Shear Migration of Chiral Particles in a Shear Flow

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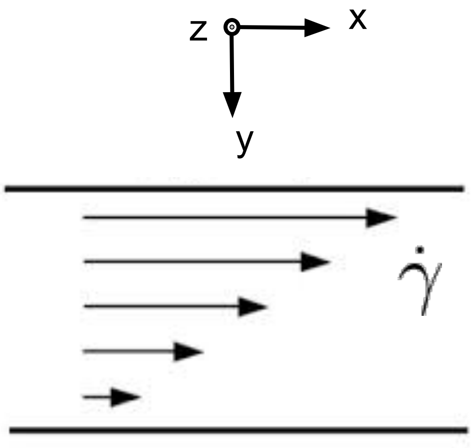
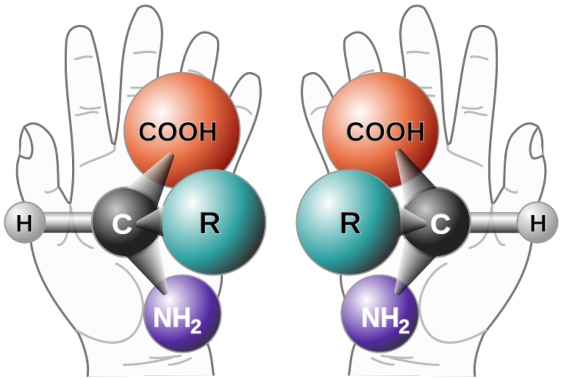
Outline

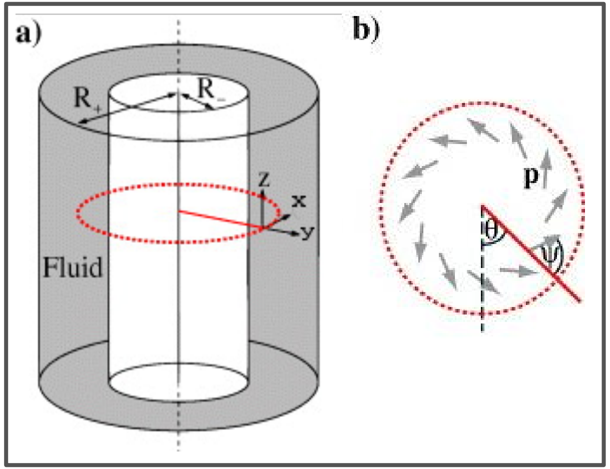
- Concept review
- Motivation -Sperm Rheotaxis, etc.
- Theory - Mathematical Interpretation
- Apparatus
- Procedure - Position, Orientation vs. Time
- Results-
- Conclusions

