Separation of Chiral Particles in Shear Flow

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This experiment examines the separation of chiral particles via shear flow. We placed 3-D printed chiral particles in a high viscosity fluid and used a Taylor-Couette apparatus to generate a shear flow. The results of this experiment support research by M. Makino and M. Doi [1–3] and give us a degree of insight into naturally occurring chiral behavior.

A. Motivation

Sorting particles based on their characteristics is a common goal in industrial and commercial applications. In biology and chemistry, small differences in molecules can change their impact on the macroscopic scale. One such physical difference is chirality. Choosing an incorrect handedness of a pharmaceutical enantiomer could have adverse or even fatal results. Furthermore, microorganisms use the handedness of their flagella to steer their locomotion[4]. Observations of chiral objects in shear flow may help us understand how such biological systems behave in certain environments.

B. Theory

We consider a sheer flow,

$$\mathbf{v}(x, y, z) = \dot{\gamma} y \hat{x}. \tag{1}$$

Here, $\mathbf{v}$ is the fluid velocity, $\dot{\gamma}$ is the shear rate, and $\hat{x}$ is the direction of shear flow, in this case a unit vector in the x direction[2]. y represents a linear gradient of force in the $\hat{y}$ direction (see Figure 1).

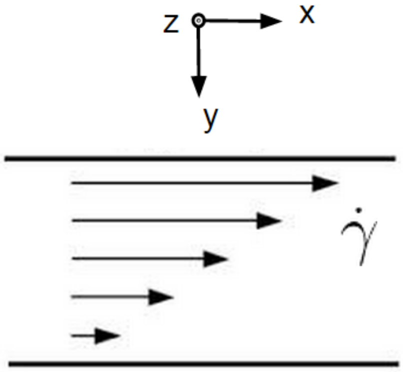

FIG. 1: Force gradient viewed from above.

We then consider a particle inserted into this flow.

$$\langle \mathbf{V}(t) \rangle = \mathbf{v} + \dot{\gamma} \langle \tilde{\mathbf{g}} \mathbf{N} \rangle \tag{2}$$

$\mathbf{V}(t)$ is the velocity of the particle, $\tilde{\mathbf{g}}$ is a tensor encompassing the geometry and size of the particle, and $\mathbf{N}$ is the direction of shear as it applies to particle geometry[1]. Summarily, the particle's velocity is a sum of flow advection ($\mathbf{v}$) and motion due to the particle's geometry in concert with applied shear. One may also include a term for Brownian motion $\mathbf{V_b}$, but the size of our particles was sufficiently large to make this term negligible. Due to the force gradient in $\hat{y}$, an inserted object experiences a torque about its $\hat{z}$ axis. This rotation created by this torque may, depending on the geometry of the object, lead to motion in the $\hat{z}$ direction. We can write this motion as

$$\langle V(z) \rangle = \chi g a \dot{\gamma}, \tag{3}$$

Where $\chi = \{0, -1, 1\}$ indicates the direction of the particle's chiraltiy, g is a constant based on particle geometry, and a is the particle size[2]. We see that this is simply a reduction of equation (2) to one dimension.

C. Methods

1. Apparatus

A Taylor-Couette device was the centerpiece of our experiment. The device consisted of a 3-D printed base and lid designed to hold the dowel in place, a transparent PVC tube, and the aforementioned dowel which was left free to rotate along the central axis of the cylinder. All parts, excepting the pvc tube, were printed on a Makerbot Replicator. The distance between the outer tube and the inner dowel gives just enough clearance to let the particles align themselves freely. The chiral particles are small helices described in Figure 2. Ten left handed particles, ten right handed particles and ten neutral particles (consisting of flat rectangles) were printed and used. The Taylor-Couette device was filled with transparent corn syrup, with a viscosity of 1450 − 2170 cSt [6]. The rotation of the inner dowel was provided by a cordless drill, connected to a power supply unit. The velocity of the rotation was controlled by regulating the voltage of the drill. For the third experiment the Taylor-Couette device

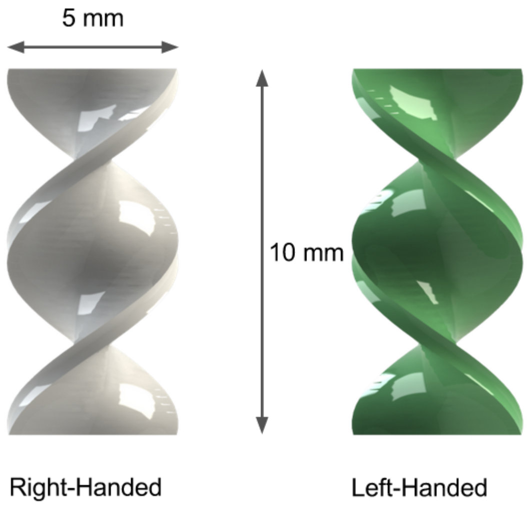

FIG. 2: Model of the left hand chiral particle used in this experiment. Length: 10 mm. Width: 5mm. Revolutions: one.

was filled with a mixture of corn syrup and a kallieroscopic fluid.

