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Clustering of long flexible fibers in two-dimensional flow fields for different Stokes numbers

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ABSTRACT

The present work studies numerically the concentration distributions of long flexible fibers in two analytical flow fields. Fibers are modeled as a set of rigid cylinders, resulting in a continuous flexible fiber. Forces are applied to the center of mass of each cylinder, thus determining cylinder motion and fiber deformation using a fourth-order Runge-Kutta method to solve the system of ordinary differential equations. The numerical code is validated against experimental data available in the literature. The analytical velocity fields are steady and two-dimensional and correspond to the Arnold-Beltrami-Childress (ABC) flows. Simulations are performed for a wide range of Stokes numbers (*St*), which relate the characteristic time of the fibers to the characteristic time of the flow. Previous studies with spherical particles from other authors show that there is a preferential concentration of particles in regions of low vorticity, with a maximum preferential concentration for *St* values around 1. In the present study, it is shown that preferential concentration of fibers for the studied ABC flows has a maximum for $St = 0.3$. Fibers tend to concentrate also in regions of low vorticity in both cases studied, and the frequency of caustics formation correlates strongly with the increase of preferential concentration.

1. Introduction

Flexible fibers are used in the paper, hygiene and insulation industries. In some of these processes, the homogeneity of the fiber distribution impacts on the final product quality. Therefore, the knowledge of which variables affect the fiber distribution is of importance in order to optimize these processes. As an example, a detailed review of the fluid mechanics involved in papermaking is presented by Lundell et al. [19].

Research has been carried out on preferential concentration of spherical particles over the years, but less information is available on the behavior of non-spherical particles and their concentration distribution. Wang and Maxey [32] performed Direct Numerical Simulations (DNS) of the motion of heavy spherical particles in isotropic homogeneous turbulence and found that particle concentration was higher in the surroundings of local vortical structures. This preferential concentration in regions of low vorticity was also found by Squires and Eaton [28], Truesdell and Elghobashi [31], Yang and Lei [35], Février et al. [10]. Furthermore, Wang and Maxey [32] found that the accumulation (or clustering) of spherical particles in those regions depended on the Stokes number (*St*). It was observed that for Stokes numbers around unity, spherical particles tend to concentrate in regions of low vorticity, while more random distributions are found both above and below that value. Hogan and Cuzzy [17] found, also through DNS, that concentration depended on *St* but was insensitive to the Reynolds number (*Re*). Rouson and Eaton [27] performed DNS of solid particles in a turbulent channel flow and, while they also observed some regions where low velocities led to preferential concentrations, in other regions of the channel particle concentration was not correlated with the local flow topology. Luo et al. [20] performed DNS to study the effects of preferential concentration on the interaction between particles and the tubes of a heat exchanger, finding that preferential concentration had a large influence on the collision and erosion between the particles and the tubes.

Gustavsson and Mehlig [15] reported extensively on clustering of heavy small particles, noting that spatial clustering in incompressible flows is an inertial effect, characterised by the Stokes number. One of the mechanisms leading to the formation of clusters of particles corresponds to singularities in the particle dynamics called caustics, in which particles are agglomerated in thin filaments that are similar to networks of optical caustics as those formed by deflection of sunlight by water waves. These caustic singularities allow nearby particles to move with significant different velocities. The consequence of this phenomenon was first seen in the numerical simulations performed by Sundaram and Collins

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Nomenclature

A	coefficient for the analytical flow velocity
B	coefficient for the analytical flow velocity
C	coefficient for the analytical flow velocity
$\bar{C}$	time-averaged concentration
C_D	drag coefficient
d	fiber diameter
f	frequency
L	fiber length
PCI	preferential concentration index
$\mathbf{r}$	position
Re	Reynolds number
St	Stokes number
t	time
$\mathbf{u}$	velocity
x	x spatial coordinate
y	y spatial coordinate
z	z spatial coordinate
Z	matrix of particle velocity gradients

Greek symbols

ν	kinematic viscosity
π	pi number
ρ'	ratio of fluid to fiber densities

Subscripts and superscripts

i	segment
f	fluid
p	particle
r	relative quantity
u	uniform field
x	x spatial coordinate
z	z spatial coordinate
$*$	dimensionless variable

[29] and was also observed in the experimental work carried out by Bewley et al. [5]. Gustavsson et al. [13] described these observations in terms of random uncorrelated motion. This phenomenon has also been described as a sling effect by Falkovich and Pumir [8], where different velocities for neighboring particles may be determined by a distant vortex. According to Gustavsson et al. [14], caustics occur more frequently at large Stokes numbers. Numerically, the caustic formation corresponds to the divergence of the trace of the matrix of the particle velocity gradients, as described by Gustavsson and Mehlig [15].

