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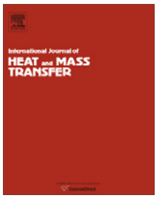

Simulating the motion of a flexible fiber in 3D tangentially injected swirling airflow in a straight pipe—Effects of some parameters

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ABSTRACT

A numerical model for particle-level simulation of fiber suspensions has been used to simulate fiber dynamics in three-dimensional tangentially injected swirling airflow in air-jet spinning nozzles. The fiber is modeled as chains of beads connected through massless rods, and its flexibility is defined by the bending and twisting displacements. The effects of some parameters, such as fiber initial position, the injection angle and the injector diameter on fiber motion and yarn properties are discussed. The springy, snake-like and week helical regimes of fiber motion are observed under the most cases. The far from the tube center the fiber release position, the smaller the fiber flexibility is. For a smaller injection angle, the self-entanglement regimes of fiber motion are observed in the downstream of the injectors. The model also predicted the complex helical configuration in the nozzle with a small injector diameter. The predictions of yarn properties coincide with the experimental results reported by several researchers.

1. Introduction

Two-phase swirling flow systems are of considerable engineering importance and have a wide range of industrial applications owing to the important features of swirling flows. For example, in combustion systems, swirling flows are used to improve and control the fuel–air mixing rate and the combustion efficiency [1]. In order to reduce the pressure drop mainly induced by a possible settling of particles, and avoid any partial or total obstruction of the device [2,3], swirling flows have been also applied in the pneumatic transportation technology. Especially, it is used in the textile industry to produce air-jet spun yarns. Different from general particle transportations, in air-jet spinning system, the long flexible fibers are transferred and twisted and wrapped each other under the effects of the swirling decaying airflows, and consequently a high quality yarn can be produced [4]. Therefore, the study on the dynamics of flexible fibers in a swirling flow is of both theoretical and practical importance. To the authors' knowledge, however, the studies in this area are rather scarce.

The dynamics of flexible fibers is significantly complicated. Much of the current understanding of flexible fiber dynamics has come from the experimental observations of Forgacs and coworkers [5–7]. Arlov et al. [5] divided the dynamics of flexible fibers into three classifications: "flexible spin", "flexible spin-rotation" and some other configurations when the fiber is extremely flexible, such as "springy rotations", "snake turn" and "S-turns". Forgacs and Mason [7] identified five regimes of fiber motion ranging from short and rigid to very long and flexible in shear flow. Especially, they observed that highly flexible fibers move in helix rotation and coiled orbits, sometimes resulting in self-entanglement. Salinas and Pittman [8] delineated springy and snake rotations and measured the minimum radius of curvature for flexible fibers orbiting in laminar shear flow. These experimental results [5–8] show that fiber dynamics is a function of the fiber stiffness, aspect ratios, initial orientation, and the ambient flow field (such as shear rate and fluid viscosity).

To understand the property of fiber suspensions, several numerical methods are developed to simulate flexible fiber motion in shear and sedimentation flows. Based on a free draining assumption, the rigid, springy and snake-like regimes of fiber motion [5,7] were confirmed both by numerical studies of Yamamoto and Matsuoka [9] and Ross and Klingenberg [10] although the fluid drag force and torque on each individual segment were calculated according to spheres [9] or spheroids [10]. Stockie and Green [11] and Takemura et al. [12] used the immersed boundary method to model the motion of flexible fibers in two dimensions viscous shear flow, and qualitatively predict the rigid, springy and snake-like regimes of motion. They also observed some complex motion for very flexible fibers, but it is inherently impossible to model the coiled regime of motion with or without self-entanglement for a two-dimensional model, due to the three-dimensional nature of these phenomena.

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Nomenclature

C_D	drag coefficient
d	injector diameter (m)
E	Young's modulus of the fiber (Pa)
F	force acting on the fiber
G	shear modulus of the fiber (GPa)
I_b	moment of inertia of the fiber ($\mathrm{kg} \cdot \mathrm{m}^2$)
I_t	polar moment of fiber inertia (m^4)
k	turbulence kinetic energy (J)
$l_{i-1,i}$	length of the fiber section ($i-1$, i) (m)
m_i	mass of the bead i (kg)
n	injector number
p	pressure (Pa)
r	radium of the fiber (m)
R	gas constant ($\mathrm{J} \cdot (\mathrm{mol} \cdot \mathrm{K})^{-1}$)
$\mathrm{Re_p}$	particle Reynolds number
S_g	swirl number
S_ϕ	source term of the variable ϕ
T	temperature (K)
V	velocity vector
x_i	position vectors of the bead i