Review

- Chirality
- Shear Flow
  - Taylor-Couette flow







Courtesy of http://www.nai.arc.nasa.gov/

Courtesy of IOP Science

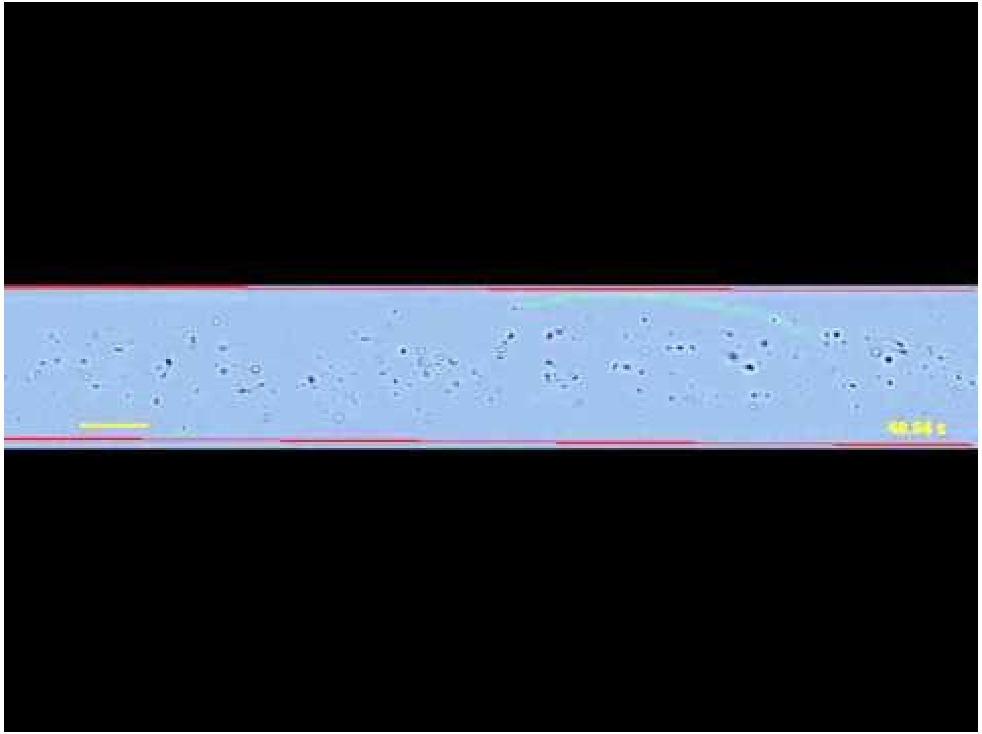
Courtesy of univ-paris-diderot.fr

Motivation

- To better understand how chiral objects behave in a shear flow
- To experimentally verify the paper by M. Makino and M. Doi

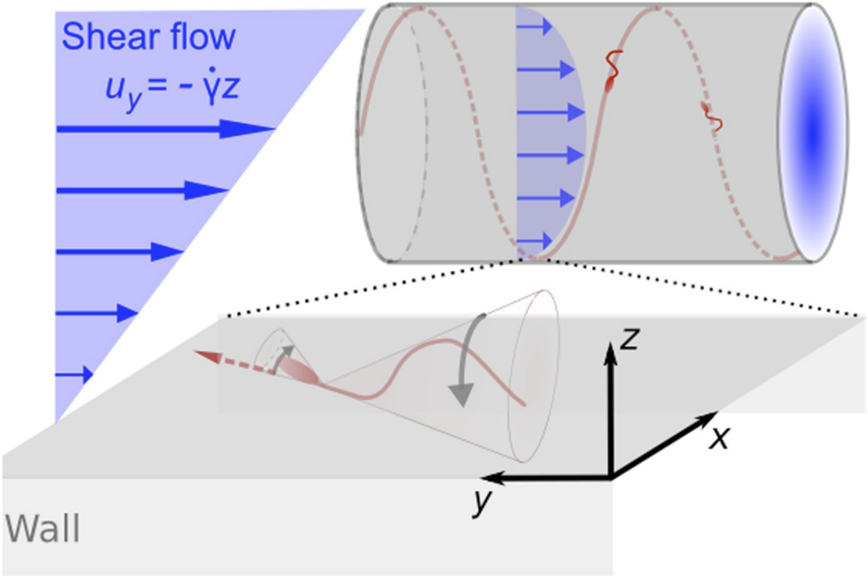
Masato Makino and Masao Doi, “Migration of twisted ribbon-like particles in simple shear flow,” *Phys. Fluids* **17**, 103605 (2005).

Motivation: Sperm Cell Rheotaxis



Kantsler, Dunkel, Blayney, and Goldstein, “Rheotaxis facilitates upstream navigation of mammalian sperm cells,” *eLIFE*, 052714 (2014).

Motivation: Sperm Cell Rheotaxis



Swim speed

Orientation

Net Velocity

Flow Advection

$$\dot{\boldsymbol{R}} = V\boldsymbol{N} + \sigma\bar{U}\boldsymbol{e}_y,$$

$$\dot{\boldsymbol{N}} = \sigma\dot{\gamma}\alpha \begin{pmatrix} N_x N_y \\ N_y^2 - 1 \end{pmatrix} + \sigma\dot{\gamma}\chi\beta \begin{pmatrix} N_z^2 - 1 \\ N_z N_y \end{pmatrix} + (2D)^{1/2}(\boldsymbol{I} - \boldsymbol{N}\boldsymbol{N}) \cdot \boldsymbol{\xi}(t).$$

Chirality (+1, -1, 0)

Amplitude

Geometry (Alignment against flow)

Geometry (Turn rate)

Gaussian white noise

Kantsler, Dunkel, Blayney, and Goldstein, “Rheotaxis facilitates upstream navigation of mammalian sperm cells,” *eLIFE*, 052714 (2014).

