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Hydrodynamic scale-up of circulating fluidized beds

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ABSTRACT

The effects of scale-up on the hydrodynamics of circulating fluidized beds (CFB) are investigated using a single cold laboratory facility with the ability to recycle fluidization gas mixtures of adjustable kinematic viscosity. Tests are conducted with a plastic powder and glass beads to simulate the high-temperature fluidization in CFB risers of 0.32 and 0.46m diameter, respectively. The hydrodynamic simulation is achieved by matching five dimensionless parameters. Particular care is taken to eliminate electrostatics from the bed using traces of an anti-static additive. Comparisons of the vertical static pressure profiles obtained with the plastic and glass powders indicate that the dimensional analysis yields the correct analogy for the global hydrodynamics of CFB risers.

INTRODUCTION

Circulating fluidization is a promising technology for designing efficient coal combustors with higher solid throughputs. Excellent contacting is achieved as solids are entrained in a vertical riser column by a stream of reactive gases at high velocity. Unfortunately, limited understanding of circulating fluidized beds (CFB) renders design extrapolations from pilot reactors to full scale plants both empirical and expensive. In particular, the behavior of large-scale units is unclear.

The hostile environment of coal combustion makes measurements challenging in CFB powerplants. Even essential flow variables like overall solid fluxes are seldom recorded. In contrast, cold facilities can produce detailed hydrodynamic data. However, because the density and viscosity of cold gases are markedly different than that of typical combustion products, the hydrodynamics of cold units may not be relevant to CFB combustors. To avoid this problem, several researchers have employed dimensional analysis to match the hydrodynamics of bubbling [1, 2, 3, 4, 5, 6, 7, 8, 9] and CFB [10, 11, 12, 13] combustors in cold laboratory facilities.

Because vessel geometry greatly affects CFB flow behavior, Horio, et al. have carefully matched the aspect ratios of CFB units of increasing sizes before comparing their hydrodynamics [11]. In contrast, we have quantified hydrodynamic scale-up effects directly using a single facility. To this end, we have constructed a cold CFB with the ability to recirculate –rather than discard– fluidization gas mixtures of adjustable density and viscosity. Using dimensional similitude, this cold CFB riser with diameter of 20cm, operating with different gas and solid systems, is made to simulate generic coal-burning CFB risers of 32cm and 46cm diameter.

In this paper, we begin with a description of the dimensional analysis and the laboratory facility. Then we present data collected with glass beads and a plastic powder to substantiate the hydrodynamic analogy.

DIMENSIONAL SIMILITUDE

Because in relatively dilute vertical gas-solid suspensions the shear in the particle phase has a negligible contribution to the overall pressure gradient [14], the global flow behavior of the CFB is largely independent of particle collisions. In the absence of inter-particle forces or electrostatics, continuum equations for gas-solid suspensions derived, for example, by Anderson and Jackson [15] yield five dimensionless parameters. These include Froude number $Fr=u/\sqrt{gd}$ and solid loading $L=G/\rho u$, which determine the operational characteristics of the bed; Archimedes number $Ar=\rho_s \rho d^3/\mu^2$ and density ratio $R=\rho/\rho_s$, which combine gas and particle properties; and ratio of riser diameter to mean particle diameter D/d. In this paper, u represents the superficial gas velocity; G is the average solid flux; ρ and ρ_s are the densities of the gas and the material of the particles, respectively; μ is the gas viscosity; and g is the acceleration of gravity.

Thus, the global hydrodynamics found in a generic CFB coal combustor can be reproduced in a cold laboratory model of identical aspect ratios by matching values of Fr, L, Ar, R and D/d. Algebraic manipulations of these numbers yield the following relations between the conditions in the cold model (subscript 1) and those in the generic combustor (subscript 0):

superficial gas velocity $$u_1/\nu_1^{1/3} = u_0/\nu_0^{1/3} , \quad (1)$$

particle size $$d_1/\nu_1^{2/3} = d_0/\nu_0^{2/3}, \quad (2)$$

particle density $\rho_{s1}/\rho_1 = \rho_{s0}/\rho_0$, (3)

solids flux $G_1/(\rho_1^{2/3}\ \mu_1^{1/3}) = G_0/(\rho_0^{2/3}\ \mu_0^{1/3})$, (4)

characteristic bed dimension $D_1/\nu_1^{2/3} = D_0/\nu_0^{2/3}$. (5)

