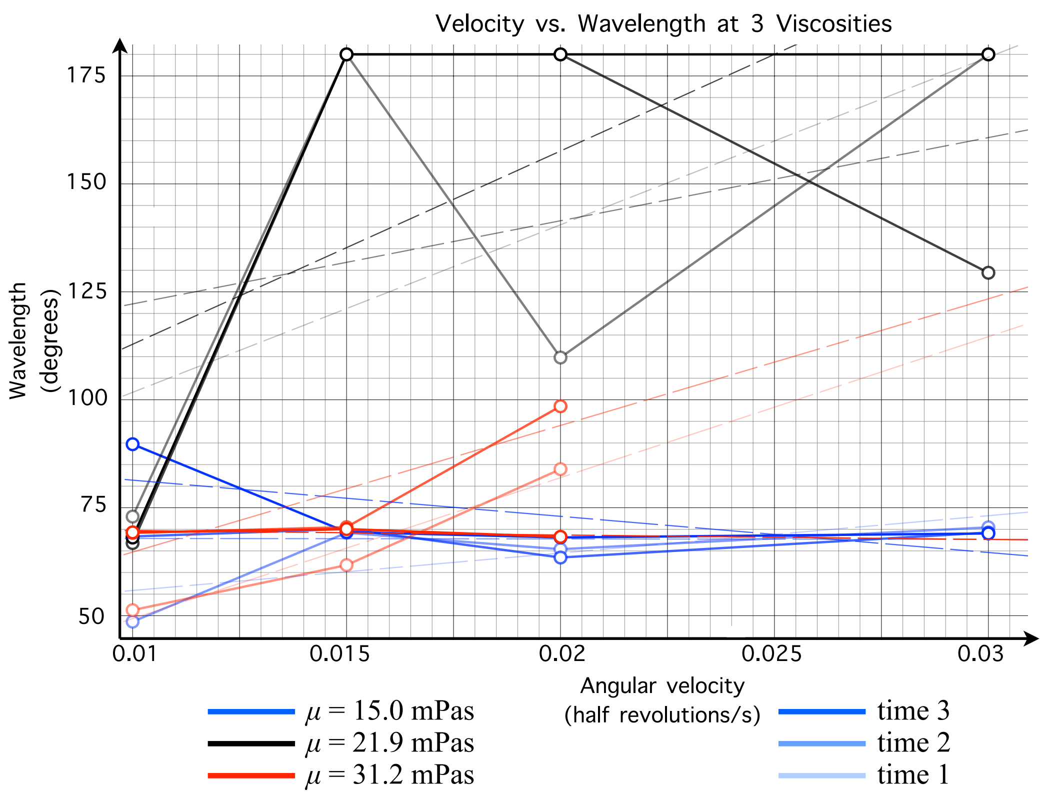

Figure 7: Here, the effect of angular velocity on wavelength is shown. Three different viscosities are shown for each velocity. At each velocity, the wavelength at three different times are shown. T1 denotes the first time, and so on. The wavelengths at any particular run can be read vertically.

stay uniform for the last 50-30 rotations.

However, there are exceptions to this typical pattern. In some cases, only a single large stripe formed (typically after forming the classic stripe pattern first). This pattern forms quicker than the typical pattern – it's typically stable around 50 revolutions.

Other exceptions happen when the drum rotates too fast or too slow. Too fast, and the particles in the flowing layer are separated by too much fluid for the segregation mechanism to work. Too slow and the steps of the stepper motor cause the thawing particles to avalanche, instead of thawing evenly. There exists a narrow range where stripes form.

In the case when the drum is rotating slightly too fast, the trailing edges of the stripes tend to be a smeared, and the both edges are curved slightly. When the drum is rotating slightly too slow, the stripes become more irregular and don't stabilize.

Typically, the stripes stayed of about consistent width over time, and increased with both viscosity and velocity. The stripes wavelength also was relatively stable over time.

Quantitative Results:

Data runs at four drum velocities (ω = 0.01, 0.15, 0.02 and 0.03 halfrevolutions/s) and four viscosities (μ = 1.063, 15.0, 21.9 and 31.2 mPas). However, one viscosity (μ = 1.063, water) and one velocity (ω = 0.03) didn't have overlap with the other viscosities and velocities, so we didn't include those points in most of the figures.