Theory

- Navier Stokes' equation

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \nabla\cdot\mathbf{T} + \mathbf{f}$$

- Peclet number

$$\mathrm{Pe} = \frac{\eta a^3 \dot{\gamma}}{k_B T}$$

- Brownian Motion

Theory

$$< V_z >= 0$$

For non chiral particle

$$< V_z >= - < V_z' >$$

For different chirality

$$< V_z >= B a\dot{\gamma}\mathrm{Pe}^2$$

For Pe << 1

$$< V_z >= C a\dot{\gamma}$$

For Pe >> 1

Particle shape

Theory

- Exponential displacement: $$\dot{z} = Ca\frac{\Omega z}{d}$$ $$z = z_0 e^{Ca\Omega t/d}$$
- Makino's work shows that:

$$\langle V_z \rangle = \frac{1}{2}\tilde{g}\dot{\gamma}\left\langle u_{3x}^2 - u_{3y}^2 \right\rangle$$

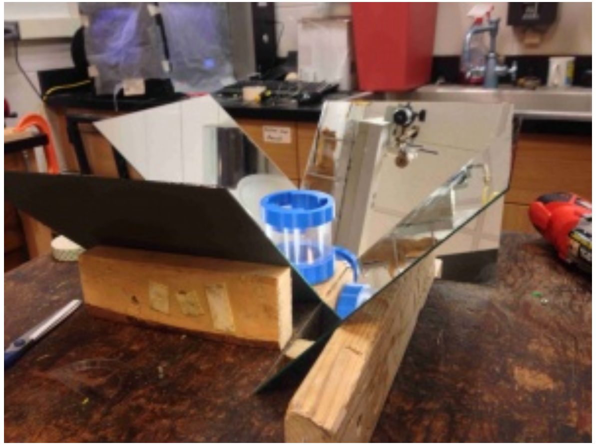
Masato Makino and Masao Doi, "Migration of twisted ribbon-like particles in simple shear flow," *Phys. Fluids* **17**, 103605 (2005).

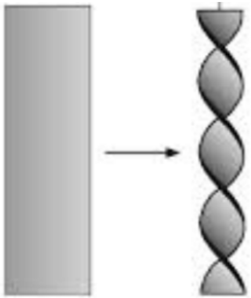
Apparatus

- 3-D printed Taylor-Couette cylinder generates shear flow

- Used corn syrup as viscous fluid (1.3806 Pa·s)

