HYDRODYNAMICS OF CONICAL SPOUTED BEDS WITH HIGH DENSITY PARTICLES

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ABSTRACT

An extensive experimental investigation of conical spouted beds with high density particles were carried out by measuring bed pressure drop, particle velocity and solids hold-up in a 15 cm ID conical spouted bed at three different cone angles (30°, 45°, 60°) with Yttria-stabilized zirconia (YSZ) particles (ρ_p = 6050 kg/m^3). The results show that the minimum external spouting velocity increases with cone angle, particle diameter and static bed height. The bed is characterized by two regions: upward moving particles with high slip in the spout and slowly downward moving particles at loosely packed conditions in the annulus.

INTRODUCTION

Due to its unique solids circulation characteristics and excellent gas-particle contact, spouted beds have wide range of applications in many industrial processes like drying, granulation and particle coating. One of the particle coating applications of the spouted beds is the chemical vapor deposition (CVD) coating of uranium dioxide kernels with pyrolytic carbon and silicon carbide to produce spherical fuel elements (known also as TRISO type fuel element) for high temperature gas cooled reactors (HTR) (1). HTR is an advanced reactor technology (still under development) recognized for its inherent safety, high fuel utilization and high efficiency in electricity generation with cogeneration possibilities. Currently, the fuel production for the prototypes of HTR technology is realized in small scale spouted bed coaters with limited capacity. Once the full scale reactors are in operation, there will be a huge need for large scale fuel coaters with mass production capability. To design, scale up and manufacture spouted bed coaters operating with heavy particles, it is of fundamental importance to have a detailed understanding of the hydrodynamics of the system. Although there are a considerable number of hydrodynamic studies published in the literature, a very limited number of these have been conducted in spouted beds operating with heavy particles (ρ_p > 2500 kg/m^3) typically encountered in CVD coating of nuclear fuels.

To the authors' knowledge, the most comprehensive study on the hydrodynamic behavior of spouted beds with high density particles is a Ph.D. dissertation from the University of Tennessee (2). In this work, the minimum spouting velocity, time-averaged and dynamic pressure drops, time-averaged fountain height and gas velocity profiles were measured in a 5 cm ID conical spouted bed at different cone angles (45°,60°,75°) operating with Yttria-stabilized zirconia (YSZ) particles (ZrO_2, also known as zirconia) having a particle density of 6050 kg/m^3. Effects of the static bed height and particle size on measurements were investigated and new correlations for minimum spouting velocity, time-average pressure drop and fountain height based on the experimental data were developed. An unpublished final project report by a group of University Tennessee researchers is also available in the open literature (3). In this report, Zhou's (2) work has been further extended with bed pressure drop, pressure fluctuations and fountain height measurements carried out with alumina particles in a 5 cm ID spouted bed for the aim of developing hydrodynamic scaling relationships.

On the computational side, Pannala et al. (4) performed a 2-D Eulerian-Eulerian simulation of a 5 cm ID spouted bed with zirconia particles using MFIX (Multiphase Flow with Interphase Exchanges) code. Centerline axial velocity and Fourier spectra of pressure fluctuations were compared with corresponding experimental data. Their simulations revealed an interesting dynamic behavior - occurrence of regular spontaneous pulsations of gas and particle flow in the spout - which was also observed by Zhou (2).

All of the aforementioned studies were performed in a 5 cm ID, conical spouted bed. However, to have a comprehensive understanding of the hydrodynamics of CVD fuel coaters for HTR reactors, further investigations need to be carried in larger inner diameter spouted beds. In addition, complete characterization of the hydrodynamics should also involve the determination of voidage and solids velocity inside the system. Therefore, the objective of this study was to investigate the hydrodynamic characteristics of spouted bed nuclear fuel coaters at cold bed conditions. To achieve this objective, experiments were performed in a 15 cm ID conical spouted bed at different static bed heights and cone angles (30°, 45°, 60°) with zirconia particles (d_p = 0.5, 1 mm; ρ_p = 6050 kg/m^3) to simulate the particle properties in hot bed conditions. Bed pressure drop and its fluctuations were measured to determine the minimum external spouting velocity. Local instantaneous particle velocities and solids hold-ups were also measured by an optical fiber probe to better understand the gas-solid dynamics in the spouted bed.