We found that stripe width scaled with velocity, and even in the one stripe cases. However, stripe width did not scale linearly with viscosity. We found that it instead increased (10 – 15°) over a small (15.2 mPas) difference in viscosity. In the one-stripe cases, stripe width increased a large amount.

It was also found that stripe wavelength tended to stay constant over both viscosity and velocity, except in the one-stripe cases (where it is 180°). The way wavelength was measured was by drawing extending two lines from the edges of two stripes, then measuring the angle between them. A better way to measure wavelength may have been to measure the angle between two lines that extend from the edges of two stripes that subtends at the center of the drum.

In addition to the graphs shown on the next page, we have also included a data table that has information about linear regression equations and R^2 values, standard deviations for error bars, as well as information about frame numbers for times 1, 2 and 3. Error bars have been left of the graphs below in interest of keeping the graphs clean and easy to read.

Photos of the stripes (at the third, most stable time) are also included, for μ = 15.0, 21.9 and 31.2 mPas and ω = 0.01, 0.15, 0.02 and 0.03 halfrevs/s. As well, photos of the flowing layer shape (one where stripes formed, and another where only one stripe formed) are also included, in Figure 9. It was originally thought that perhaps the shape of the flowing layer may cause the one-stripe pattern. However, the shapes of the flowing layers are very similar, so this hypothesis is ruled out.

Error may have come from several places. Fill level may have varied slightly between some trials, or the beads may have worn, becoming not-quite perfectly spherical, which changes their behaviors and properties.

Summary:

In this study, we investigated the effects of interstitial fluid and drum angular velocity on stripe width and stripe wavelength. For stripe width, we found moderate increases for viscosity (due to the narrow range) and larger increases for angular velocity. For wavelength, we found little to no increase (except in the one-stripe case), which may have been due to the way wavelength was measured.

Future work may include investigating the effect of size ratios and/or density ratios on the width and wavelength of the stripes, investigating the effect of velocity and viscosity over a larger range (although there exists a narrow range where the flow regime is between avalanching and fluidization).

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(1) Hill, K.M., Gioia, G., Amaravadi, D. 2004. Radial segregation patterns in rotating granular mixtures: Waviness selection. Physical Review Letters, 93: 224301.
(2) N. Jain, J. M. Ottino and R. M. Lueptow (2004). Effect of interstitial fluid on a granular flowing layer. Journal of Fluid Mechanics, 508, pp 23-44
(3) N. Jain, J.M. Ottino, R.M. Lueptow. 2005. Regimes of segregation and mixing in combined size and density systems: an experimental study. Granular Matter 7: 69-81.
(4) N. Thomas. 2000. Reverse and intermediate segregation of large beads in dry granular media. Physical Review E. Volume 62, Issue 1.