- Ribbon shaped chiral particles and flat particles, color coded

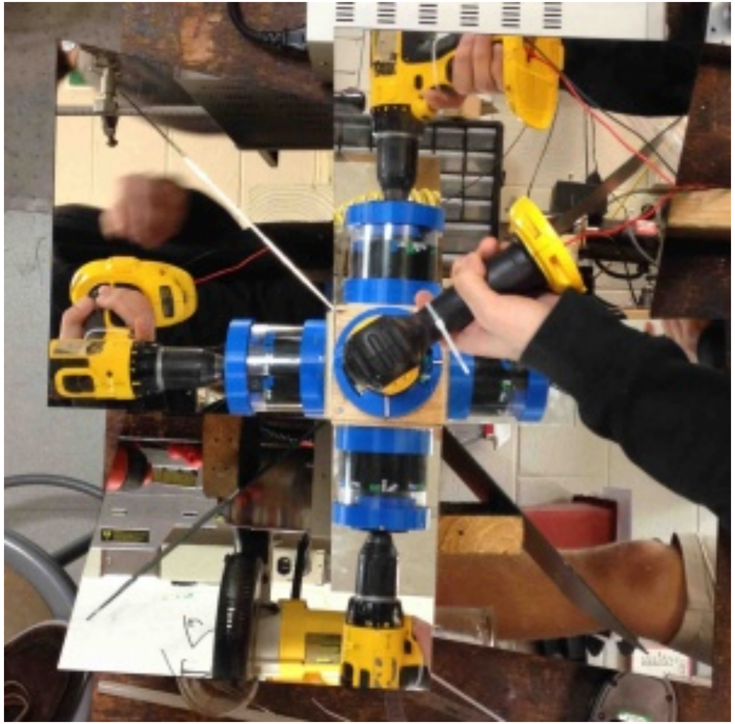


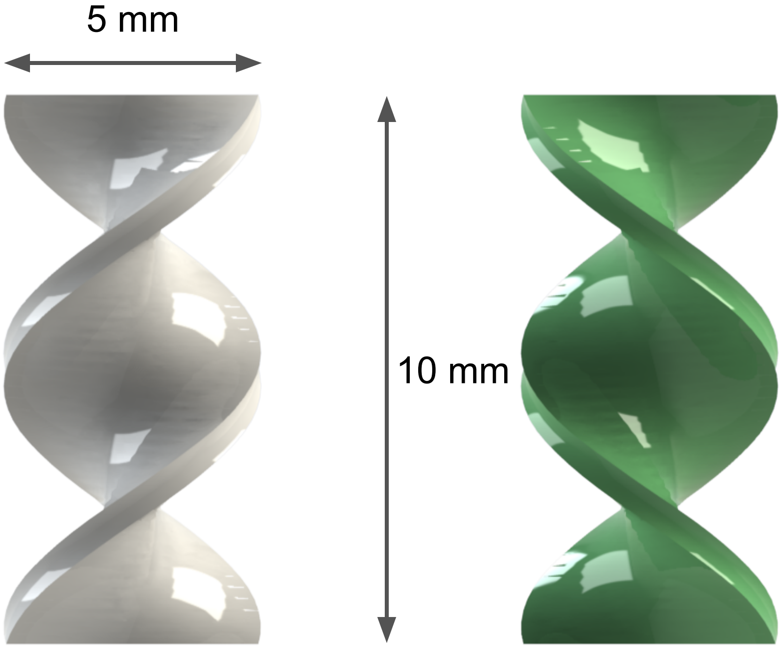


Picture courtesy of nature.com

All Sides Simultaneous View

Apparatus: Pictures

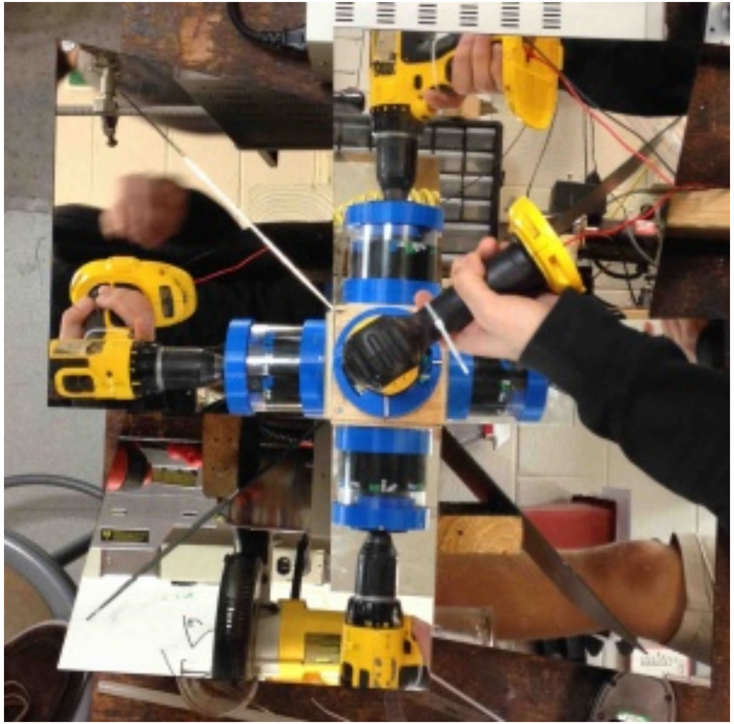


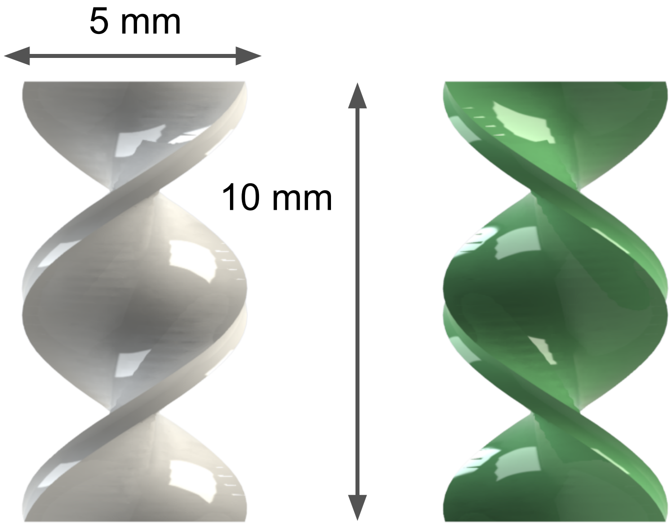


Right-Handed

Left-Handed

Apparatus: Pictures





