Clustering of Rigid Fibers in a Conical Taylor-Couette Flow

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Introduction

Non-spherical particles in turbulent fluid flows occur in such wide-ranging phenomena as blood flow in the human vascular system, circulation of ice crystals in the atmosphere, the movement of plankton in the ocean, and production of paper and pharmaceuticals. [1, 2] Our research focuses on fluid suspensions of fiber-shaped particles.

Due to their elongated shape, fibers interact with each other at much lower concentrations than spherical particles, making both modeling their behavior in fluids and tracking fiber motion in experiments difficult. Presence of fibers in turbulent suspensions further complicates research as the particles impact the behavior of the fluid itself. Depending on the orientation of fibers in a suspension, the contribution particles make to the fluid's stress tensor varies. Our aim is to develop a predictive understanding of how the behavior of individual fibers impacts the behavior of the suspension as a whole.

Research Focus

Unlike other groups studying fiber suspensions who have examined fiber orientations only at low concentrations [3] or only mean fiber dynamics at high concentrations [4], our group has focused on three-dimensional imaging of fiber dynamics at higher concentrations throughout the volume of turbulent flows. To achieve this, we developed an apparatus consisting of a rotating inner wall and floor and stationary outer wall. Using images from four cameras at different positions above the apparatus, we can reconstruct the orientation and motion of individual fibers throughout this apparatus.

Initial experiments using this apparatus revealed a fascinating phenomenon: fibers with a greater density than water settled downward and outward into the junction between the outer wall and floor, breaking the symmetry of the system by accumulating into high-concentration clusters. We have since focused our efforts on further investigating this clustering phenomenon. This behavior allows us to study small volumes of higher fiber concentration without the common challenges associated with imaging high-concentration density-matched suspensions.

