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Hydrodynamic modeling of downward gas–solid flow. Part II: Co-current flow

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ABSTRACT

The one-dimensional model of accelerating turbulent downward co-current gas–solid flow of coarse particles was formulated and experimentally verified by measuring the pressure distribution along the transport tube. The continuity and momentum equations were used in the model formulation and variational model was used for the prediction of the fluid–particle interphase drag coefficient.

The experiments were performed by transporting spherical glass particles 1.94 mm in diameter in a 16 mm i.d. acrylic tube at constant solid mass flux of 392.8 kg/m^2 s. Tube Reynolds number ranged from 880 to 11,300 and the slip Reynolds number from 32 to 670. At these conditions, the loading ratio G_p/G_f was in the range from 395 to 31. Experimental data for the static fluid pressure distribution along the transport tube agree quite well with the model predictions.

The results measured at a distance of 1.51 m from the transport tube inlet show that the particle velocity and the mean voidage increase with the increase in superficial gas velocity. The slip velocity changes from negative values at low gas superficial velocities to positive values at high gas superficial velocities. The same trend was observed for the change of the pressure gradient in the system.

The values of the pressure gradient, porosity, particle velocity and slip velocity along the tube were calculated according to the formulated model. The distance from the transport tube inlet at which the slip velocity changes its sign from positive to negative is the function of the gas superficial velocity. At positive slip velocity both gravity and drag contribute to particle acceleration. At negative slip velocity the drag force acts in upward direction resisting the particle acceleration. In downward co-current gas–solid flow acceleration length is relatively long, about two times longer compared to the upward co-current gas–solid flow.

1. Introduction

Gas–solid co-current downers possess some unique features when compared to other gas–solid systems: relatively homogenous dilute flow structure, nearly plug-flow of phases, low solid hold-up, short residence time and relatively large loading ratio. Due to these properties downers attracted attention both in fundamental research and for practical applications. An abundant literature about these contacting systems exists and several papers give good insight into this area [1–3].

Cheng et al. [1] pointed out that fast catalytic conversion of heavy oil and other hydrocarbons and the pyrolysis of biomass, coals, and solid wastes are the two most promising processes for a downer co-current reactor. Several other processes have also been studied: drying in downward co-current flow regime [4], ozone decomposition [5,6], liquid–solid combined system downer–riser for protein recovery from the feed broth [7], selective synthesis of single-walled carbon nanotubes from methane in a coupled downer–turbulent fluidized bed reactor [8], simultaneous carbon and nitrogen removal with bioparticle circulation in a coupled riser–downer system [9] and a plasma downstream reactor for particle surface modification [10].

Different aspects of downer reactors have been investigated in the literature. Hydrodynamic studies include flow structure investigation and characterization [11–14], the study of particle velocity, solid concentration profiles, solid flux profiles and pressure gradient distributions including radial variations in the downer reactor under different operating conditions [15,16], slip velocity between phases [17] and particle clustering [18]. Li et al. [19] developed a mathematical model to describe the hydrodynamics in the fully developed region of a downer reactor and used it successfully to predict local solid holdup and gas–solid velocities. Bolkan et al. [20] also developed a mathematical model based on fluid dynamic fundamentals for simulation of a downer reactor. It could be used to estimate the average size of agglomerates formed within the downer. Deng et al. [21] formulated a one-dimensional model based on momentum equations and continuity equations coupled with the reaction kinetics in order to study downer reactor performance at varying gas superficial velocities. The predictions obtained using their model agree well with the experimental observations. Since during certain chemical reactions gas volume, i.e. gas superficial velocity, varies with the axial distance

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from the tube entrance, a model for such system is important for the application of downer reactors. Friction between phases has been investigated by Qi et al. [22]. Qi et al. [23] also investigated solid concentration in the fully developed region of co-current downward gas–solid flow and proposed an empirical correlation to predict the solid concentrations in the fully developed region of CFB downers. The correlation is in good agreement with the experimental data of their work and of the literature data.

Ma and Zhu [24,25] measured the heat transfer coefficient between the suspended surface and the gas–particle flow suspension. It was found that the radial profiles of heat transfer coefficients were consistent with the solid holdup profiles. The average heat transfer coefficient decreased with decreasing solid circulation rate, due to decreased solid holdup. Kim et al. [26] found that heat transfer coefficient increased with decreasing particle size.

There are a large number of papers dealing with Computational Fluid Dynamics (CFD) modeling of the gas–solid flow in co-current downer reactors. In most of these studies, the fine solid particles were investigated, most frequently FCC catalyst particles.

Ropelato et al. [27] used the Eulerian–Eulerian approach in CFD study of gas–solid behavior and compared it to the experimental data from the literature. They concluded that CFD modeling can be a useful tool for fluid dynamic prediction. Vaishali et al. [28] used the CFD simulations to investigate the most suitable closures for the force interactions in the system. The results were presented for mean solid velocities, volume fraction and slip velocities for different operating conditions. Chalermsinsuwan et al. [29] investigated the effect of the various modeling parameters in the circulating fluidized bed downer. The predicted values of the solid volume fraction, solid mass flux and system pressure were in agreement with the experimental measurements.