The data acquisition was performed with a single camera. In the first experiment the dowel was placed in the midst of four mirrors tilted at a 45 degree angle, and the camera was placed above the apparatus. This ensured a 360 degree view of the Taylor-Couette device, as seen in figure 3. In the second and third experiments the camera was mounted facing the side of the Taylor-Couette device, and no mirrors were used.

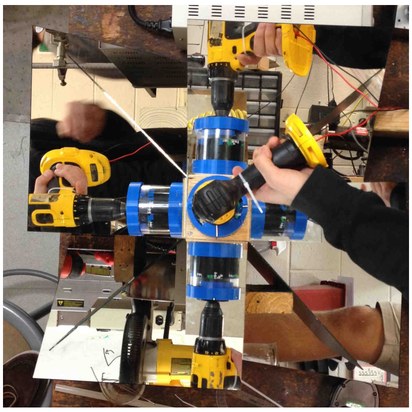

FIG. 3: Birdseye view of the setup for the first part of the experiment

2. *Procedure*

During the first experiment the Taylor-Couette device was loaded with ten right handed particles, ten left handed particles and ten non chiral particles. The system was spun for approximately one minute in clockwise and counterclockwise directions at 5.0 V, 1.4 revolutions per second. The data was then imported into Matlab via a manual tracking algorithm. The mean z position of each particle type was calculated and plotted as a function of time.

During the second experiment the Taylor-Couette device was loaded with one left handed particle and one right handed particle, each placed on opposite sides of the center dowel. The rotation speed was varied between 1.9 and 0.6 revolutions per second. The alignment angles of the particles were recorded with a manual tracking algorithm in Matlab and plotted as a function of time.

During the third experiment the Taylor-Couette device was filled with different mixtures of corn syrup and kallieroscope fluid. We first tested kallieroscope fluid at 3 to 6 V, and next a mixture of syrup and kallieroscope fluid at 3 to 15 V. These experiments were conducted in order to observe the potential formation of Taylor vortices (see Figure 4. These vorticies are of interest given that they, if present at the shear rates in our experiment, would effect the orientation of the particles.

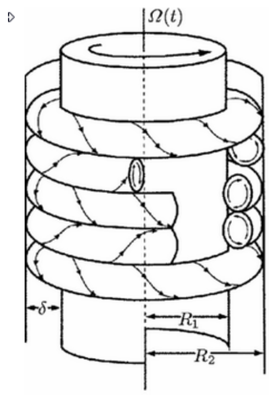

FIG. 4: An illustration of Taylor vorticies in a Taylor-Couette cylinder, courtesy APS.org[5].

D. Results

Data for the average z position of each handedness versus time is shown in Figure 5. From these plots, we see that left handed particles have a negative separation velocity in clockwise fluid flow, as do right handed particles in counter-clockwise flow. This negative velocity drops off as the particles begin to reach the bottom of the cylinder, creating a "knee" in the plot. This is further demonstrated by Figure 6, which shows an average negative velocity up to about 29 seconds. Additionally, the blue particles show no change in position for either direction of fluid flow, as expected.

We also took a linear fit of the position data for the right-handed particles, cutting off the fit before the knee at 25 seconds. The fit has an r^2 value of 0.79, indicating that the trend is indeed linear as expected. However,

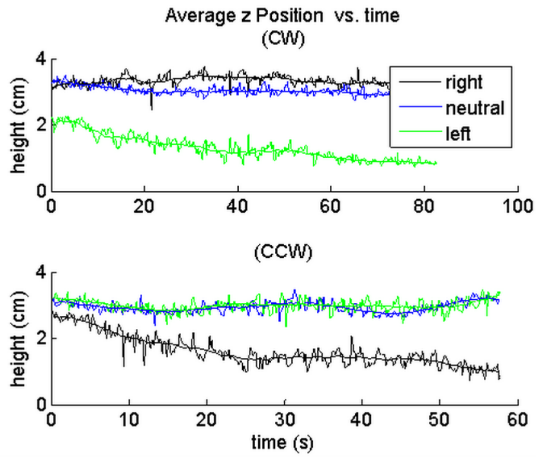

FIG. 5: The average positions of ten particles of each handedness versus time. Data is shown for one clockwise (CW) and one counter-clockwise (CCW) experiment.