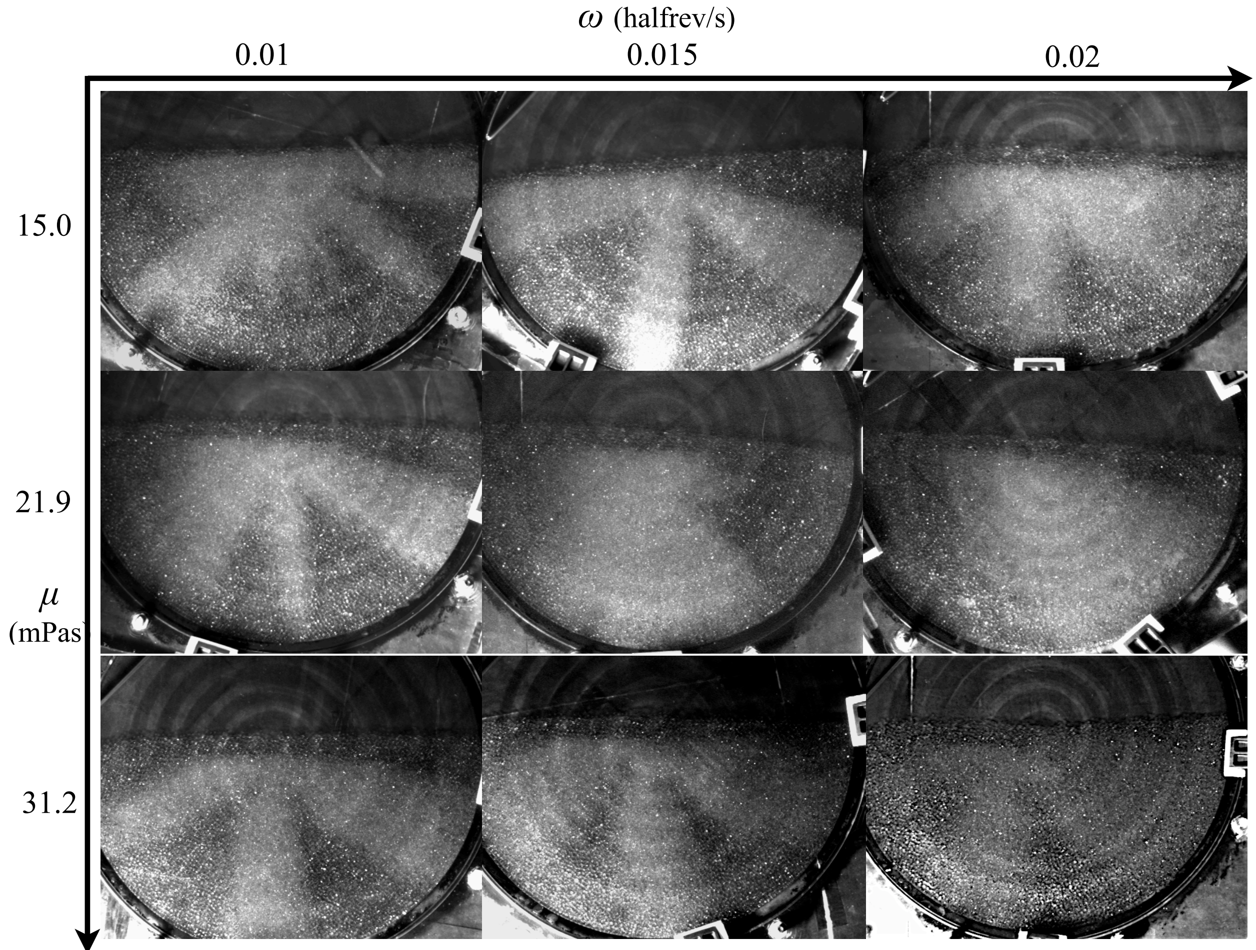

Figure 8: Selected images at time 3, showing the stripe pattern, for each viscosity (μ = 15.0, 21.9, 31.2 mPas) and angular velocity (ω = 0.01, 0.015, 0.02 halfrevolutions/s).