Fiber Behavior: The Clustering Phenomenon

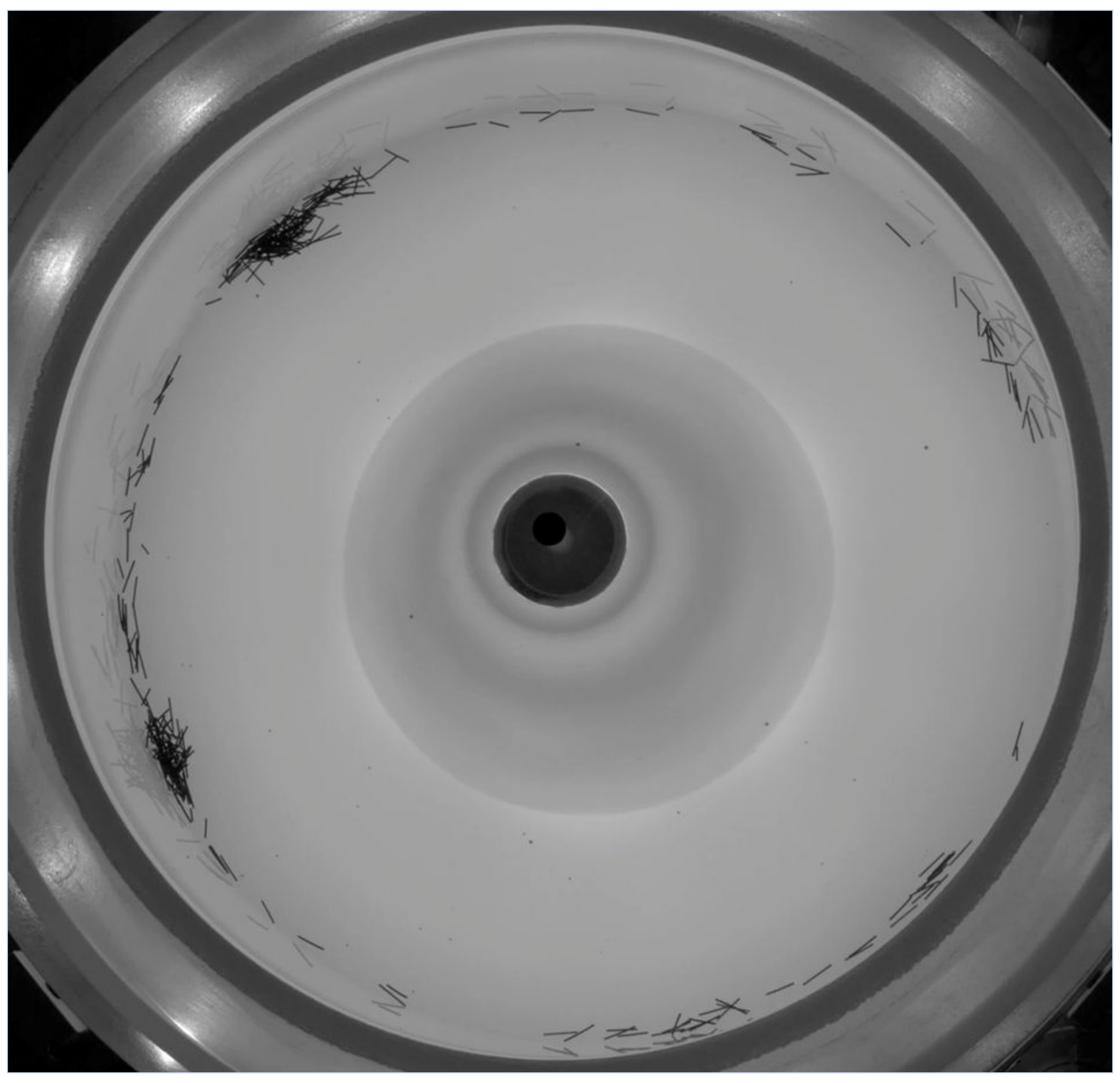

Fig. 3: Image of the fiber clustering phenomenon (left). The photograph shows a grouping of of dense fiber clusters as the apparatus rotates at a rate of ½ Hz. Key to note is how the fibers break from the rotational symmetry of the apparatus by clustering instead of remaining evenly distributed.

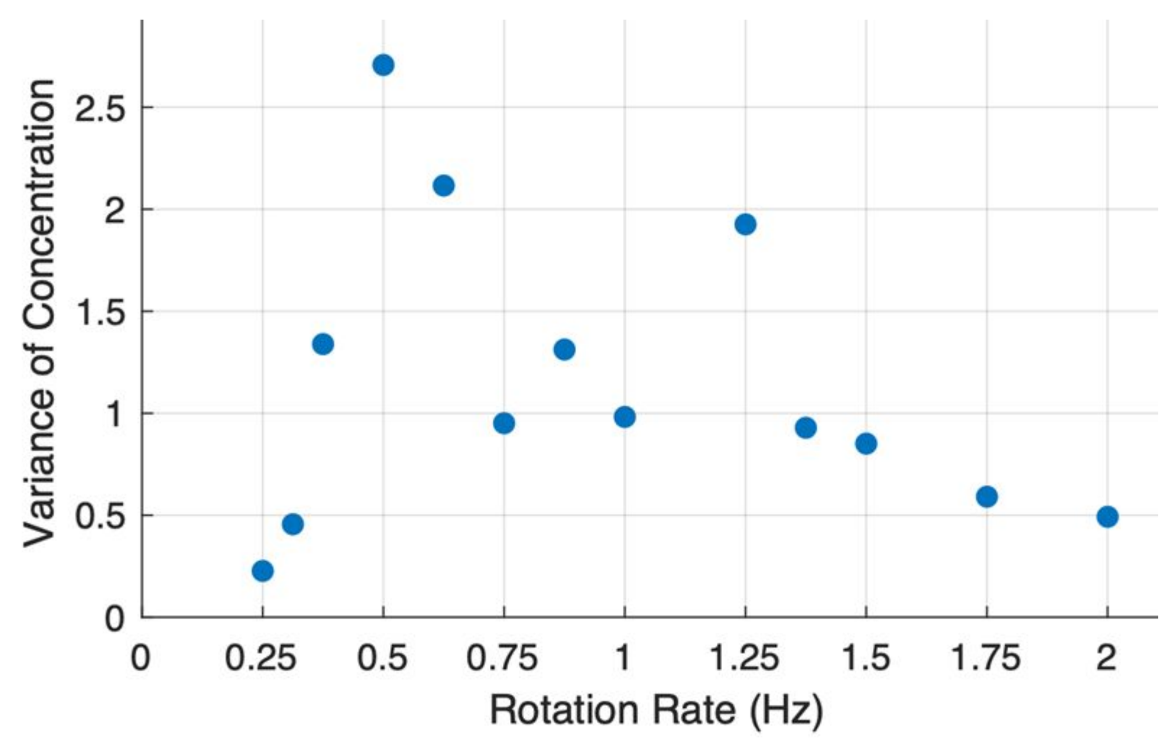

Fig. 4: Cluster amplitude graph (above). The graph shows variance in concentration at different rotation rates. The variance measurement peaks at two values: dense clusters form at the slower rate of 0.5 Hz, while more dispersed clusters form at the faster rotation rate of 1.25 Hz.

