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Simulation of orientation of fibre particles in a stirred tank and its influential factors

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ABSTRACT

Different from spherical particles, orientation is an important property of fibre particles. It influences processing and utilizing of the irregular particles. In this paper, orientation distribution of fibre particles under different conditions in a turbulent stirred tank is simulated. The influences of virtual mass force and aspect ratio of fibre particles on the orientation are studied. The simulation is performed in a standard baffled tank stirred by a six-blade Rushton turbine impeller. Two-fluid model is employed to simulate the turbulent solid-liquid two-phase flow with fibre particles of different sizes and concentrations in the stirred tank. A novel method, which employs the rigid particle rotation equation directly, is presented for simulation of the orientation of fibre particles. Simulation results show that the inclusion of virtual mass force in the momentum equation changes the orientations. The effects of virtual mass force vary in different regions. Near the impeller blades, the influence of virtual mass force on orientation is nearly negligible at the center region. While near the wall of the tank, the orientation presents obvious difference with and without virtual mass force. The orientation of fibre particles varies with the aspect ratio. In the impeller discharging region, the orientations vary little with the aspect ratio in the center. Far from the center, the orientation decreases with the aspect ratio above the impeller and increases with the aspect ratio below the impeller. The inclusion of virtual mass force is unnecessary for spheres. However, for particles of irregular shape, especially those with different orientations, the presence of virtual mass force and aspect ratio can have significant effect on orientations.

1. Introduction

Fibre particle is an important ingredient in many industries. Owing to the special shape, fibre particles differ from spheres in many different ways. In particular, the orientation characteristics fibre particles and is also crucial to its many industrial applications. For example, papermaking is an important process involving fibres in stirred tanks. The flow and orientation of fibre particle influence the paper quality greatly. There are many influential factors on the orientation of fibre particles. Virtual mass force and aspect ratio are two of them.

Virtual mass force, also called added mass force, apparent mass force, originates from the relative acceleration of one phase to another phase. The virtual mass force is dominant in a few cases. The formulation of virtual mass force in terms of the virtual mass coefficient C_v is expressed as [1]:

$$F_v = C_v \rho_l \left[\frac{\partial}{\partial t}(u_s - u_l) + u' \frac{\partial}{\partial z}(u_s - u_l) \right] \tag{1}$$

It accounts for the force needed to overcome the additional friction and contributes to the kinetic energy change of the liquid around the accelerating bubble. u' is a characteristic convective velocity of the induced liquid flow. Selection of u' results in different forms of the virtual mass force. For example, Murry [2] chose $u' = u_s - u_l$. Soo [3] and Wallis [4] employed $u' = u_s$.

Some other forms of virtual mass force include the one suggested by Lahey [5], the convective part of this force as

$$F_v = C_v \rho_l \left(u_s \frac{\partial u_s}{\partial z} + u_l \frac{\partial u_l}{\partial z} - 2 u_s \frac{\partial u_l}{\partial z} \right) \tag{2}$$

The virtual mass force given by Winjgaarden [6] is expressed as

$$F_v = C_v \rho_l \alpha_s \left(\frac{du_l}{dt} - \frac{du_s}{dt} \right) \tag{3}$$

No matter which form of virtual mass force is chosen, the value of C_v depends mainly on the shape of particles in addition to other unclarified parameters. For rigid spherical particles in inviscid fluid, C_v is found to be 0.5 [7], while for an oblate ellipsoid particle in a uniform potential flow, C_v is 1.12 [1].

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Nomenclature

Ar^*, [−]	revised Archimedes number, $Ar^* = d_p^3(\rho_p - \rho_l)^2 g/\mu^2$
a_r, [−]	aspect ratio
C_D, [−]	drag coefficient
C_v, [−]	virtual mass coefficient
C_μ, [−]	constant
d_p, [m]	diameter of particle
F_{cd}, [N]	external force
F_v, [N]	virtual mass force
F_d, [N]	drag force
g, [m/s^2]	acceleration of gravity
k, [m^2·s^{-2}]	turbulent kinetic energy
M, [N·m]	moment
P, [Pa]	pressure
r, [m]	radial coordinate
R, [m]	diameter of the impeller
S, [m^2]	projected area in the direction vertical to its velocity
S_ϕ, [−]	source term
T, [m]	diameter of the tank
t, [s]	time
u, [m/s]	velocity
u′, [m/s]	characteristic convective velocity of the induced liquid flow
z, [m]	axial position
α, [−]	volume fraction
ρ, [kg/m^3]	density
μ, [Pa·s]	viscosity
μ_{eff}, [Pa·s]	effective viscosity
ν_t, [m^2/s]	shear viscosity
ϕ, [rad.]	angle between the particle and the velocity
τ_t, [s^{-1}]	turbulent fluctuation time for liquid, $\tau_t = \sqrt{\frac{3}{2}}C_\mu^{\frac{3}{4}}\frac{k}{\varepsilon}$
τ_{rs}, [s^{-1}]	relaxation time of particle, $\tau_{rs} = \frac{\rho_s d_p^2}{18\mu_l}$
Γ, [kg·m]	the moment of inertia
ε, [m^2·s^{-3}]	dissipation