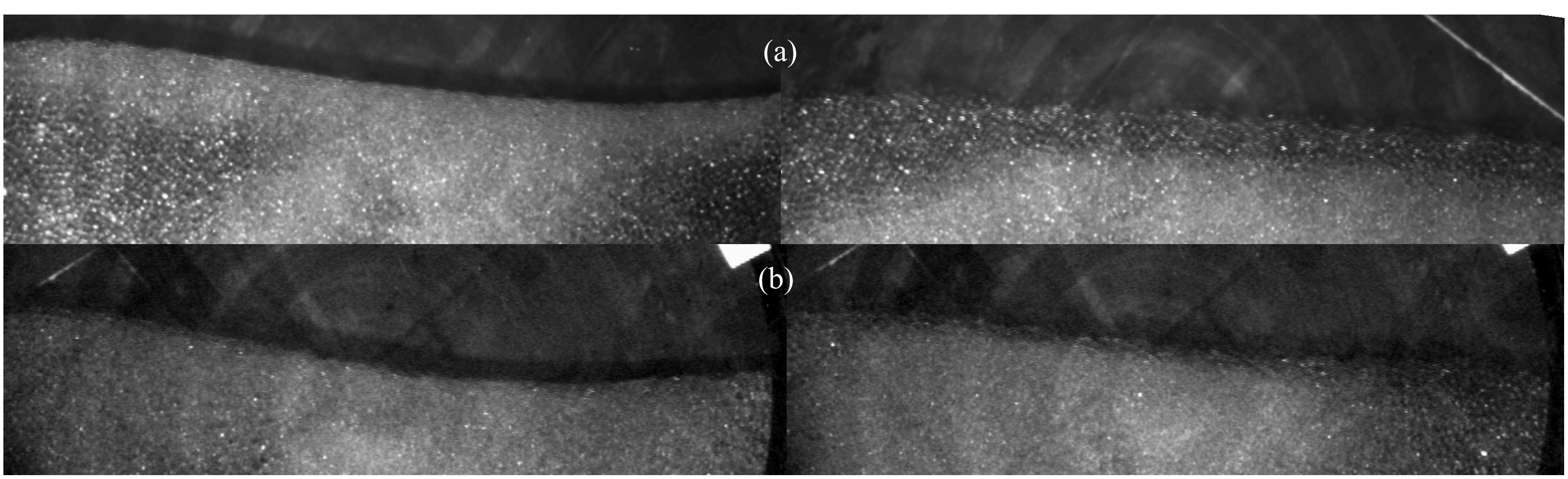

FIgure 9: Flowing layers at time three, while either the small (white) beads or large (black) are in the flowing layer. (a) is ω=0.015 hrev/s, which formed multiple stripes, and (b) is ω=0.02, which only formed one stripe. Both are at viscosity μ = 21.9 mPas.

velocity halfrevs/s)	Width T1	Width T2	Width T3	Std T1	Std T2	Std T3	T1 (frame number)	T2	T3
0.01	18.44	20.93	16.28	2.76	7.82	3.25	20	100	180
0.015	22.98	23.30	22.53	4.31	4.71	3.35	40	102	180
0.02	33.24	27.24	28.95	6.02	3.92	9.98	30	105	180
0.03	36.35	36.01	36.20	10.97	5.44	5.57	30	105	180
0.01	18.06	20.21	19.90	5.82	4.85	6.41	35	100	170
0.015	53.52	56.95	64.24	10.41	14.26	6.42	35	102	180
0.02	60.05	92.53	81.01	30.75	9.18	8.07	25	75	130
0.03	107.28	99.33	106.89	13.75	21.25	9.92	25	90	140
0.01	22.04	27.74	26.38	6.25	11.67	6.37	25	153	223
0.015	35.27	35.21	34.75	14.26	6.81	4.59	30	120	210
0.02	62.12	54.94	40.06	9.75	18.98	15.34	40	125	220

Table 1: Stripe width table. This table has information about stripe width, and assorted metadata, such as the frame numbers (each frame = 1/2 revolution) of times 1, 2 & 3 (T1, T2 & T3), as well as the standard deviation of the stripe widths, over ~10 frames.

Velocity	Lamda T1	Lamda T2	Lamda T3	Std T1	Std T2	Std T3	T1 (frame numbers)	T2	T3
0.01	48.62	68.34	89.71	13.79	19.94	28.50	20	100	180
0.015	69.19	70.09	69.36	10.17	4.96	5.24	40	102	180
0.02	65.40	63.47	68.12	15.50	11.34	14.60	30	105	180
0.03	70.45	69.26	69.04	18.06	8.57	6.53	30	105	180
0.01	72.95	66.81	68.10	13.58	11.57	24.78	35	100	170
0.015	180.00	180.00	180.00	0.00	0.00	0.00	35	102	180
0.02	109.79	180.00	180.00	44.63	0.00	0.00	35	92	150
0.03	180.00	129.42	180.00	0.00	49.86	0.00	25	102	180
0.01	51.28	69.17	69.29	14.45	16.16	9.54	25	153	223
0.015	61.71	70.50	70.06	15.31	9.98	7.94	32	121	210
0.02	83.93	98.50	68.26	19.46	16.94	21.06	30	125	220

Table 2: Stripe wavelength table. This table has information about stripe wavelength, and assorted metadata, such as the frame numbers (each frame = 1/2 revolution) of times 1, 2 & 3 (T1, T2 & T3), as well as the standard deviation of the stripe wavelengths, over ~10 frames.