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Original Research Paper

Dynamics of bi-dispersed settling suspension of non-colloidal particles in rotating cylinder

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ABSTRACT

Non-neutrally buoyant suspension of bi-dispersed non-colloidal particles in viscous fluid rotating in a horizontal cylinder displays in-homogeneities in particle distribution with alternate bands of high and low particle concentrations along the symmetric axis of the cylinder. Experiments were carried out to characterize the axial segregation in bi-dispersed suspension at various filling fraction and rotation speed of cylinder. The mixture of same particles in absence of any suspending fluid did not show any segregation. However, in case of particles suspended in water it was observed that the rate of segregation increases with increase in filling fraction. Once the particles get segregated along the full length of the cylinder, these bands start to migrate along the tube axis finally merging to give wider bands. For a given filling fraction the rate of segregation increases with the angular speed of the rotating cylinder. When the tube is partially filled the particle segregation is observed at higher angular speed, whereas in fully filled case the segregation starts at much lower rotation speed for the same concentration of particles. The segregation pattern changes as the rotation speed is increased. At higher speed the centrifugal force dominates over gravitational and viscous drag forces and this result into completely different segregation patterns. We have also analyzed the evolution of concentration profile from the image analysis of the particles.

1. Introduction

Suspension of solid rigid particles in viscous fluid has many practical applications in chemical, metallurgical, plastics, pharmaceutical and food processing industries. For example, mixing of different sizes of particles dispersed in fluid medium is carried out in a rotating drum to prepare pastes for manufacture of composite membranes. Cement kilns also employ rotating drums for mixing of particles. Pan coater (which is a rotating tube device) is commonly used in pharmaceutical industries for coating different sizes of capsules and tablets. To improve the coating performance of such devices it is essential to understand the movement of particles and fluid inside the pan coater [1]. In mixing operations it is desired that the particles remain homogeneously dispersed and do not segregate [2]. On the other hand the phenomenon of particle segregation also provides an easy way of separating the particles by taking advantage of segregation caused by simply rotation of the cylinder. In some recent studies it has been observed that suspension of mono-dispersed neutrally buoyant particles in a partially filled horizontally rotating cylinder segregates into bands of particles that are separated by regions of pure fluid [3,4]. In another experiment Timberlake and Morris [5] observed alternate bands of relatively concentrated and dilute particle fraction along the axis of a partially filled inclined concentric cylinder. The number of bands was found to increase with the rotation speed of the cylinder. In these studies the fluid-air interface is thought to be important for axial segregation as no segregation was observed when the tube was fully filled with the neutrally buoyant particles. Subsequent to these experiments, Breu et al. [6] studied the flow of non-neutrally buoyant suspension of mono-dispersed particles in a completely filled cylinder. They observed similar instabilities and pattern formations at high rotation speeds where centrifugal forces on the particles dominated over other forces. The reason for this observation was thought to be the density difference between the fluid and particles. Matson et al. [7] further demonstrated that a suspension of non-colloidal settling particles in a completely filled horizontal cylinder demonstrates a rich array of concentration and velocity patterns at various rotation rates. In case of non-neutrally buoyant, mono-dispersed suspension the particles approach in downward side and expel in upward side and the formation of clusters depends on the rotation speed [8]. Kalyankar et al. [9] have also observed unique concentration and velocity patterns in a horizontally

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Nomenclature

a	radius of suspending particles (μm)	Ω	angular speed of rotation of the cylinder (rad/s)
N	rotation rate of cylinder (rpm)	X_f	filling fraction of suspension in the tube
R	cylinder radius (m)	R_{ew}	Reynolds number based on wall speed and cylinder radius
ρ_s	density of suspending fluid (kg/m^3)		
η	viscosity of the suspending fluid (kg/m-s)	δ	size ratio of bigger and smaller particle

rotating cylinder completely filled with a mono-dispersed suspension of non-Brownian particles. To our knowledge there are no reported studies on suspension of bi-dispersed non-neutrally buoyant particles in rotating cylinder. In most of the practical applications the suspensions often have particles of different sizes. This motivated us to study the segregation pattern for bi-dispersed system.