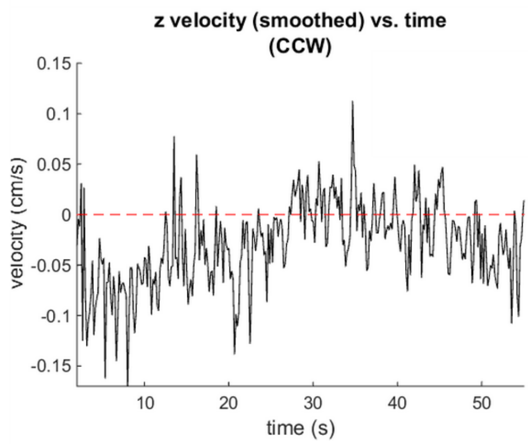

FIG. 6: Plot of velocity versus time generated from the time derivitive of the couter-clockwise position vs. time data in Figure 5

there is significant noise in the data. Future repetition of this experiment with a taller cylinder should help to confirm a linear trend for position.

The alignment plots (Figures 8, 9) merits further explanation. Since the alignment was only recorded from one direction, there are gaps in the data. This isn't a problem however, since we are testing, Makino paper's [3] prediction that the particles should align. That effect should be visible even if only one side of the cylinder is observed. Another thing worth pointing out is that a collision occurred at $t = 5s$ in Figure 8, which introduced an abrupt change in alignment.

For the kallieroscope-corn syrup mixture, we did not observe banding in the voltage regime (3-5 V) of our above experiments. The first indication of banding appeared between 9-12 volts. This indicates that Taylor vorticies did not play a role in particle orientation.

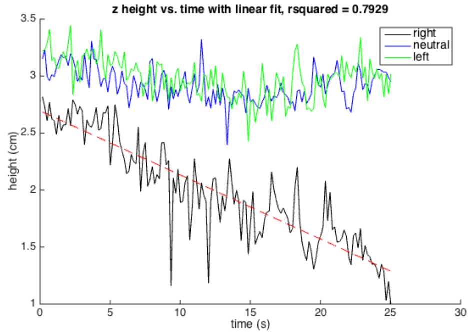

FIG. 7: Example of a linear function fit to the first data points, rsquare = 0.7929

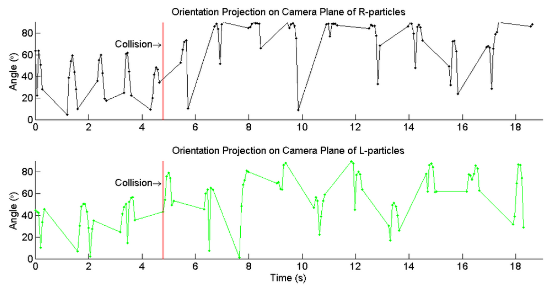

FIG. 8: The alignment of one right handed and one left handed particle over time, 1.88 rev/s

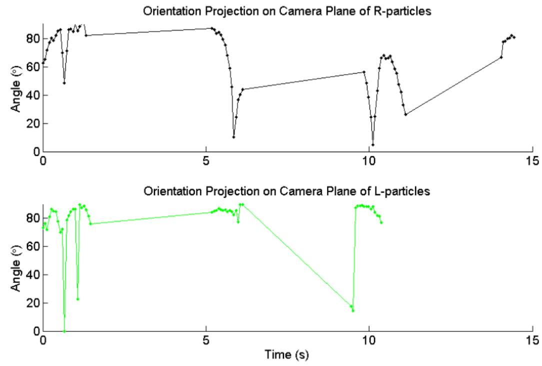

FIG. 9: The alignment of one right handed and one left handed particle over time, 0.578 rev/s

E. Conclusions

The data from the first experiment clearly demonstrates that the separation effect does appear in practice for helices in a Taylor-Couette device. The z displacement appears to be linear, but the noise makes it hard to determine.

From the data in Figures 8, 9 there are no signs of the alignment effect mentioned in the paper by Makino [3] that would indicate the particles align themselves over time. Data was collected for a duration of about 20 seconds, but no visible alignment could be observed for tests of longer durations (about 90 seconds) either. From our kallieroscope experiments, we were also able to demonstrate that there were no Taylor vortices present at 5V that might interfere with particle alignment.