Greek symbols

Γ_ϕ	diffusion coefficient of the variable ϕ
Ψ	particle sphericity
ε	turbulence dissipation rate (J)
θ	injection angle (°)
ρ_f	fiber density ($\mathrm{kg} \cdot \mathrm{m}^{-3}$)
ρ_g	air density ($\mathrm{kg} \cdot \mathrm{m}^{-3}$)
ϕ	conserved property

Subscripts/superscripts

b	bending deflection of the fiber
d	drag force
f	fiber
g	air phase
t	twisting deflection of the fiber

In three dimensions, Schmid et al. [13] developed a particle-level simulation technique to study the flocculation of fibers in sheared suspensions. They qualitatively predicted the rigid, springy and snake-like motion as well. Based the method of Ross and Klingenberg [10], Skjetne et al. [14] observed a wide variety of fiber configurational dynamics, which agreed with the experimental observations by Arlov et al. [5]. Qi [15] simulated the rigid and springy fiber motion in three dimensions, using the Lattice Boltzman method for calculating the flow, and taking the two-way coupling between phases into account. Unfortunately, these three-dimensional numerical investigations [13–15] cannot quantitatively predict the coiled regimes of motion for straight fibers yet. Only the simulations of Lindström and Uesaka [16] successfully reproduced the different regimes of motion for threadlike particles [7], ranging from rigid fiber motion to complicated orbiting behavior, including coiling with and without self-entanglement. It is noteworthy that the coiled motion could only be provoked in their simulations by attributing a permanent deformation to the fibers.

Due to the exceedingly high computational demands of direct numerical simulations of flexible fiber dynamics, particle-level simulation, where fibers are represented by multi-rigid-body systems of simple particles, is an alternative tool for studying the dynamics of flexible fibers at the required resolution. There are three main models: bead chain, needle chain and bead-rod chain. Yamamoto and Matsuoka [9] and Joung et al. [17] modeled suspended fibers using interconnected spheres (call as bead chain), while several other researchers used interconnected 'coarse-grained' particles (i.e. needle chain) such as ellipsoidal [10,14], cylindrical [13,15,16,18], or any other shapes [11,12]. Flexibility of the fibers in both models can be obtained and changed according to the parameters of bond stretching, bending and twisting. The former approach has the advantage of simplicity, but it requires enormous computational resources to maintain chain connectivity for a long flexible fiber; while the latter reduces the number of unit bodies of the system, thus improving computational efficiency. It also should note that the longer the 'coarse-grained' particle length, the larger the error of the simulation as compared to the bead chain model [18]. In addition, a bead-rod chain, in which the rods only serve to transmit forces and maintain the configuration of the fiber, was proposed to simulate the motion of the flexible fiber in a swirling flow [19,20]. This model can also save computational time because of fewer beads adopted.

It is well known that the dynamics of flexible fiber depends on its stiffness, initial orientation, fiber length and the ambient flow field. For the swirling flow, swirl intensity determines the fluid behaviors, and thus influences the fiber motion. In air-jet spinning system, the forming yarn is 'twisted' by operating two swirling air currents in mutually opposite directions in two nozzles. According to the different function of two nozzles, normally the first and second nozzles are made of cylindrical and conical shapes, respectively. Spinning experiments have shown that the nozzle geometric parameters, such as injection angle and the injector diameter, are significantly related to yarn properties [21,22]. Our previous studies [23] also showed that the nozzle geometric parameters influence the swirling flow characteristics, and further affect the fiber dynamics and the yarn quality. According to the principle of the yarn formation [4,24] and the swirling flow behaviors, the release position of a fiber will also influence the fiber motion. Based on above, the present work is dedicated to the effects of both the first nozzle geometric parameters and initial position on the flexible fiber motion. The case of the second nozzle will be dealt with in a subsequent paper.

In this study, the fiber suspension model of Guo and Xu [19,20] is employed to simulate the dynamics of a flexible fiber in the three-dimensional turbulent swirling flow induced by tangential inlets in a straight tube. A brief outline of the model is provided in Section 2, in which the one-way coupling Euler–Lagrange approach is utilized. Since the injector diameter and injection angle are two most important parameters in air-jet spinning, their effects on fiber motion and, consequently, on yarn structure and yarn quality, are discussed in Section 3. The effects of releasing position are also studied in this section. The final section makes some conclusions.

2. Theory

The bead-rod fiber model [19,20] and the computational method [20] used in this work were described in detail, and validated [19,20] for the case of isolated fiber by Guo and Xu. Here, only the most important aspects of the theoretical framework are outlined. The one-way coupling Euler–Lagrange approach is taken into account. In the nozzle of air-jet spinning, since high-velocity compressed air is forced into the twisting chamber through the