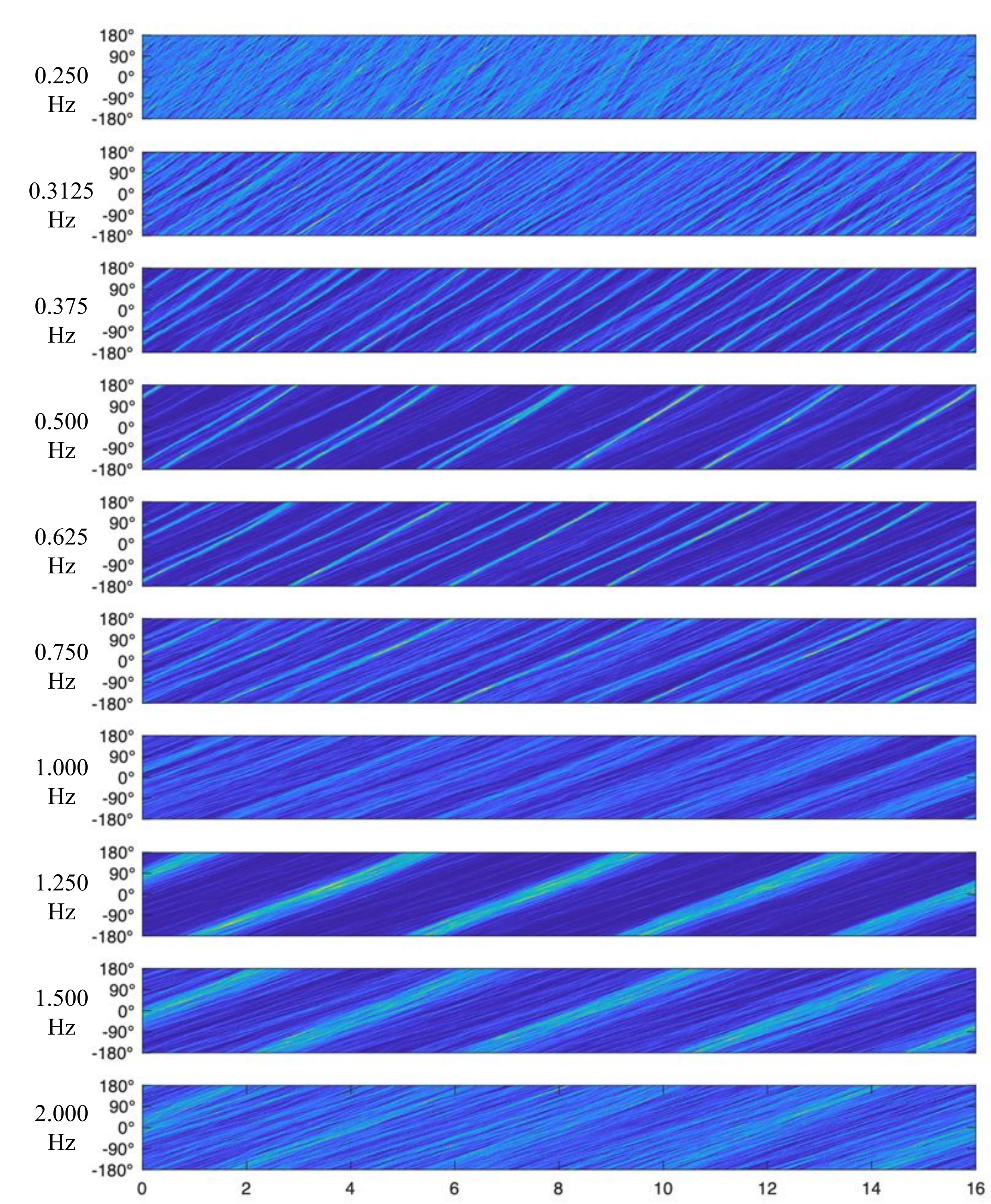

Fig. 5: Space vs. time plot (above). Each pixel represents the fiber presence within a given area of the apparatus at a given time. Brightly-colored diagonal lines show the circulation of fiber clusters. More compact clusters occur at 0.5 Hz, while dispersed clusters prevail at 1.25 Hz.

