Contents lists available at SciVerse ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Numerical simulation of fiber orientation distribution in round turbulent jet of fiber suspension

J.Z. Lin[a,b,*], *X.Y. Liang*[a], *S.L. Zhang*[c]

[a] *China Jiliang University, Hangzhou 310018, China*
[b] *State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China*
[c] *Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA*

ABSTRACT

The Reynolds averaged Navier–Stokes equation was solved numerically with the Reynolds stress model to get the mean fluid velocity and the turbulent kinetic energy in a round turbulent jet of fiber suspension. The fluctuating fluid velocity was described as a Fourier series with random coefficients. Then the slender-body theory was used to calculate the fiber orientation distribution and orientation tensor. Numerical results of mean axial velocity and turbulent shear stress along the lateral direction were validated by comparing with the experimental ones. The results show that most fibers are aligned with the flow direction as they go downstream, and fibers are more aligned with the flow direction within the region near the jet core. The fibers with high aspect ratio tend much easier to align with the flow direction, and the fiber orientation distribution is not sensitive to fiber aspect ratio when fiber aspect ratio is larger than 5. Fiber density has no obvious influence on the fiber orientation distribution and fiber orientation tensor. The randomizing effect of turbulence is insignificant in the regions near outside and jet core, and becomes significant in the region between outside and jet core. The randomizing effect increases with the increasing of the distance from the jet exit. Different components of fiber orientation tensor show a similar distribution pattern.

Keywords: Turbulent fiber suspension; Round jet; Fiber orientation distribution; Numerical simulation

1. Introduction

Turbulent fiber suspensions are of interest in chemical engineering applications. The production of fiber based materials, such as paper, composites, and some insulation materials, involves turbulent fiber suspension flows. For example, it is impossible to operate a present-day pulp or paper mill without large quantities of turbulent liquid to serve as a dispersing, transporting, and handling medium for the fibers which ultimately become the paper sheet. Physical properties of these products are to a large extent determined by fiber–flow interactions. The orientation behavior of fibers is a major concern in the chemical processes, such as extrusion, injection, and compression molding. The orientation distribution of fibers determines the mechanical properties of the fiber suspensions. The product is stiffer and stronger in the direction of greatest orientation, and weaker and more compliant in the direction of least orientation.

There has existed some literature dealing with the turbulent fiber suspension during the last 30 years. Steen (1991) presented calculations of flocculation intensity in a fully developed pipe flow at two different Reynolds numbers. The results show higher flocculation intensity in the center of the pipe than in the wall region. Flocculation intensity in the center of the pipe is greater at the lower Re. Minimum flocculation intensity was predicted at a certain distance downstream of the step. Bernstein and Shapiro (1994) measured orientation distribution function of glass fiber suspended in turbulent shear flows in a water tunnel. They found that the orientation distribution function is affected by the flow velocity gradients and the fibers' rotational diffusivities, both acting in competition with each other. In addition to the fibers' rotational

* *Corresponding author at*: State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China. Tel.: +86 571 86836009.
E-mail address: mecjzlin@public.zju.edu.cn (J.Z. Lin).

Received 25 February 2011; Received in revised form 15 July 2011; Accepted 26 September 2011
0263-8762/$ – see front matter © 2011 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.cherd.2011.09.016

Nomenclature

Notations

A	converting matrix
$a_{ijkl,\gamma}$	moment of the orientation distribution function
d	distance from the wall
$\boldsymbol{f}(s)$	force exerted on the fiber by fluid
J_1, J_2, J_3	fiber moment of inertia for principal axis 1, 2 and 3
L	toque exerted on fiber
L_1, L_2, L_3	three components of torque in coordinate system-123
m	fiber mass
$\boldsymbol{p}$	unit orientation vector along fiber principal axis
p_i	component of the orientation vector $\boldsymbol{p}$
s	dimensionless coordinate on the fiber
T	torque vector of the fiber in the coordinate system-xyz
U	characteristic velocity of the flow
$\boldsymbol{u}$	undisturbed instantaneous background fluid velocity
V	induced velocity
$\boldsymbol{x}_c$	coordinate of the fiber mass center
a	fiber radius
D	diameter of jet pipe
F	force exerted on a fiber
$\mathbf{G}(\boldsymbol{x})$	Green tensor
k	turbulent kinetic energy
l	fiber length
l_m	mth segment of the fiber
N	total number of fibers
P	mean fluid pressure
p'	fluctuating fluid pressure
St	Stokes number
$\mathbf{U}_p$	fiber velocity
U_i	mean fluid velocity
u'_i	fluctuating fluid velocity
$\boldsymbol{v}$	translation velocity of fiber
x	distance from the jet exit