Right-Handed

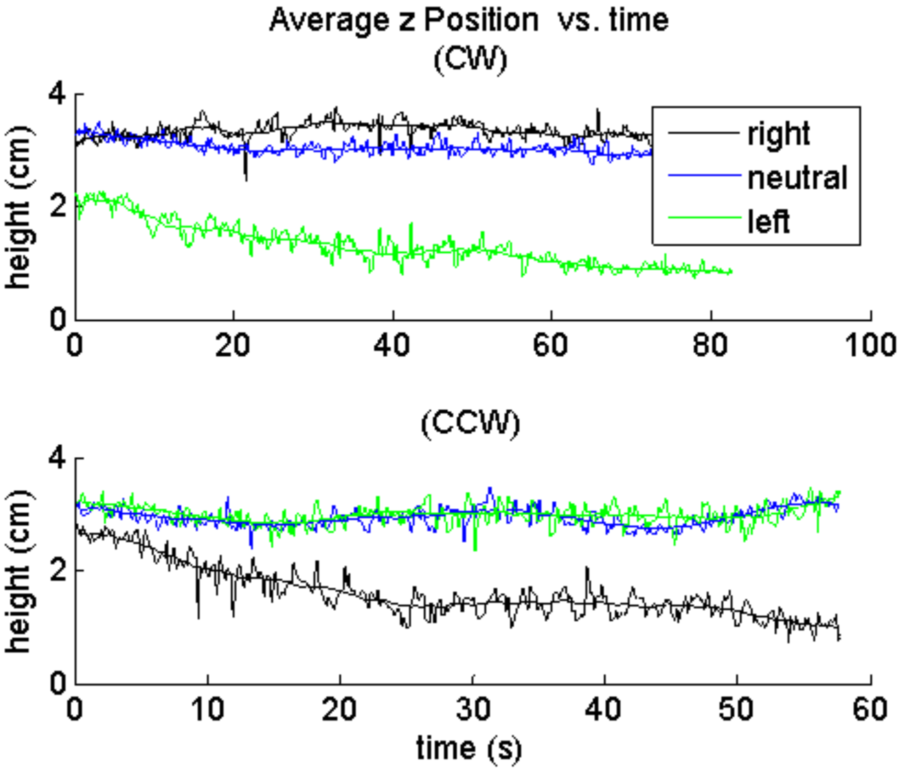
Left-Handed

Non-Chiral

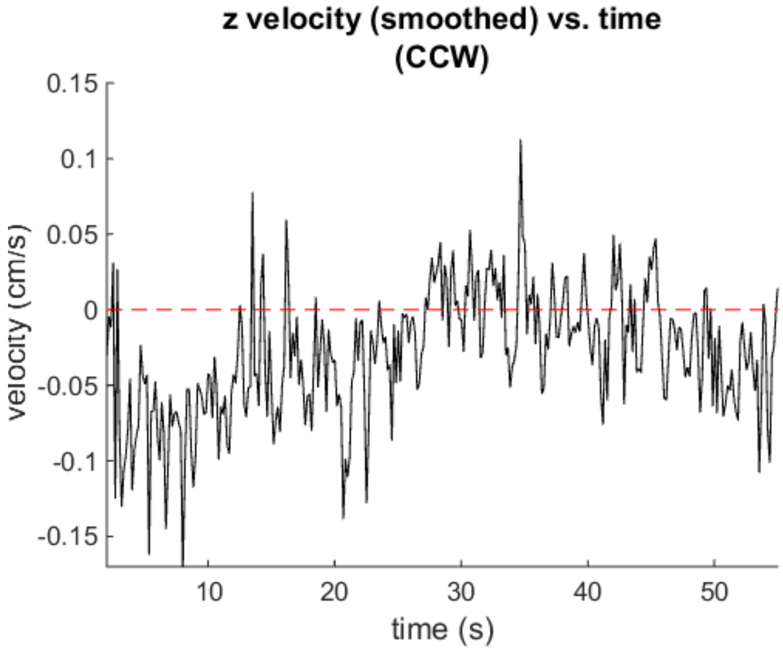
Procedure

- Spun dowel using power drill with voltage controlled power supply and recorded particle motion
  - clockwise, 5V- 1.4 rev/sec
  - counter-clockwise
- Projection of orientation on camera plane for single particles
  - 2 particle system