[1] M. Makino and M. Doi, Migration of twisted ribbon-like particles in simple shear flow, *Phys. Fluids* **17**, 103605 (2005).
[2] M. Makino, L. Arai, and M. Doi, Shear Migration of Chiral Particle in Parallel-Disk, *Jour. Phys. Soc. Japan* **77**(6), 064404 (2008).
[3] M. Makino and M. Doi, "Motion of micro-particles of complex shape," *Prog Polym Sci* **30**(8), 876 (2005).
[4] V. Kantsler, J. Dunkel, M. Blaney, R. Goldstein, "Rheotaxis facilitates upstream navigation of mammalian sperm cells," *eLife*, 3:e02403 (2014)
[5] A. Youd and C. Barenghi, "Reversing and nonreversing modulated Taylor-Couette flow at finite aspect ratio," *Phys. Rev.* **72**, 056321 (2005)
[6] "Viscosity Chart," Available on `http://www.research-equipment.com/viscosity\%20chart.html`

Appendix A: Corn syrup-kallieroscope mixture

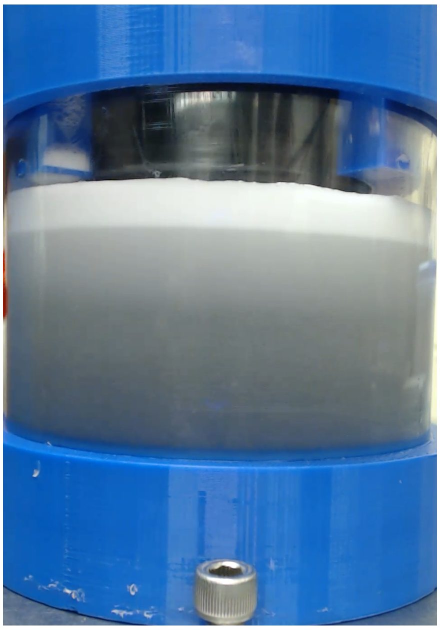

FIG. 10: Corn syrup-kallieroscope mixture spinning at 3V.

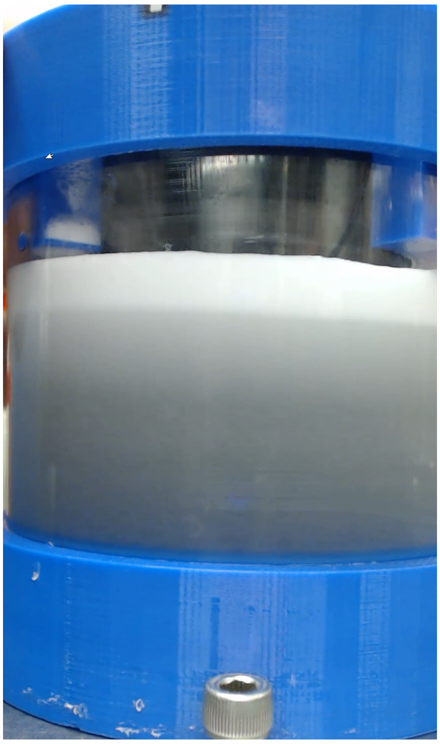

FIG. 11: Corn syrup-kallieroscope mixture spinning at 5V.

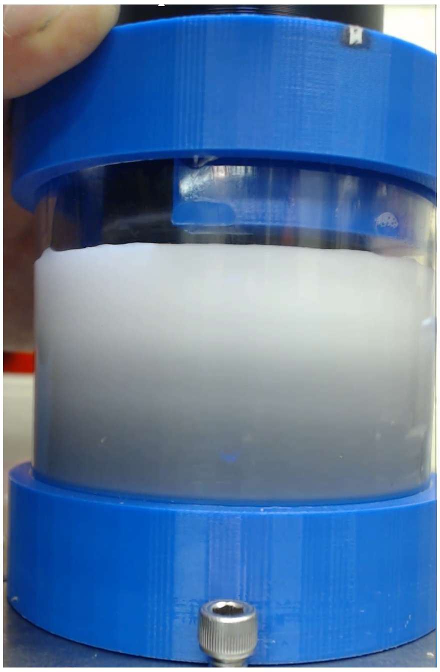

FIG. 12: Corn syrup-kallieroscope mixture spinning at 15V..

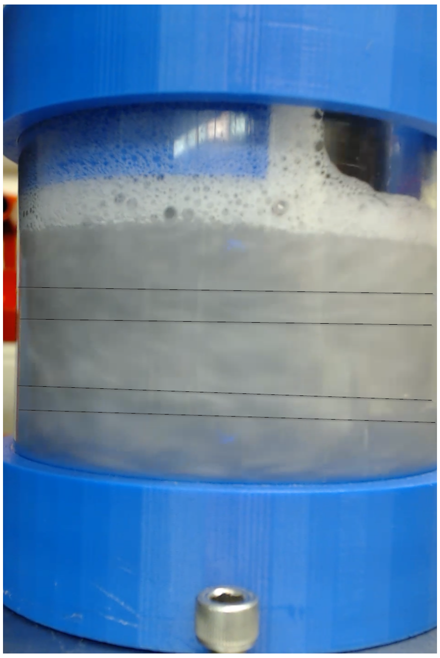

FIG. 13: Reference picture of kallieroscope only spinning at 5V. Relatively dark reigons between convection bands are highlighted between black lines.