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A comparative study on hydrodynamics of circulating fluidized bed riser and downer

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ABSTRACT

Hydrodynamics in a 76 mm i.d., 10.2 m high circulating fluidized bed (CFB) riser and a 76 mm i.d., 5.8 m high CFB downer were studied for superficial gas velocities ranging from 2 to 5 m/s and solid circulation rates up to 100 kg/(m^{2}s). Solid holdup, particle velocity and solid flux profiles in the radial and axial positions were presented. Under these operating conditions, axial solid holdup profiles in the riser and the downer could be approximated by an exponential decay function. The radial gradients of the solid holdup profiles in the riser were much higher than those in the downer, showing that the downer had much more uniform solid distribution. The average solid holdup for the entire riser was about 1.5 times higher than the predicted value from $G_s/(\rho_p U_g)$. However, for the downer reactor this ratio dropped to 0.45–0.98 which increased with increasing superficial gas velocity and decreasing solid circulation rate. Solid flow developed much slower in the riser than in the downer. Negative particle velocity was observed in the near-wall region for nearly the entire height of the riser. The average particle velocity for the entire riser was 0.8–0.96 times higher than the superficial gas velocity, and increased with increasing superficial gas velocity and decreasing solid circulation rate. However, in the downer the average particle velocity was 1.13–2.13 times higher than the superficial gas velocity, and increased with both superficial gas velocity and solid circulation rate. High local solid fluxes were observed in the near wall region of the CFB riser and downer reactor. Over-estimation of the calculated cross-sectional average solid flux over the solid circulation rate in the CFB riser was attributed to the fluctuations of the solid holdup and particle velocity.

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1. Introduction

The commercial interest in circulating fluidized bed (CFB) technology can be dated back to the 1940s when the fluid catalytic cracking (FCC) process was first developed [1,2]. But due to low catalyst activity and other technical difficulties, it was not until in the 1970s when high velocity CFB technology was “re-invented” [3].

CFB reactor has been providing many advantages over bubbling fluidized bed reactors such as higher gas–solid contact efficiency, reduced axial dispersion for both gas and solid phases and higher gas/solid throughput [4,5]. The CFB riser reactor has been widely used in various industries [4,6] such as combustion of low-grade fuels, mineral processing, FCC and as a catalytic reactor for the production of a number of specialty chemicals [7]. On the other hand, the CFB riser suffers from solid backmixing, macro segregations of gas and solid phases due to the non-uniform flow structure in radial and axial directions, and micro segregations caused by particle clustering. These drawbacks are results of both gas and solids flowing against gravity [5], which reduce gas-solid contact efficiency and lead to undesired distribution of products due to reduced selectivity.

The disadvantages of the riser reactor may be overcome in a new type of chemical reactor – a CFB downer reactor [5,8,9], where gas and solid phases flow co-currently downward, in the same direction as gravity force. In a CFB downer, particles accelerate much more quickly since they gain momentum from both the gas and the force of gravity. Hydrodynamic studies show that the radial distribution of flow parameters such as solid holdup and particle velocity in the CFB downers is more uniform than that in the CFB risers [10–12]. This radial uniformity further reduces gas and solid dispersion and leads to nearly plug flow for both phases in the downer [12,13]. With reduced axial dispersion and more uniform gas and solid residence times, CFB downer reactors become more advantageous than CFB risers for reactions requiring short residence times [9], especially where intermediates are the desired products, such as the FCC and residual fluidized catalytic cracking processes [5,12].

Hydrodynamic studies are very important in understanding the CFB riser and downer reactors. In spite of numerous earlier studies on hydrodynamics in CFB reactors, this study provides a complete mapping of the local volumetric solid holdup, particle velocity, and solid flux at variable radial and axial positions in the 76 mm i.d. riser and downer reactors with superficial gas velocity ranging from 2 to 5 m/s and solid circulation rates at 50 and 100 kg/(m$^2\cdot$s).

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2. Experimental

2.1. CFB experimental setup

Experiments were carried out in a circulating fluidized bed system illustrated in Fig. 1. Major components included a 76 mm i.d., 10.2 m high CFB riser, a 203 mm i.d. downcomer, a 457 mm i.d. storage tank, a 76 mm i.d., 5.8 m high CFB downer and another 51 mm i.d., 4.9 m high CFB downer, sampling ports, gas distributors, and cyclones and bagfilter for gas solid separation. The entire fluidized bed system used aluminum as the main construction material and was electrically grounded to remove electrostatic charges formed in the columns. A measuring device for solid circulation rate was installed in the top section of the downcomer. By regulating the ball valve located in the solid feeding line connecting the storage tank and the riser column, the solid circulation rate was adjusted and maintained at a desired value during each experiment.

For CFB riser operations, solid particles fluidized by auxiliary air entered into the bottom of the riser and obtained momentum from the air passing through the gas distributor made of perforated plates (9.5 mm × 30 holes, 47 % voids). The solid particles flowed upward together with the air, and were separated by the cyclones and returned to the downcomer. Fine particles leaving the cyclones were trapped by the bagfilter and returned periodically to the downcomer. This was, however, a very small amount of solids compared to the flow in CFB columns due to high efficiency of the cyclones.