A wide range of kinematic viscosities ν_1 is obtained by fluidizing the cold facility with adjustable mixtures of helium and carbon dioxide, which are gases of greatly different densities. By virtue of equation (5), each new value of ν_1 makes the flow in the cold riser analogous to that in a new combustor of diameter D_0. In this way, a single facility is sufficient to investigate the effect of scale-up on the hydrodynamics of ideal CFB combustors, without the need to build several coal-burning pilot plants of increasing size.

In this study, we assume that a generic coal combustor operates at constant properties under the following conditions: particle mean diameter $d_0 \approx 250$ μm and density $\rho_{s0} \approx 1500$ kg/m^3 (mixture of coal and limestone); temperature T_0 =1070 °K (i.e., $\rho_0 \approx 0.3$ kg/m^3, $\mu_0 \approx 4\ 10^{-5}$ kg/m/sec); superficial gas velocity $u_0 \approx 5$ to 9m/s and solid flux $G_0 \approx 7$ to 100kg/m^2/sec. Because these parameters are set, the choice of a test powder with density ρ_{s1} imposes the gas density ρ_1 through equation (3) and it determines the composition of the fluidization gas mixture. The resulting value of μ_1, which is evaluated using Wilke's semi-empirical formula [16], yields the analogous combustor diameter D_0 through (5), the mean size of the test powder d_1 through (2), and the operating conditions u_1 and G_1 through (1) and (4).

To ensure hydrodynamic similitude, the particle-size-distribution relative to the mean (PSD) and the particle sphericity should also be identical in the generic combustor and its cold model. Whereas it is relatively straightforward –albeit time-consuming– to generate the same PSD in all experiments through sieving and blending, it is more difficult to find test particles of identical sphericity at an affordable cost. Because the sphericity φ affects the global hydrodynamics of fluidized beds through the product φd, we have adjusted this product in each test and modified equation (2) as follows:

$$\varphi_1 d_1/\nu_1^{2/3} = \varphi_0 d_0/\nu_0^{2/3}. \quad (6)$$

Table 1 presents the gas mixture properties, particle diameters and analogous combustor diameters associated with the glass and plastic powders used in this study. Figure 1 shows the cumulative PSD relative to the mean for these two solids.

Table 1

Fluidization gases				Solid powders				Analogous
He	CO_2	ρ_1	$\mu_1 \times 10^5$	type	ρ_{s1}	d_1	φd_1	Diameter D_0
%	%	kg/m^3	kg/m.sec		g/cm^3	μm	μm	m
92	8	0.30	2.0	plastic grit	1.5	234	161	0.32
80	20	0.49	1.9	glass spheres	2.5	109	109	0.47

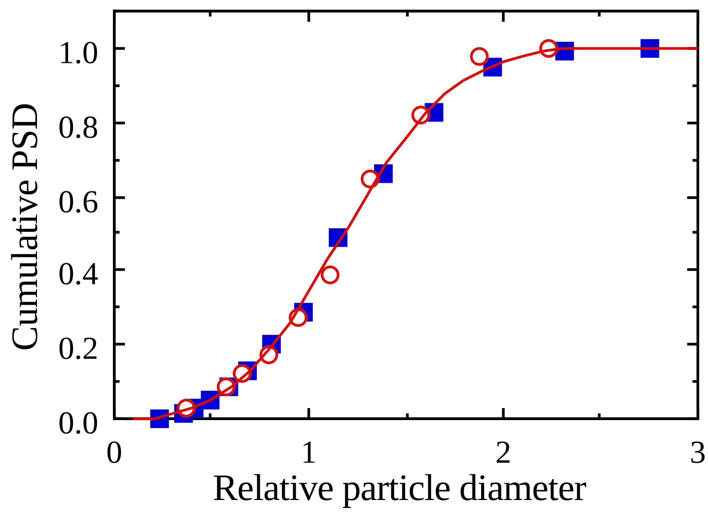

Fig. 1. Cumulative PSD relative to the sieve mean diameter. The open circles and solid squares represent the plastic powder and the glass beads, respectively. The solid line is a typical PSD for a CFB coal combustor.