EXPERIMENTAL SET-UP

The experimental study was carried out in three full circular conical spouted beds made of Polyoxymethylene (also known as Delrin) which is an excellent thermoplastic that can withstand the continuous impact of hard zirconia particles without significant erosion. A schematic diagram of the units is given in Fig. 1 and their geometric parameters and operating conditions are presented in Table 1. Spherical Yttria-stabilized zirconia (YSZ) particles (d_p = 0.5, 1 mm; ρ_p = 6050 kg/m^3) were used to simulate the particle properties in hot bed conditions and compressed air at ambient temperature was used as the spouting gas. The total pressure drop across the spouted bed was measured by a differential pressure transducer (Omega PX142-005D5V) connected to the bed internal wall at the base of the conical section. The other line of the transducer was open to atmosphere. The data was fed to a computer by a high speed data acquisition board (National Instruments PCI-6280) and processed using LabVIEW version 8. The sampling was performed at a frequency of 1 kHz for 20 seconds. Each measurement was repeated for three times and the corresponding averages are reported. To eliminate the possible effects of the initial packing status on the measurements, following the approach proposed by

Wang (5), the spouted beds were operated for 1 hour prior to each experimental run.

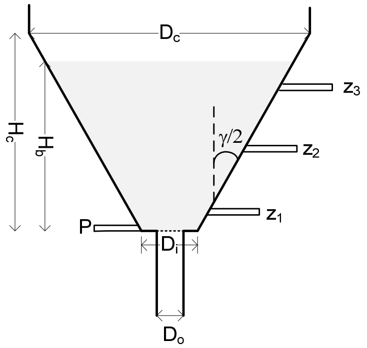

Figure 1. Geometric sketch of conical spouted beds.

Table 1. Geometric parameters of the spouted beds and experimental operating conditions.

Data Sets	γ	d_p (mm)	D_i (mm)	D_o (mm)	D_c (mm)	H_c (mm)	H_b (mm)
1	60	0.5	25	15	150	108	100
2		1					100
3	45	0.5	25	15	150	151	100
4		1					100
5		1					140
6	30	0.5	25	15	150	233	100
7		1					100
8		1					140
9		1					180
10		1					220

A multi-fiber optical probe, PV-6, developed by the Institute of Process Engineering, Chinese Academy of Sciences, was used to measure simultaneously local instantaneous particle velocities and solids volume concentrations. The probe consists of two bundles of optical fibers. Inside each bundle, there are alternating arrays of light emitting and receiving fibers. The fibers have a uniform diameter of 15 μm. Light was projected into multiphase suspension through the emitting fibers. The backscattered light from the particles were transmitted by the receiving fibers to two photomultipliers, one for each bundle, and was converted to voltage signal. The signals were digitized by the high speed data acquisition board and processed by using LabVIEW version 8. If the flow structure does not change between these two bundles and the particles move in the same direction, the two signals would be identical, but separated by a time delay, τ. This time delay, which was obtained by cross-correlating the two signals, was used to calculate the axial particle velocity in Eq. (1):

$$U_p = \frac{L_e}{\tau} \qquad (1)$$

where L_e is the effective distance between the two bundles. In this study, L_e was determined to be 2.11 mm through the calibration studies performed with rotating disks with different designs and rotating disks with particles glued. Since the particle velocity changed significantly in different radial locations of the spouted bed, the sampling frequency and time had to be varied correspondingly. For each measurement, a total of 180,000-500,000 data were collected through each bundle with a sampling frequency of 1-100 kHz. During the particle velocity measurements, particles may reverse directions, or a flow structure travelling non-vertically passing one bundle may not be detected by the second one, causing the cross-correlation coefficients to be low or indeterminate. Such uncorrelatable or poorly correlated data need to be eliminated. In this study, following the approach proposed by Kirbas et al. (6), in order for the results to be acceptable, the correlation coefficients were required to exceed 0.7, and individual calculated velocities were required to differ by no more than 3 standard deviations from the average.

The optical fiber probe was capable of simultaneously measuring solids concentration together with particle velocity. The same data used in the calculation of particle velocity was integrated over time and by utilizing a calibration equation, solid hold ups were calculated. Before experiments, the probe was calibrated by using original+black colored zirconium particle mixtures. For this purpose, different concentration mixtures were prepared by combining known masses of original zirconium particles and black color painted zirconium particles. Since the painted zirconium particles were black and therefore absorbed most visible light, it was assumed that they behaved as voids, while only original particles reflected light. The calibration was performed in a system similar to the one described in (7). Using different concentration mixtures, solids hold ups were simulated. A linear relationship was observed between the voltage and solids hold-up.