For CFB downer operations, solid particles were lifted through the riser, separated by the cyclones and fed into the downer. Gas and solid phases passed through the distributor (with its detail design also shown in Fig. 1), and then together flowed downward along the column. After fast separation at the exit of the downer column, most particles were retained in the storage tank, with the remaining particles captured by the primary and secondary cyclones and the bagfilter.

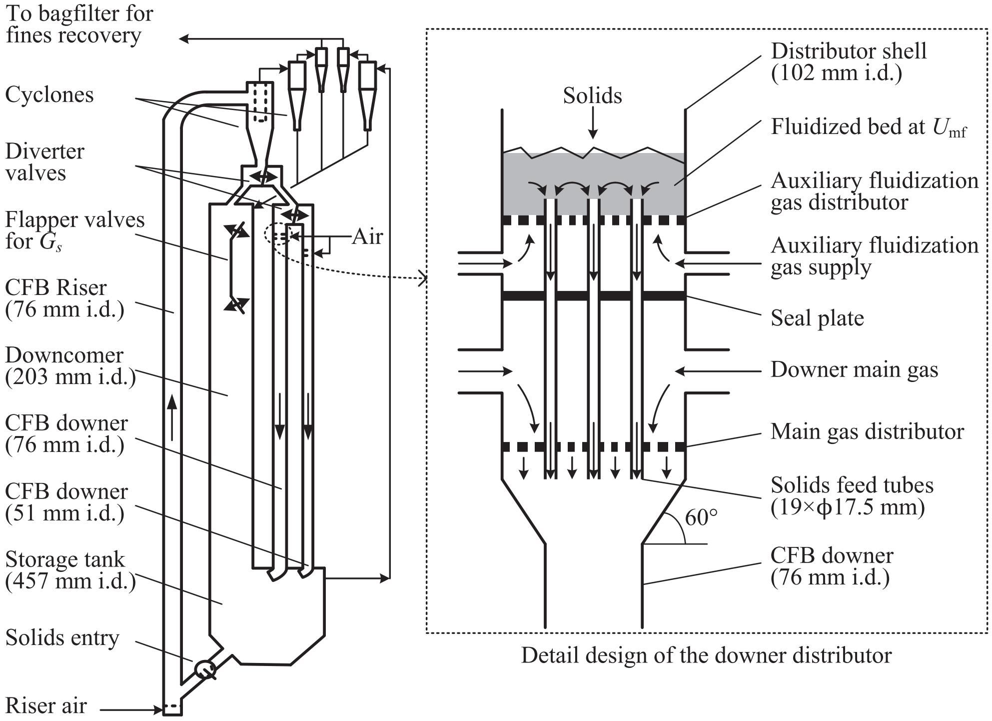
The operating conditions were superficial velocities of 2, 3, 4, and 5 m/s, with solid circulation rates being 50 and 100 kg/(m^{2}s). The axial sampling positions were 0.11, 0.57, 1.02, 1.48, 1.94, 2.39, 2.85, 4.78, 7.32, 9.61 m above the gas distributor for the riser, and 0.22, 0.61, 1.12, 1.63, 2.13, 2.64, 3.26, 4.02, and 4.99 m below the gas distributor plate for the downer. The dimensionless radial sampling positions (r/R) for both the CFB riser and the downer were 0 (center), 0.316, 0.548, 0.707, 0.837 and 0.949 (close to wall).

2.2. Solid particles

Fresh FCC catalyst particles impregnated with ferric oxide (Fe_2O_3) were used in this hydrodynamic study and other catalytic ozone decomposition studies by the authors [14,15]. Since particle size is an important factor affecting the hydrodynamics in the fluidized beds [4,6], to achieve a stable particle size distribution (PSD) for the CFB experiments the particles after the impregnation process were subjected to run through the riser for 7 days to remove the fines. More details on the catalyst impregnation process, and how the particle size distribution changed during catalyst preparation can be found in the research paper by Li et al. [14]. When stable PSD was achieved, the Sauter mean particle size was 60 μm, and the apparent particle density (ρ_p) and bulk density (ρ_b) were determined to be 1370 kg/m^3 and 795 kg/m^3, respectively.

2.3. Measurement and calculation of solid holdups

Reflective-type optical fiber probes offer a simple and more affordable way to measure local solid holdup in fluidized bed systems, providing many advantages such as minimum disturbance to the gas–solid flow and negligible interference by temperature, humidity, electrostatics and electromagnetic fields [16]. In this study PV-5 optical fiber probes (manufactured by the Institute of Process Engineering, Chinese Academy of Sciences) were used to measure the local volumetric solid holdup. An illustration of the optical fiber probe and the measurement principle is provided in Fig. 2. The diameter of the probe is 4 mm, with 2 vertically aligned sub-probes in a square shape of 1 × 1 mm^2. The maximum distance the probe can be inserted into the column is 400 mm. The optical fiber probe has both light emitting and receiving



Detail design of the downer distributor

Fig. 1. The CFB experimental setup.

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