Regarding non-spherical particles, Andric et al. [2] implemented a model for flexible fibers which was validated against experimental data of fiber motion in shear flow. Andric et al. [3] applied that model to a suspension of fibers in the swirling flow of a conical diffuser, finding that fiber inertia had a significant effect on fiber reorientation while its length had a minor effect on reorientation for constant fiber density. Guo et al. [12] simulated the motion of a flexible fiber in the three-dimensional swirling flow induced by tangential inlets in a straight tube, observing three different regimes of fiber motion: springy, snake-like and helical regimes. The significant impact of fiber inertia on fiber reorientation was also found in a turbulent channel flow by Andric et al. [4]. Fan et al. [9] simulated fiber motion in shear flow. Their results showed that fibers are aligned mostly with the shear direction in the semi-concentrated and concentrated regimes. Wang et al. [33] studied numerically the diffusion of fibers in simple shear flow, finding that curved fibers presented larger diffusivities than straight fibers. Dong et al. [6] simulated the distribution of pulp fibers in a turbulent channel flow, finding that fiber concentration increased near the wall while being approximately constant farther from the wall. Marchioli et al. [21] performed numerical simulations of fibers in turbulent channel flow, finding that longer fibers tended to deposit on the wall at higher rates, while no preferential orientation was observed in the channel centerline. They also found, when comparing fibers behavior with that of spherical particles, that the aspect ratio of the fiber had no significant effect on preferential concentration.

Alben et al. [1] performed experiments with a flexible fiber immersed in a flowing soap film. They showed that the bending of the fiber by the flow led to a drag reduction. That effect was also seen by Yang et al. [36], who simulated numerically the interaction between flexible fibers and viscous fluids. They used a mesh-free particle method to simulate the flow and coupled it with an element bending group method for modeling the fiber-flow interaction. The results they obtained for the drag force on the fiber agreed with experimental observations. The same approach was used by Yang and Liu [37] to study the bending modes of a flexible fiber immersed in a viscous fluid, reporting that the variation in drag was closely related to the deformation patterns of the fiber.

Different simulation approaches for papermaking flows were reviewed by Hämäläinen et al. [16], including particle-level simulations, meso-scale simulations and up to full flow geometry size simulations. Olson [24] used a probability distribution function of fiber concentration and position to describe the state of fibers suspended in a fluid, finding that the Lagrangian time scale for translation was larger than for rotation. A convection-dispersion equation for fiber orientation was also used by Hyensjö et al. [18] to study the effect of the vane types and positions and the wall boundary layer on the fiber orientation distribution in a planar contraction. They found that the fiber orientation distribution was wider in the boundary layer, while the blunt vane tip had a more important effect on the fiber orientation distribution at the outlet on the contraction than the tapered vane tip. Olson et al. [25] applied that convection-dispersion model also to a planar contraction, showing that increasing the contraction ratio increased the alignment of fibers. They also suggested that the fiber orientation was dependent on the fluid contraction ratio, the inlet velocity, the contraction length and a rotational dispersion coefficient. A stochastic aerodynamic force model that allows the simulation of long slender elastic fibers immersed in turbulent flows was developed by Marheineke and Wegener [22], and their predictions of velocity distributions were favorably compared to experimental data. Wu and Aidun [34] used the lattice Boltzmann method to simulate flexible fiber suspensions and compared their results to experimental data available in the literature, with the simulations predicting a slightly higher shear viscosity than the experimental one in the dilute regime.

The objective of this work is to study the concentration distribution of long flexible fibers and the factors leading to the formation of clusters of fibers in flows. In order to do so and as a first step in this research, two different analytical two-dimensional flow fields are used in the numerical simulations.

2. Fiber modeling

The flexible fiber is modeled as a set of rigid cylinders. The segment displacements determine the fiber motion and bending, and thus the flexibility to the fiber. Increasing the number of segments