Results



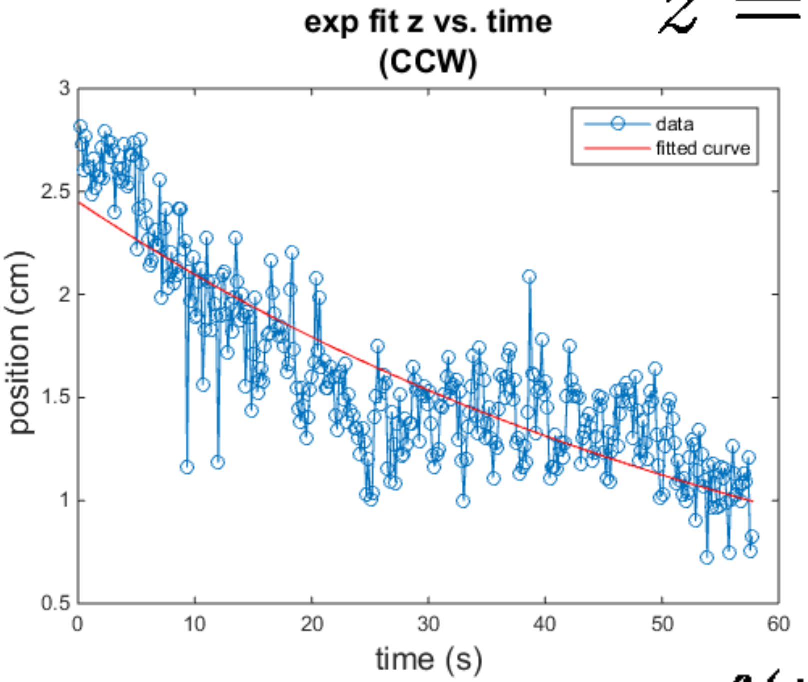
Average z Position vs. time
(CW)
height (cm)
right
neutral
left
0
2
4
0
20
40
60
80
100
(CCW)
height (cm)
0
2
4
0
10
20
30
40
50
60
time (s)



z velocity (smoothed) vs. time
(CCW)
velocity (cm/s)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
10
20
30
40
50
time (s)

