Chemical Engineering Science 153 (2016) 75–86

Contents lists available at ScienceDirect

Chemical Engineering Science

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

On fiber behavior in turbulent vertical channel flow

Niranjan Reddy Challabotla, Lihao Zhao *, Helge I. Andersson

Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

HIGHLIGHTS

- Dynamics of inertial fibers in turbulent vertical channel flow has been investigated.
- Eulerian–Lagrangian methodology was adopted to simulate fiber orientation and motion.
- The drift velocity of the fibers towards the wall was substantially higher in downward flow.
- Suppressed drift velocity in upward flow resulted in a more uniform fiber distribution.
- Presence of gravity induced preferential alignment of inertial fibers with flow direction at the channel center.

ARTICLE INFO

Article history:
Received 13 January 2016
Received in revised form
17 June 2016
Accepted 3 July 2016
Available online 5 July 2016

Keywords:
Fiber suspension
Turbulent flow
Gravity
Gas–solid flow
Direct Numerical Simulation
Eulerian–Lagrangian approach

ABSTRACT

In the present work, the dynamic behavior of inertial fibers suspended in a turbulent vertical channel flow has been investigated. The three-dimensional turbulent flow field was obtained from the Navier–Stokes equations by means of direct numerical simulation in an Eulerian reference frame. The fibers were modeled as prolate spheroidal particles in a Lagrangian frame and characterized by their inertia and shape. The translation and rotation of the individual fibers were governed by viscous forces and torques as well as by gravity and buoyancy according to Newton's laws of motion. The test matrix comprised four different Stokes numbers (inertia) and three different aspect ratios (shape). The twelve different fiber types were suspended both in a downward and in an upward channel flow. Fiber orientation and velocity statistics were compared with channel flow results in absence of gravity.

The results showed that gravity has a negligible effect for fibers with modest inertia, i.e. low Stokes numbers, whereas gravity turned out to have a major impact on the dynamics of highly inertial fibers. Irrespective of the bulk flow direction, a preferential alignment of the inertial fibers with the gravity force was found in the channel center where fibers have been known to orient randomly in absence of gravity. In the downward channel flow, the drift velocity of the fibers towards the walls was substantially higher for fibers than for spheres and also higher than when gravity was neglected. In the upward flow configuration, the modest drift velocity of inertial spheres was totally quenched for all fibers irrespective of shape. The suppressed drift velocity resulted in a more uniform fiber distribution throughout the channel as compared to the distinct near-wall accumulation in downward flow and in absence of gravity. This suggests that an upward flow configuration should be the preferred choice if a uniform fiber distribution is desired, as in a biomass combustion reactor.

1. Introduction

Turbulent suspension flows of non-spherical particles occur in many industrial, environmental, and biological applications such as in paper making processes (Lundell et al., 2011), fluidized bed reactors (Loranger et al., 2009), biomass combustion (Ma et al., 2007), aerosol transport (Kleinstreuer and Feng, 2013), pneumatic conveying (Hilton and Cleary, 2011), and phytoplankton transport in the ocean (Guasto et al., 2012). Studies of the dynamics of non-spherical particles in turbulent flows play an important role in the advancement of design of industrial processes and better understanding of natural processes. In the literature there exists a large number of studies focusing on spherical particle suspensions in wall-bounded turbulent flows (Kulick et al., 1994; Marchioli et al., 2007; Marchioli and Soldati, 2002; Maxey and Riley, 1983; Mortensen et al., 2007; Nilsen et al., 2013; Rouson and Eaton, 2001). Non-spherical particles suspended in fluid turbulence have received considerably less attention compared to suspensions of spherical particles. In the majority of applications, the non-spherical particle can be closely approximated by a regularly-shaped

* Corresponding author.
E-mail address: lihao.zhao@ntnu.no (L. Zhao).

http://dx.doi.org/10.1016/j.ces.2016.07.002

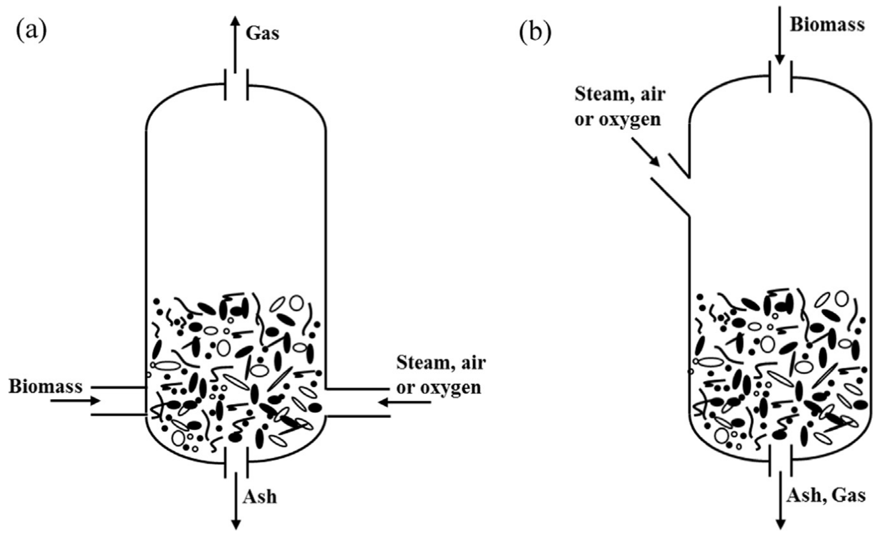

Fig. 1. Two qualitatively different types of entrained flow gasifiers: (a) side feed reactor, and (b) top feed reactor (adapted from Basu (2010)).