There are several studies on the axial segregation of bi-modal granular mixtures [10,11] but not many on the particulate suspensions. Hill and kakalios [12] reported on the segregation of binary mixture of glass beads into sharp bands of alternating large and small particles along the axis of rotation. They have shown that the segregation bands were visible at higher angular speed which disappeared when the angular speed was decreased. They also noted that if the granular particles have different dynamic angle of repose, then a drift current will develop along the axis of rotation which tends to separate them into the two sizes. The particles with various bi-dispersivity were classified based on their segregation behavior as per the following three categories; no segregation at any rotation speed, non-reversible axial segregation and reversible axial segregation [13,14]. In our work on particulate suspensions the bi-dispersed particles were chosen which comes under the first category i.e., no segregation at any rotating speed under dry granular rotation. Jain et al. [15] reported alternate band formation in wet granular media or slurries as well as for dry granular mixtures. They found that particle segregation in dry granular mixture is significantly faster compared to that in suspensions in liquid media. These works have shown that for bi-dispersed mixture of granular particles the axial and radial segregation of small and large particles occurs when the static angles of repose of these particles are unequal. The particles undergo a solid body rotation about the cylinder axis. The particles experience convective motion due to the shear flow and a random motion resulting from particle–particle collisions. The mechanism of pattern and size segregation in suspensions can be quite different as the hydrodynamic forces play an important role here which are absent in granular mixtures.

Gans and Zupanski [16] have described a system for generation of vortices in rapidly rotating cylinder partially filled with water. They performed experiments in a regime dominated by inertial forces and obtained results which are independent of viscosity and surface tension of the fluid. Krasnopol et al. [17] have shown eight different flow patterns in pure fluid as well as granular materials rotating in a partially filled horizontally rotating cylinder. It has been shown in the above mentioned studies that the viscous drag, gravitational and centrifugal forces play a vital role in segregation. Lee and Ladd [18] have performed numerical simulations of non-neutrally buoyant particles in rotating cylinders and observed regular bands of high and low concentration along the symmetric axis as observed in the experiments [19,20].

Despite their industrial importance there are no reported studies on the size segregation of bi-dispersed suspensions in horizontally rotating cylinder. There are several factors which contribute to the instability of suspension in rotating cylinder and this instability leads to axial segregation of smaller and bigger particles, forming a number of alternate bands. Our objective here is to study the segregation behavior of bi-dispersed suspensions at various rotation speed of the cylinder as well as examine the effect of filling fraction on size segregation.

2. Experimental details

The experimental setup used in the present study is shown in Fig. 1. It consists of a 0.207 m long horizontally aligned transparent

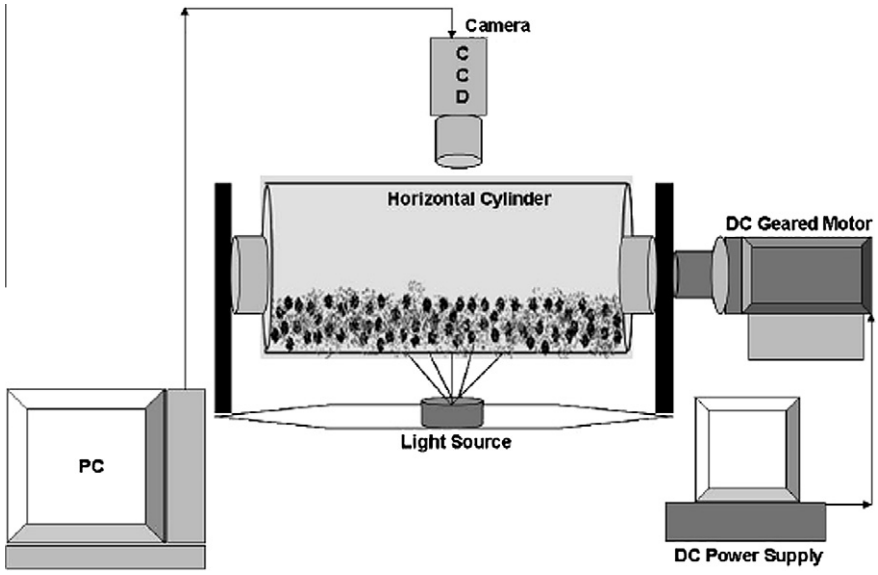

Fig. 1. Schematic diagram of the experimental setup of horizontally rotating cylinder.