APPARATUS

The circulating fluidized bed facility used in the present experiments was described elsewhere [17]. Its unique feature is the ability to recycle fluidization gases and to monitor their contents using a thermal conductivity detector (figure 2). In addition, an oxygen analyzer constantly draws gas samples from the facility to detect possible leaks into the closed facility. The hot gases leaving the blower are cooled to the ambient temperature using a compact heat exchanger. The facility is made of aluminum to enhance the discharge of electrostatic charges at the wall.

Pressure readings are taken every 30 cm using 25 taps mounted along the height of the riser. Another 12 taps are located in the downcomer and the solid return leg to complete the pressure profile along the entire circulation loop. The pressure taps are read in sequence using a scanning valve connected to a single pressure transducer (Validyne model DP 103). The pressure signals are acquired by a computer system that also controls the position of the valve. The system samples each static pressure tap for nine seconds at a sampling rate of 60Hz. After scanning the entire loop four times, the computer calculates the average pressure at each tap.

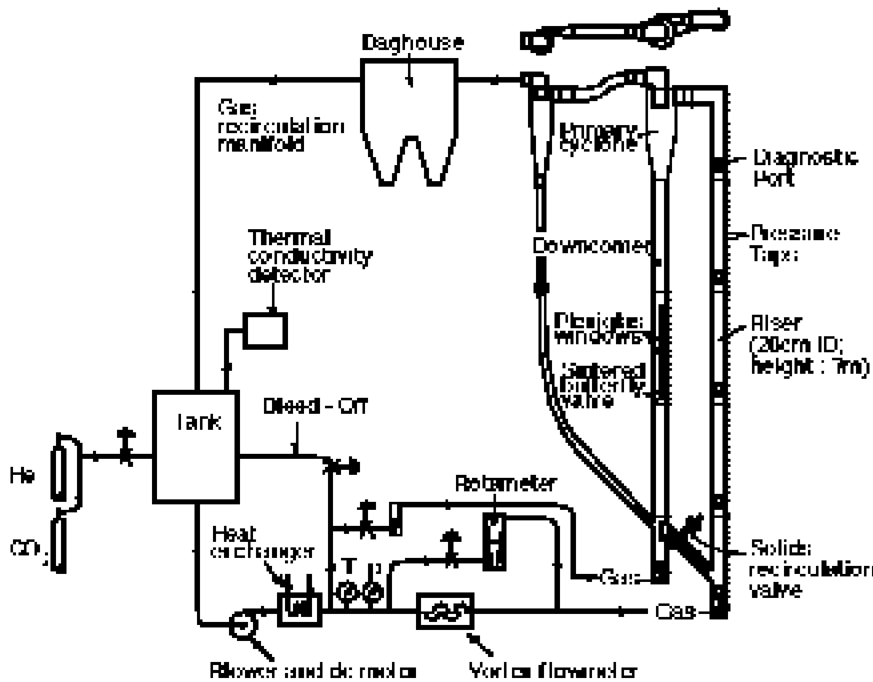

Fig. 2: The circulating fluidized bed facility. Mixtures of carbon dioxide and helium are recycled to achieve hydrodynamic analogy with a coal combustor.

RESULTS AND DISCUSSIONS

Clearly, the dimensional analogy described earlier would break down if electrostatics generated forces of magnitude comparable to the hydrodynamic forces on the particles. In this context, we have noted significant levels of electrostatic charging with the plastic powder, despite carefully grounding the aluminum walls of the facility. A convenient measure of the severity of the electrostatic effect is provided by capacitance probes, which are sensitive to the presence of free charges near their measurement volume [18]. With the plastic powder, we have found it nearly impossible to carry out stable capacitance measurements. Another evidence of electrostatics is the adhesion of particles on plexiglas windows located in the downcomer and the return leg to the riser. Unlike previous studies of CFB hydrodynamics, we cannot suppress electrostatics by humidifying the fluidization gases, because unacceptable changes in the gas properties would result.