Local instantaneous particle velocities and solids hold ups were measured at several radial positions and three heights in the spouted bed with a cone angle, γ, of 45° operating at 1.25 U_{ms}.

RESULTS AND DISCUSSION

Bed Pressure Drop Measurements

Effects of ascending and descending inlet gas velocity, static bed height, particle diameter and cone angle on bed pressure drop were investigated in this study. Besides, the inlet gas velocity at which the external spouting begins (denoted by U_{ms}) at each case were visually determined and indicated on relevant pressure drop figures with corresponding arrows.

The effect of the ascending and descending inlet gas velocity, U_o, on the bed pressure drop in the bed is shown in Fig. 2 (Data set 4 in Table 1). The inlet gas velocity, U_o, is simply the superficial gas velocity based on D_o. The descending velocity case does not show a steep peak as in the case of ascending velocity although the average pressure drop after the external spouting begins is the same. Furthermore, the external spouting is observed at the exact same velocity for both cases. The peak observed for the ascending velocity case is attributed to resistance that needs to be overcome as the internal spout first forms at the bottom of the bed.

Fig. 3 shows the effect of the cone angle on the bed pressure drop (Data sets 2, 4 and 7 in Table 1). The figure shows that the minimum external spouting velocity increases as the cone angle increases. As the bed wall becomes more horizontal with increasing cone angle, it becomes more difficult to move particles downward near the wall and in turn a higher velocity is needed to create a spout at the center and establish a circulation pattern typically observed in spouted beds. The same trend is also obtained for the inlet gas velocity at which the pressure peak is observed. Hence, the pressure drop curve shifts to the left as the cone angle increases. Increasing the cone angle also decreases the average bed pressure drop after the external spouting since the weight of the particles is carried more and more by the wall.

Fig. 4 shows the effect of particle diameter on the bed pressure drop (Data sets 1 and 2 in Table 1). The minimum external spouting velocity increases with particle diameter. The effect of the static bed height on the bed pressure drop is shown in Fig. 5 (Data sets 7, 8, 9, 10 in Table 1). The bed pressure drop increases with static bed height. Both trends observed in Figs. 4 and 5 are consistent with literature.

Fig. 6 shows a complete picture of the effect of the static bed height and cone angle on the minimum external spouting velocity. The minimum external spouting velocity increases linearly with static bed height for all cone angles tested in this work.

Radial Particle Velocity and Solids Hold Up Measurements

The local particle velocities and solids-hold-ups measured in the spouted bed with a cone angle of 45° operating at U_o = 56.3 m/s (1.25U_{ms}) with a bed pressure drop of 3054 Pa are illustrated in Figure 7 (Data set 5 in Table 1).

As depicted in this figure, the spouted bed is made up of two distinct regions: spout and annulus. A high velocity gas (56.3 m/s) enters the bed and the particles are carried up in the spout. It is interesting to note that at z = 42 mm, the local particle velocity at the axis is around 2.5 m/s indicating a large slip between gas and particles. In the annulus, the particles falling down from the fountain move slowly downwards with particle velocities of approximately -0.003 m/s. The particle velocity at any axial location decreases from its maximum value at the axis to zero at the spout-annulus interface. When the evolution of spout diameter is monitored, it is observed that at the two axial locations above the entrance, the spout has a diameter of approximately 17 mm which is close to the value of the inlet diameter of the spouted bed (D_o = 15 mm). The spout then starts widening up and its diameter becomes approximately 21 mm at the highest measurement level (z = 120 mm).

When the solids hold up profiles are examined it is observed that in the spout solids hold up is much lower compared to the annulus where particles are in close contact with each other and the solids fraction is uniform and almost equal to the loosely packed solids hold up at all levels. The solids hold up increases sharply at the interface between the spout and the annular zones.