Zhang et al. [30] combined the CFD modeling with the discrete element method and predicted the existence of particle clusters in downer reactors and studied their type and behavior. The cluster formation was also investigated by Naren et al. [31]. In order to improve the simulation results, the authors proposed the introduction of the new interphase drag correlation which takes into account particle clustering effect which is important for small particle systems. Zhao et al. [32] applied the CFD-DEM approach to simulate particle distribution profiles in a downer. The simulation results were compared with experimental measurements obtained using Electrical Capacitance Tomography (ECT) and good agreement was observed.

Almost all the studies from literature deal with fine particles, most frequently FCC catalyst ($d_p \approx 70$ μm). In this study new experimental data for coarse particles ($d_p = 1.94$ mm) are presented. The one-dimensional model of dilute accelerating turbulent co-current downward gas–solid flow of coarse particles is formulated and experimentally verified by measuring the pressure distribution along the transport tube. Essentially, the model of upward mixture flow and downward counter-current flow proposed earlier [33,34] was modified for the application in downward co-current gas–solid flow.

2. Experimental

The experiments were carried out in air–particle system, using the pneumatic transport tube schematically shown in Fig. 1. In the co-current experimental setup in this paper, the particles move downward by free falling from the feeding reservoir (b) while the downward air flow is induced using the air-pump (k). The transport tube (a) was of internal diameter 16 mm and 2230 mm of length. The pressure profile along the tube was measured at three points (p_1, p_2 and p_3) using manometers. The concentration of the particles in the transport tube was measured using two closing traps placed at a distance of 800 mm from each other (e_1 and e_2). The traps were operated using an electromagnetic valve (g) in such a way that they closed simultaneously. The traps were made of perforated plates in order to collect the particles, and to allow the air flow through them. The collected particles were weighed and the solid concentration was calculated using these data. The other elements of the pneumatic transport tube are shown in Fig. 1.

Spherical glass particles 1.94 mm in diameter were used in the experiments. Basic particle and fluid characteristic were [34]: $\rho_p = 2507$ kg/m^3,

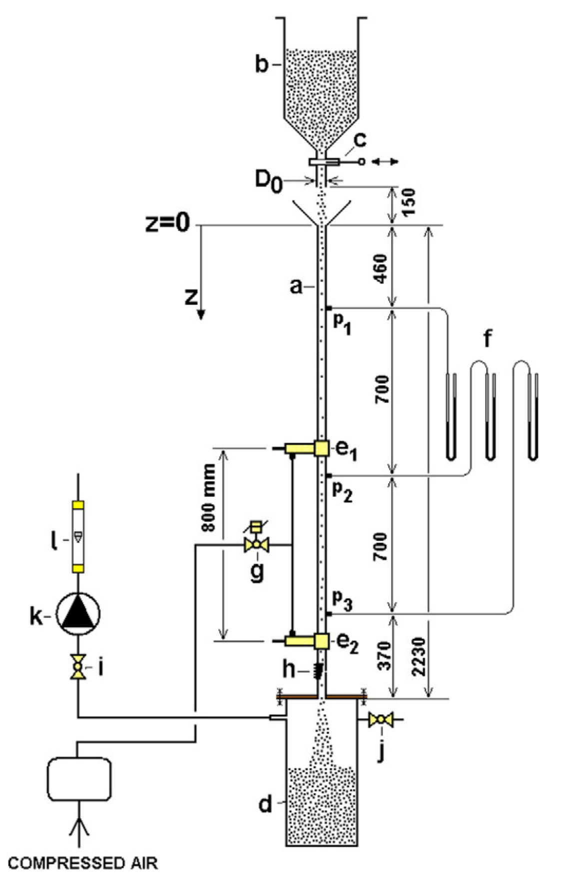

Fig. 1. Schematic diagram of the experimental system. a — transport tube, 16 mm i.d.; b — feeding reservoir (hopper); c — knife valve; d — receiving reservoir; e1, e2 — traps; f — manometers; g — electromagnetic valve for closing traps; h — connection point; i — valve; j — on-off valve; k — pump; l — rotameter; p1 … p3 — pressure taps.

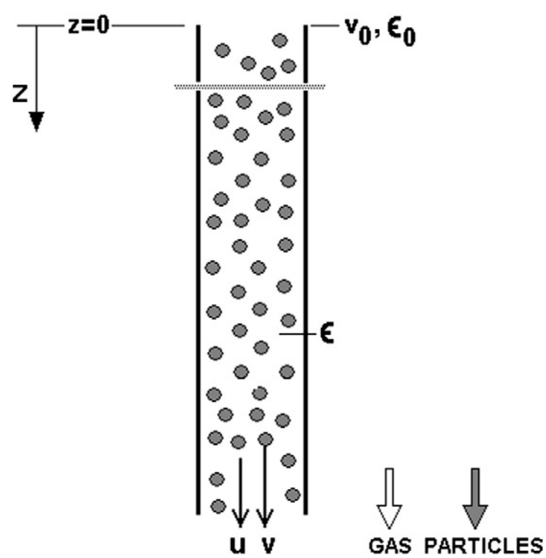

Fig. 2. Schematic diagram of co-current gas–solid flow.