To solve this problem, we have found a convenient powder of a few microns in diameter that eliminates electrostatics when it is added to the bed inventory. This anti-static powder is available commercially under the brand name of Larostat 519 (Mazer Chemicals). Because in our tests this powder typically represents less than 0.1% by weight of the bed material, the fines that it introduces are unlikely to affect the hydrodynamics of the bed. However, in the case of plastic particles, we have observed reductions of the total pressure drop across the riser as high as 70% after employing the anti-static additive (figure 3). Because these dramatic pressure reductions were also accompanied by stable capacitance signals and no particle adhesion, they clearly resulted from the elimination of static charges. In contrast, the experiments with glass beads brought little evidence of electrostatics, and no noticeable pressure change was observed after adding the Larostat powder.

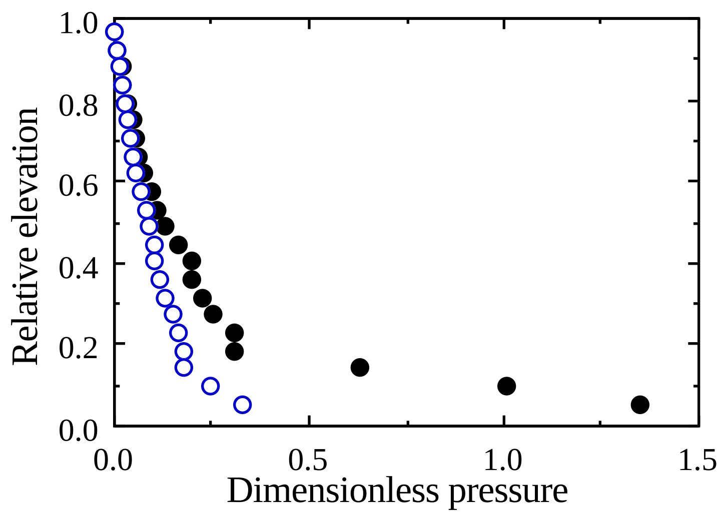

Fig. 3. Vertical profiles of dimensionless pressure $(p-p_{top})/\rho_s gD$ for the conditions Fr = 102, L = 5. The elevation z is relative to the riser height H. The material is plastic powder. The open circles represent the test with anti-static powder and the solid circles without it.

Experiments were conducted to compare vertical pressure profiles obtained with the glass and plastic powders under identical dimensionless conditions. In these experiments, the Froude number ranged between 102 and 174, and the solid loading between 5 and 34.

Nine distinct sets of values for Fr and L were produced in these tests. The ratio D/φd of the riser diameter to the corrected particle diameter was 1830 for the glass particles and 1240 for the plastic powder. The Archimedes number and density ratio were fixed at values typical of a generic coal combustor namely, Ar = 46 and R = 2 10^{-3}. Particular care was taken to eliminate electrostatics.

Figures 4 to 6 show typical pressure profiles obtained with the two powders. For all values of the parameters Fr, L, Ar and R under consideration, the pressure profiles from the two distinct powders are virtually identical despite the different values of D/φd, provided that they are scaled with the product $\rho_s gD$:

$$\frac{p-p_{top}}{\rho_s gD} = f\left(\frac{z}{H}\,;\, L, Fr, Ar, R\,;\, \frac{H}{D}\right) . \qquad (7)$$

Here p_{top} is the pressure at the top of the riser, z is the vertical coordinate, and H/D is the ratio of the riser height to its diameter.