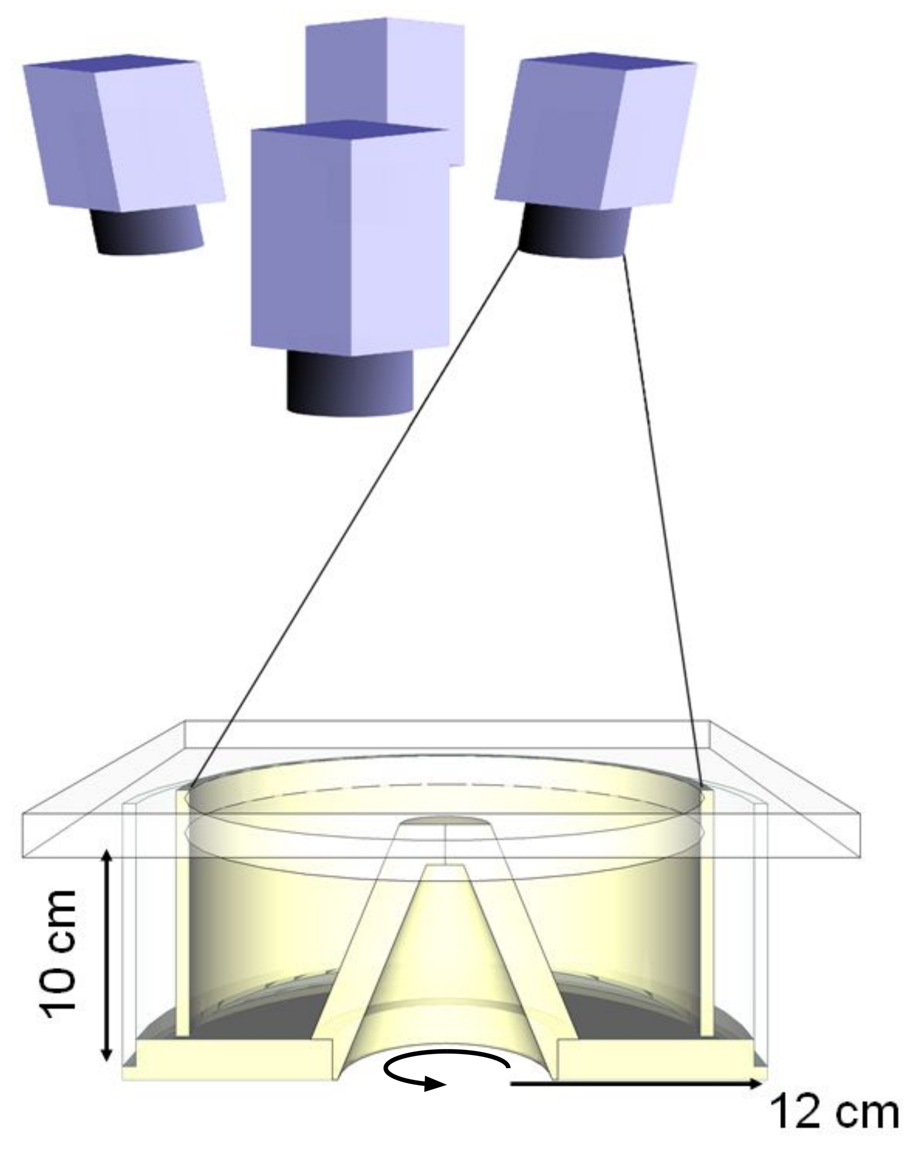

Fig. 1: A diagram of the experimental set-up used to measure full-field three-dimensional dynamics of fiber suspensions.