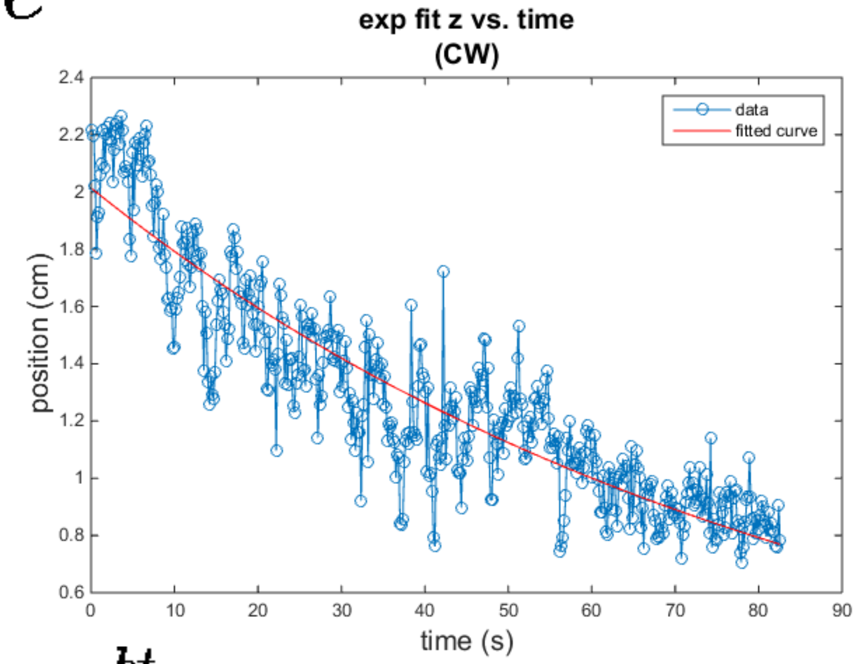
Results

$$z = z_0 e^{Ca\Omega t/d}$$



r^2: 0.73
a = 2.45; b= -0.016

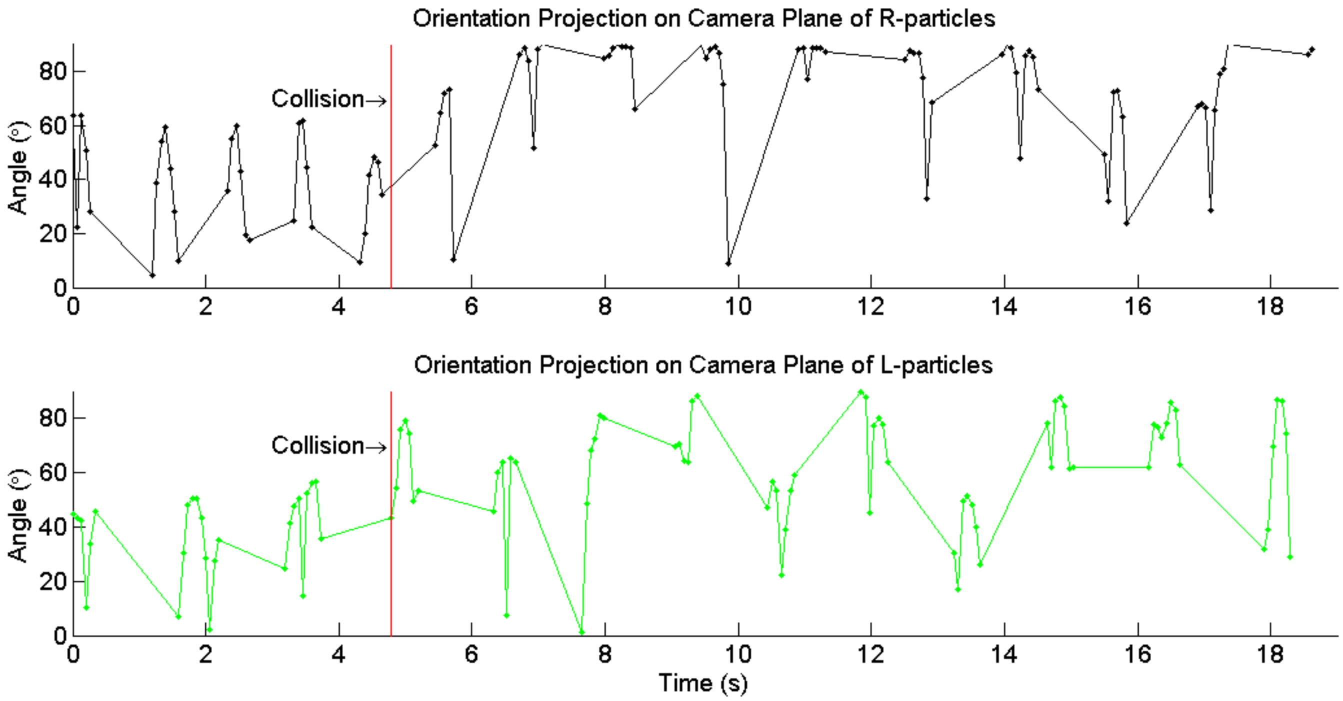
$$f(t) = ae^{bt}$$



r^2: 0.83
a = 2.01; b= -0.011

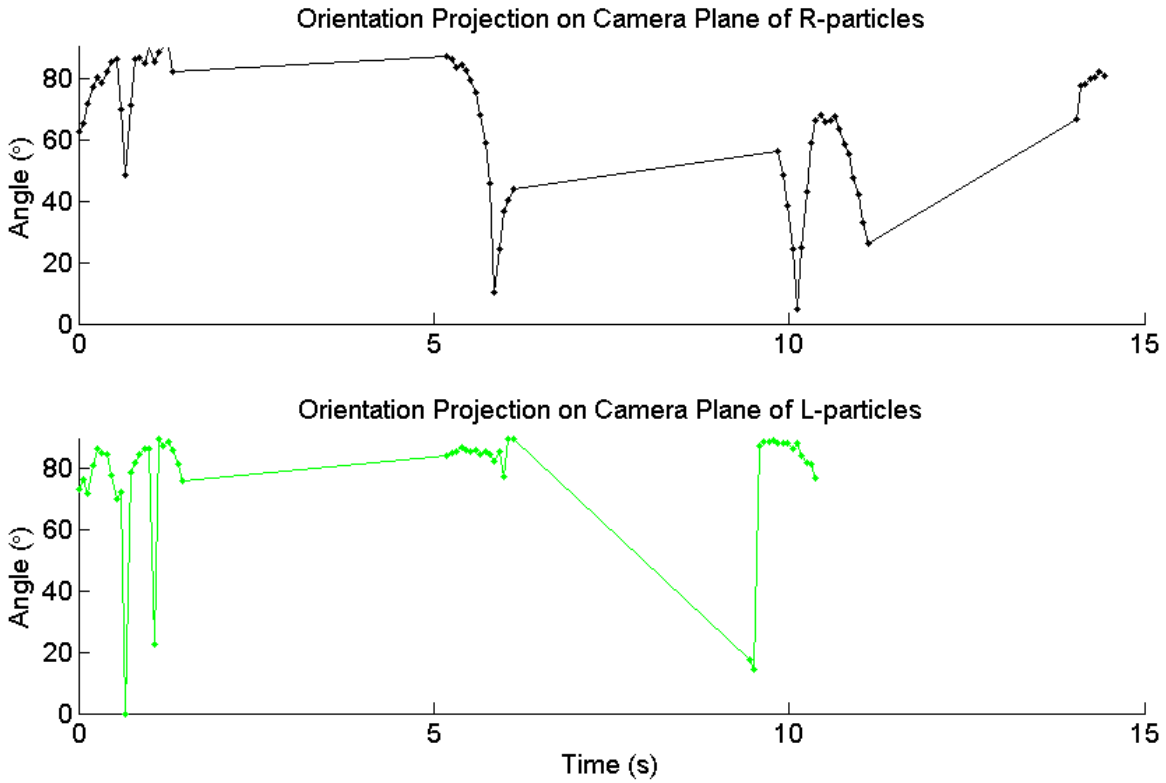
Results- Particle Orientation in T-C Flow

Cylinder: CW
1.8789 rev/s



Results- Particle Orientation in T-C Flow

Cylinder: CW
0.5781 rev/s

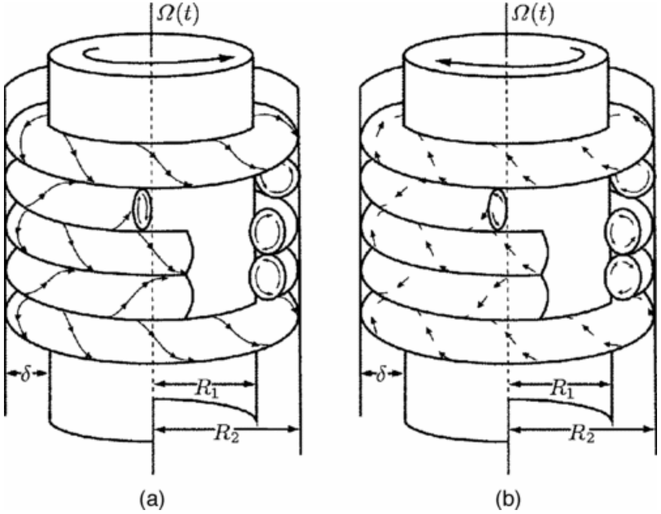


Conclusions

- Clearly observed separation
- Separation is exponential, which agrees with theory
- Particles do not seem to orient themselves over time
- Possible periodicity in orientation

Future Considerations

- At high flow rate Taylor-couette flow profile has vortices
- Collision reduction
- Increased tank height
- Improved tracking methods



Courtesy of APS.org

References

[1] Kantsler, Dunkel, Blayney, and Goldstein, "Rheotaxis facilitates upstream navigation of mammalian sperm cells," *eLIFE*, 052714 (2014).

[2] Masato Makino and Masao Doi, "Migration of twisted ribbon-like particles in simple shear flow," *Phys. Fluids* **17**, 103605 (2005).

[3] Masato Makino, Leo Arai, and Masao Doi, "Shear Migration of Chiral Particle in Parallel-Disk," *Jour. Phys. Soc. Japan* **77**(6), 064404 (2008).