Greek symbols

β	fiber aspect ratio
γ	angle between the projection of the fiber on the x–z plane and the x axis
$\boldsymbol{\delta}$	unit matrix
θ	orientational angle
ν	fluid kinematic viscosity
ϕ	orientational angle
$\boldsymbol{\omega}$	fiber angular velocity
$\omega_1, \omega_2, \omega_3$	three components of fiber angular velocity in the coordinate system-123
ε	turbulent dissipation rate
μ	fluid viscosity
ρ_f	fluid density
$\mathbf{x}_c$	orientation distribution function

Peclet number, the flow regime has a profound influence on the fibers' orientation. Li and Odberg (1997) investigated the effects of retention aids on the flow behavior of pulp suspensions. Both axial velocity profiles and pressure drops were measured simultaneously as a function of the mean bulk flow rate after addition of retention aid. It is demonstrated that, at low flow rate, adding polymeric flocculant to a dilute hardwood fiber suspension can induce a slip velocity between the dense fiber aggregates and the remainder of the suspension. Introducing retention aids at fully turbulent flow results in the formation of plug flow immediately after the addition. Arola et al. (1998) measured velocity profiles of pulp suspension flowing through a circular pipe in the vicinity of a 1:1.7 tubular expansion. They found that the expansion plane imparts shear layer instabilities that disrupt the fiber floc network. The fiber reflocculation length is proportional to the bulk flow rate. Newsom and Bruce (1998) studied two-dimensional orientation properties of relatively large fibrous aerosols dispersed in the turbulent atmospheric boundary layer, and found a distinctive correlation between the horizontal orientation averaged over an ensemble of dispersed fibers and the turbulence level under real atmospheric conditions. Olson and Kerekes (1998) and Olson (2001) simulated numerically the motion of short fibers in a homogeneous and isotropic turbulence and obtained their rotational diffusion coefficient, under the assumptions that there is no velocity difference between the fibers and the local fluids and the total moment on each fiber is zero.

Andersson and Rasmuson (2000) studied the flow and transition of fiber suspensions to turbulence in a rotary shear tester. They found that the velocity profile of boundary layer at the bottom wall is linear close to the wall even with fibers present. The presence of the fibers flattened the profiles, indicating an increased momentum transfer. Yasuda et al. (2002) obtained the fiber orientation, concentration distribution and the relationship of total shear strain vs. orientation angle in a slit flow. Dong et al. (2003) studied numerically the concentration of pulp fibers in a 3-D fully developed turbulent channel, the results showed that the concentration increased linearly with the distance from the wall and became approximately constant farther from the wall. Lin et al. (2004) simulated numerically the spatial and orientational distribution of fiber in turbulent pipe flow. They found that the spatial and orientational distributions become more homogeneous with increasing Reynolds number, and the fluctuation intensity of fiber velocity in the streamwise direction is larger than that in the other two directions, in contrast to the fluctuation intensity of the fiber angular velocity, which is weaker in the streamwise direction. Pettersson and Rasmuson (2004) studied detailed continuous phase flow measurements by laser Doppler anemometry of a turbulent gas/fiber/liquid suspension in a rotary shear tester. It is found that both RMS and mean velocities decrease with increasing gas and fiber contents. Xu and Aidun (2005) measured velocity profile of fiber suspension flow in a rectangular channel and investigated the effect of fiber concentration and Reynolds number on the shape of the velocity profile. They showed that the turbulent velocity profiles of fiber suspension can be described by a correlation with fiber concentration and Reynolds number as the main parameters. The presence of fiber in the suspension will reduce the turbulence intensity and thus reduce the turbulent momentum transfer. On the other hand, fibers in the suspension have the tendency to form fiber networks, which will increase the momentum transfer. The relative contribution of these two types of momentum flux will determine the final shape of the velocity profile. Paschkewitz et al. (2005) calculated the orientation moments and stresses for a suspension of rigid fibers along Lagrangian pathlines in a drag-reduced turbulent channel flow. They found that the largest