Experimental Design

Methods: To study the behavior of fiber suspensions, we begin by filling the apparatus with water and the fibers, which sediment to the bottom due to their higher density. After beginning the rotation of the apparatus' floor and inner wall, we begin data collection when the suspension reaches a steady turbulent state. Using the images taken from four cameras positioned above our apparatus, we utilize stereo tracking to reconstruct a three-dimensional model of the fiber suspension.

Flow Behavior: Understanding the behavior of the fluid itself within our apparatus is the first step to informing our analysis of fiber behavior. Given that the fluid is driven by the rotating floor and inner wall of the apparatus, the primary flow direction is azimuthal and the secondary flow is an outward circulation of fluid along the bottom of the apparatus. As the rotation rate of the apparatus increases, the fluid transitions into a turbulent state with a fluctuating turbulent velocity field. The fluid in the apparatus has the highest velocity in near-wall regions known as turbulent boundary layers.

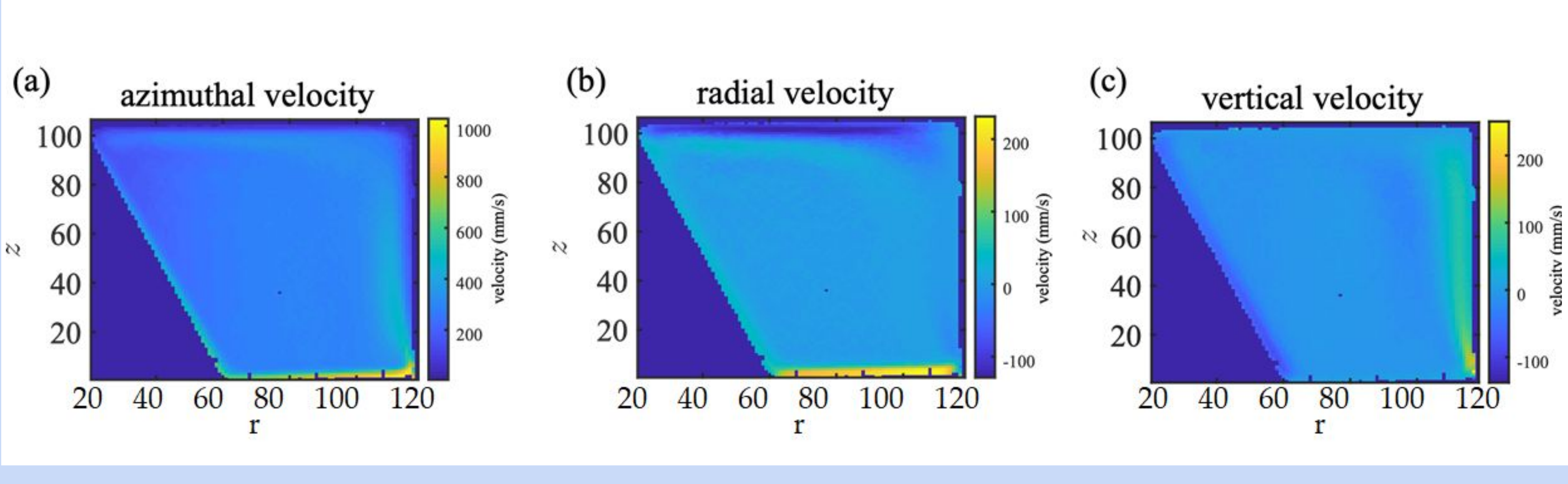

Fig. 2: Azimuthal, radial, and vertical components of the mean fluid velocity field in a cross-section of the apparatus.

Conclusions

Using a multi-camera system and novel apparatus, we can study the three-dimensional full-field dynamics of turbulent fiber suspensions. Initial investigations uncovered that fibers in turbulence break from the rotational symmetry of the system by accumulating in traveling clusters at certain rotation rates.

Results indicate that fibers group into compact clusters at a rotation rate of 0.5 Hz due to interactions in the turbulent boundary layer. As speeds increase, turbulence suspends some fibers into the bulk of the fluid and clusters disperse. Clustering peaks again at higher speeds (approximately 1.25 Hz) when particles are fully in turbulent suspension, though these clusters are more dispersed and travel more slowly. These suspended clusters are particularly interesting for future research of fiber clusters as the internal dynamics of the clusters are visible.

In the future, we hope to bring these initial results to publication. Further research of fiber suspensions will focus on the relationship between fiber orientation and their contribution to the fluid stress tensor.

References

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