axi-symmetric particle, notably a spheroidal particle which is characterized by its shape and inertia quantified by the aspect ratio λ and the response time τ_p, respectively. Following the seminal mathematical analysis by Jeffery (1922) for an ellipsoidal particle suspended in a creeping flow, several researchers (Brenner, 1963, 1964; Gallily and Cohen, 1979; Harper and Chang, 1968) have contributed to the advancement of the theory related to the translational and rotational motion of spheroidal particles in shear flows. In all these studies Stokes-flow conditions were assumed around the particle and both the effects of fluid and particle inertia were thus neglected. Lin et al. (2003) summarized the work related to the dynamics of non-spherical particles in laminar shear flows. In the absence of fluid inertia, particle inertia results in a drift towards tumbling of rods with modest inertia (Lundell and Carlsson, 2010; Subramanian and Koch, 2006) whereas spinning is observed for heavy rods (Lundell and Carlsson, 2010; Nilsen and Andersson, 2013). Computer simulations using a lattice Boltzmann method were used to identify different rotational states of a spheroidal particle as a function of the particle Reynolds number $Re_p = Gd^2\nu^{-1}$ based on the equatorial diameter d and the shear rate G (Huang et al., 2012; Qi and Luo, 2003; Rosén et al., 2014; Yu et al., 2007). Recently Rosén et al. (2015) reported the different rotational states observed for a prolate spheroidal particle due to the combined effects of fluid and particle inertia.

The dynamics of non-spherical particles in turbulent flows is exceedingly more complex than in laminar shear flows. The prevailing approach has been to consider the motion of spherical particles and how they concentrate themselves in the turbulent environment. Recently there is an increased focus on the understanding of the behavior of non-spherical particles in turbulent flows. The dynamics of non-spherical particles in homogeneous isotropic turbulence have been explored in experimental investigations (Bellani et al., 2012; Ni et al., 2015; Parsa et al., 2011) and computational studies (Byron et al., 2015; Fan and Ahmadi, 1995; Gustavsson et al., 2014; Marcus et al., 2014; Ni et al., 2014; Olson, 2001; Parsa et al., 2012; Shin and Koch, 2005).

Experimental studies on non-spherical particles in wall-bounded turbulent flows are scarce (Abbasi Hoseini et al., 2015). Yin et al. (2003) and Zastawny et al. (2012) developed a methodology for modeling the dynamics of non-spherical particle-laden flows by assuming shape and orientation dependent drag and lift-force correlations. Later this methodology has been adopted by Njobuenwu and Fairweather (2014, 2015) to investigate the influence of a wide range of particle shapes and inertia on the translational and rotational behavior of ellipsoidal particles in wall-bounded turbulent flows. More accurate direct numerical simulations (DNSs) of the turbulent flow field coupled with a Lagrangian point-particle tracking methodology were successfully employed by some different research groups to investigate the dynamics of non-spherical inertial particles in wall-bounded turbulent flows. Zhang et al. (2001), and later followed by several others (Challabotla et al., 2015; Marchioli et al., 2010; Mortensen et al., 2008a, b; Zhao and van Wachem, 2013; Zhao et al., 2015) focused on the orientation, transport, and deposition of fibers suspended in a turbulent channel flow over a wide range of particle parameters (aspect ratio λ and inertia τ_p). The fiber inertia resulted in accumulation of fibers in the near-wall region and preferential concentration in the low-speed streaks which characterize wall turbulence. The fibers in the near-wall region moreover tended to preferentially orient themselves in the streamwise direction and this tendency increased with aspect ratio. A first attempt towards fully-resolved simulations of finite-size rod-like particles suspended in a turbulent channel by means of a lattice Boltzmann approach was recently reported by Do-Quang et al. (2014).

The role of gravity is believed to be of practical importance in fiber-suspended turbulent flows. In all industrial applications and experimental studies gravity is inevitably present, but in most of the abovementioned computational investigations the gravity force has been neglected. For example in bio-mass combustion reactors, as depicted in Fig. 1, the injection of biomass fibers either from the top or the bottom might have significant effect on the influence of the combustion efficiency. In order to optimize the reactor design, it is essential to better understand the fiber dynamics in different gravity configurations. Only a few systematic investigations have been carried out with the view to understand the effect of gravity on the dynamics of particle-laden turbulent flows. Gravity effects on spherical particle dispersion and deposition via the crossing trajectory mechanism in a vertical pipe flow were reported by Uijttewaal and Oliemans (1996). A comprehensive and systematic study of gravity and lift force effects on spherical particle velocity and deposition statistics in a turbulent vertical channel flow were reported by Marchioli et al. (2007). Recently, Nilsen et al. (2013) showed that gravity has a significant influence on the slip velocity of inertial spheres. The statistics deduced for the heaviest spherical particles were strongly dependent on the actual gravity configuration. Zhang et al. (2001) studied transport and deposition of ellipsoidal particles in a turbulent channel flow and observed strong effects of gravity at low