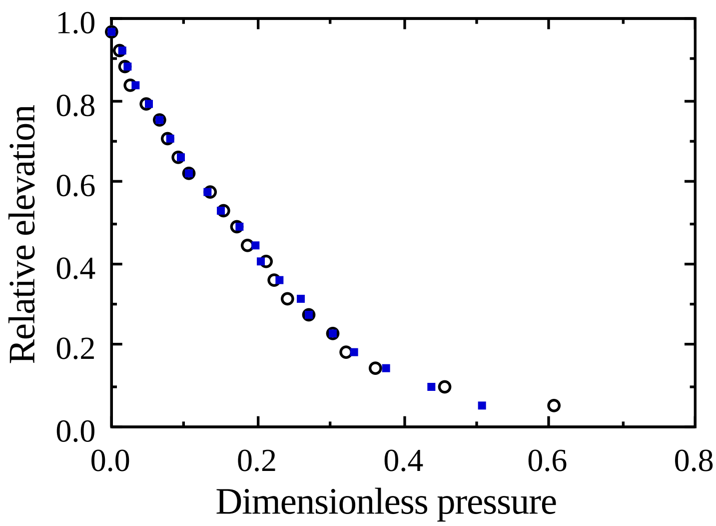

Fig. 4. Vertical profiles of $(p-p_{top})/\rho_s gD$ *vs*. z/H for the conditions Fr = 132, L = 10. The open circles and solid squares correspond to the plastic powder and the glass beads, respectively.

Because this result is reproducible over a wide range of dimensionless conditions, it demonstrates that the product $\rho_s gD$ is the appropriate scaling for the vertical pressure profile with D/φd in the range 1240 to 1830, and that the dimensional analysis has produced the correct analogy for the global hydrodynamics of CFB risers, as long as electrostatics is eliminated from the cold riser.

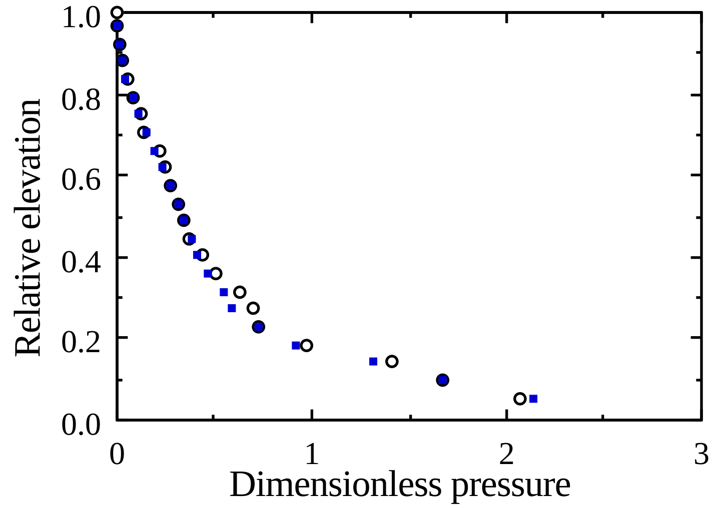

Fig. 5. Vertical profiles of $(p-p_{top})/\rho_s gD$ *vs*. z/H for the conditions Fr = 132, L = 21. Symbols have the same meaning as in figure 4.

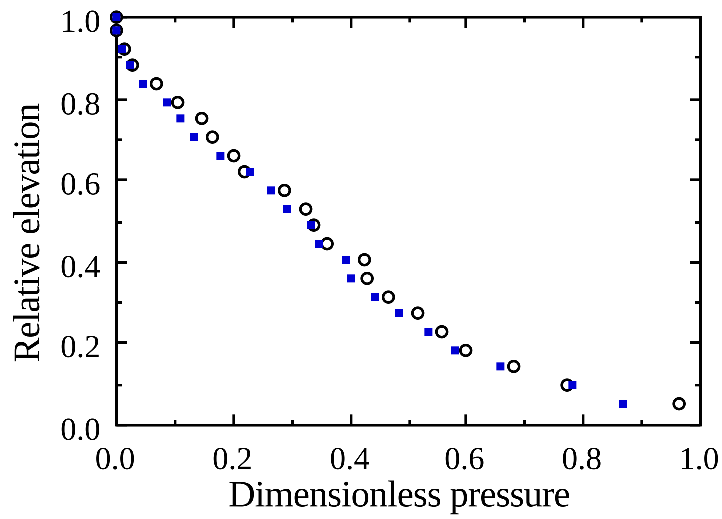

Fig. 6. Vertical profiles of $(p-p_{top})/\rho_s gD$ *vs*. z/H for the conditions Fr = 174, L = 19. Symbols have the same meaning as in figure 4.

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