Subscript

g	gas
l	liquid
q	liquid, or solid
s	solid
ϕ	k, or ε

Usually virtual mass force is taken into account when gas bubbles are involved, while it has negligible effect on solid particles. Ho [8] did both experimental and simulation work on nylon fibres in a hydrocyclone and found that the virtual mass force did not have any effect on the fibre particle's radial velocity in the centrifugal field. Sankaranarayanan et al. [9] analyzed the drag and virtual mass force in the simulation of gas-liquid two-phase flow. They presented a simple model for the virtual mass coefficient which was applicable to both spherical and distorted bubbles. The virtual mass coefficient for isolated bubbles could be correlated with the aspect ratio of the bubbles. Van der Gerld [10] investigated the infinite, two-dimensional added mass tensor of an axisymmetric bubble near a wall and found the Lagrangian approach to be very useful in determining the added mass force for a rapidly growing bubble. Konstantinifis [11] focused on the two-dimensional flow around a circular cylinder oscillating transversely in a free stream. They found that the added mass force contributed to the transverse force for an oscillating cylinder. The inertial force was also conceptualized as the product of added mass and added-mass acceleration.

Another important parameter for fibre particles is aspect ratio. Aspect ratio is the length-to-diameter ratio. It is usually used to describe the shape of non-spherical particles. Even though the aspect ratio is used frequently to characterize non-spherical particles, few papers paid attention to it. Mckay et al. [12] reviewed the influence of aspect ratio and fluid viscosity on velocities of cylinders during sedimentation. They found that when the aspect ratio was >1, the terminal velocity approached an asymptotic value with the increasing aspect ratio.

For fibre particles, the influences of virtual mass force and aspect ratio have not been investigated in detail. Most of the papers about fibre orientation are limited to fibres in polymeric composite materials. The fibre orientation depends on parameters of material, such as moulding factors, fibre content, etc. [13]. This is completely different from the present research. To the best knowledge of the authors, very limited paper mentioned the fibre orientations in two or three dimensional flow fields. Zeng et al. [14] modeled the fibre motion in a high-speed airflow with mixed Euler-Lagrange approach. A bead-elastic rod model was used for fibre motion, which included the effects of elastic modulus and flexural rigidity of the fibre. However they only simulated one fibre's motion, instead of a group of fibres. Lin et al. [15] derived the equation of probability distribution function for mean fibre orientation, based on the instantaneous motion equation of fibre suspension and the equation of probability distribution function for fibre orientation in a turbulent channel flow. Dou et al. [16] simulated the fibre orientation in dilute suspensions using level set method. The motion of fibres was described using Jeffery's equation. They found that the fibre orientation was not always along the direction of velocity in the process of mold filling. The fibre near the centerline in the region of fountain flow was more extended along the transverse direction.

In this paper, the orientations and velocity fields involving fibre particles in a turbulent stirred vessel are first obtained by simulation and corroborated by experiments. Detailed information upon the experiments with Digital Particle Image Velocimetry (DPIV) can be referred to [17,18]. Based on these, the influences of virtual mass force and aspect ratio on orientations of fibre particles are investigated. Their effects on velocity and solid concentration of fibre particles in this three-dimensional turbulent flow field are examined as well.

2. Hydrodynamic model

2.1. Governing equations

Two-fluid model proposed by Ishii [19] is employed to simulate turbulent solid-liquid two-phase flow in a stirred tank, where both phases are assumed to coexist at every point in space in the form of interpenetrating continua. It is proposed that the fluid is incompressible, and the interactions between particles are negligible.

In the cylindrical coordinate (Fig. 1), continuity equations and momentum equations of liquid and solid are expressed as the followings:

$$\frac{\partial}{\partial x_j}\left(\alpha_q q_k \overline{u}_{qj}\right) = 0 \tag{4}$$

$$\frac{\partial}{\partial x_j}\left(\alpha_q \rho_q \overline{u}_{qi}\overline{u}_{qj}\right) = -\alpha_q \frac{\partial \overline{P}_q}{\partial x_j} + \rho_q \alpha_q g_i + \overline{F}_{qi} + \frac{\partial\left(\alpha_q \overline{\tau}_{qij}\right)}{\partial x_j} \tag{5}$$

$$\alpha_l + \alpha_s = 1 \tag{6}$$