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Designing an Experimental Apparatus for Rotational Mixing in Stokes Flow

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Designing an Experimental Apparatus for Rotational Mixing

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Abstract

We report on the design, construction, and operation of a rotational mixing apparatus that magnetically rotates a thin metal rod interacting with tracers suspended in a high-viscosity fluid. The objective is to achieve Stokes flow, defined as having a Reynolds number below 0.001, where viscous forces dominate over inertial forces in a fluid system. The apparatus, designed using 3D modeling software, uses a magnetic field to hold a rod at a fixed angle and rotate the rod conically about a fixed axis. Tracer trajectories within the fluid are tracked using a custom implementation of the Open-CV python library that analyzes video of the fluid mixing captured by a document camera. It is intended that this apparatus will be used in future research to investigate rotational mixing of viscous fluids, with applications in medical science research.

Motivation

- Rotational fluid mixing caused by a rotating rod models a number of biological systems, including hormone mixing in embryonic spaces and movement of particles by cilia through the lungs.
- Data from our apparatus could help to inform medical research on the mechanisms behind these, and other, biological processes.

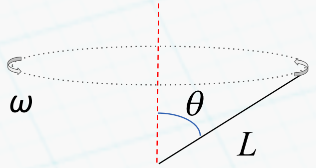
Theory

- Stokes flow processes are non-turbulent and reversible.
- For a fluid to be in Stokes flow, the Reynolds number must be below 0.001
- The Reynolds number is given by:

$$Re = L^2 2\pi \sin(\theta)\, \omega\rho/\mu$$

where Re is the Reynolds number, ρ is the density of the fluid, L is the length of the rod, θ is the angle of the rod from vertical, ω is the angular velocity of the rod, and μ is the dynamic viscosity of the fluid.

- The equations describing the velocity field that generates the particle trajectories, as derived by Dr. Leiterman [1], assume that: (1) Stokes flow has been achieved, (2) tracers in the fluid can be approximated as point particles, (3) the fluid rotates about a fixed axis, and (4) the boundaries of the container are infinite.
- Therefore, to model rotational mixing that occurs in the body, Stokes flow about a fixed axis must be demonstrated.

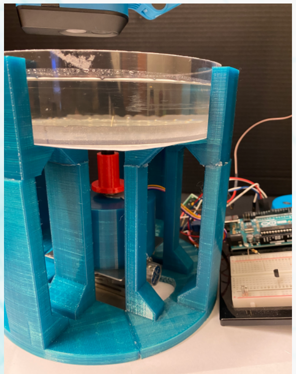


Experimental Apparatus

- Rotates a rod conically about a fixed axis using magnetic fields.
- Permanent magnets are placed within a 3D-printed holder, rotated by a stepper motor controlled by an Arduino Uno microcontroller, which sets the speed and direction of the rotation.
- A 3D-printed stand holds the fluid container above the magnets
- To control the strength of the magnetic field experienced by the rod, an optical stand was placed under the rotational system to adjust the height of the magnets.
- The container used was large enough to approximate the boundaries as infinite.
- A high viscosity fluid (corn syrup) was used to help achieve the desired Reynolds number.

Data Acquisition

- Tracers (bubbles, paper shards) are introduced into the fluid.
- Tracers are tracked using a custom implementation of the Open-CV library that analyzes video captured by a document camera.
- A known length is captured by the camera to define a scale, and the base of the rod is defined as the origin of the coordinate system.
- The rotation of the magnets is driven slowly (1 rpm) by the stepper-motor for a fixed number of revolutions and is then reversed for an equal number of revolutions.
- In order to track the tracers, successive frames are compared to determine changes in color, indicating displacement of the tracers.
- A second camera allows for tracking in three dimensions.
- Displacement vs. time data is recorded and plotted for each tracer.



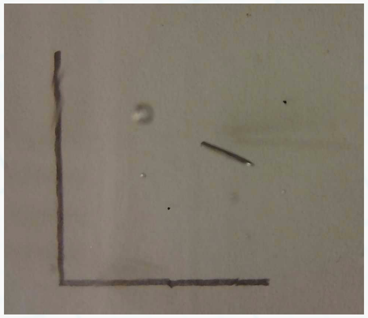
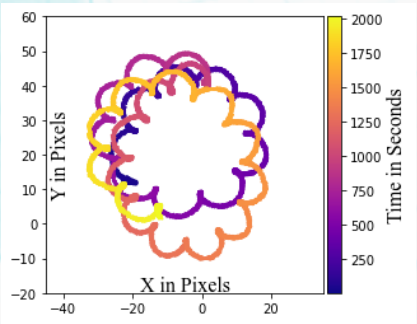


Image of rod and tracers in fluid..

Fluid container, rotating magnet holder (red), document camera, Arduino microprocessor, and 3D-printed stand.

Results & Conclusions



Plot (Y vs. X) of tracer trajectories demonstrates reversibility of fluid mixing.

Apparatus as constructed reproduces the low Reynolds number and approximates the infinite boundaries necessary to accurately model Stokes flow.

Accurate and precise tracking achieved with inexpensive, off-the-shelf parts, 3D-printed components, and open-source libraries.

Citations:

[1] Bouzarth, Elizabeth L., et al. "Epicyclic orbits in a viscous fluid about a precessing rod: theory and experiments at the micro-and macro-scales." *Physical Review E* 76.1 (2007): 016313.

Acknowledgements:

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