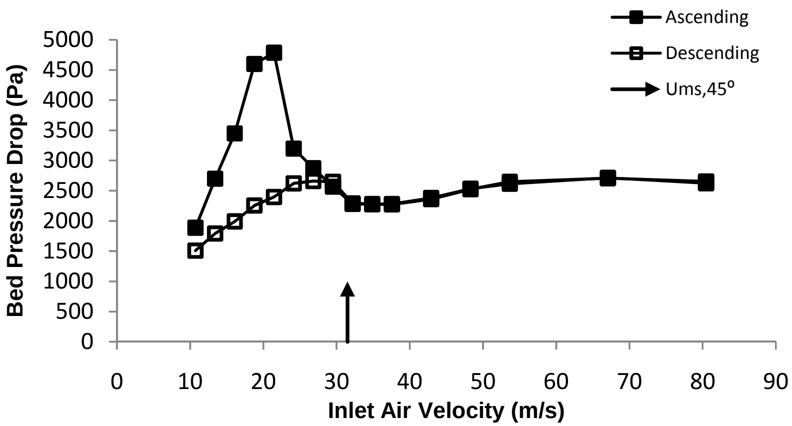

Figure 2. Effect of ascending and descending inlet gas velocity on the bed pressure drop.

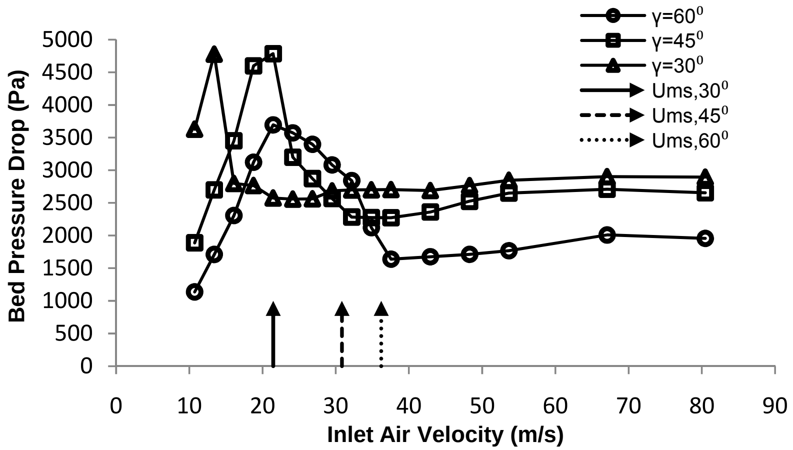

Figure 3. Effect of cone angle on the bed pressure drop.

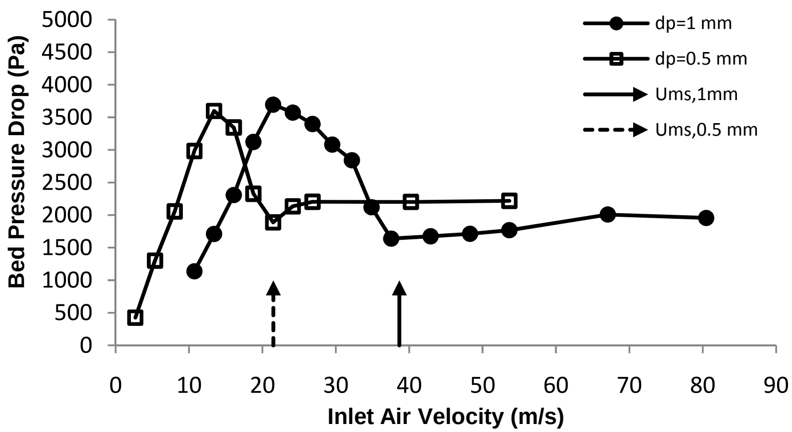

Figure 4. Effect of the particle diameter on the bed pressure drop.

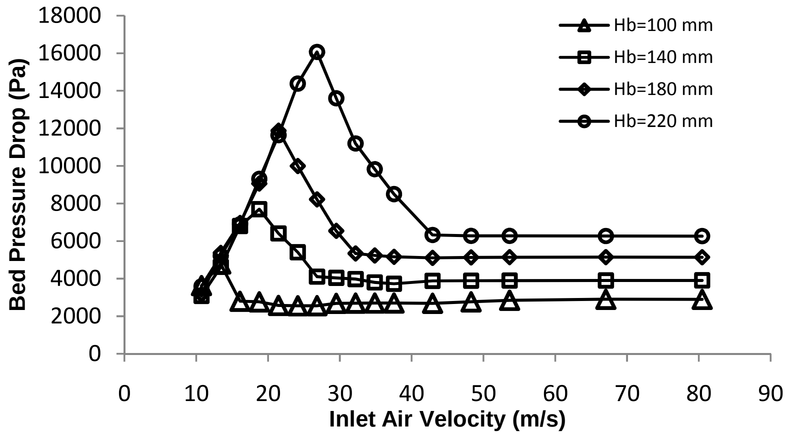

Figure 5. Effect of the static bed height on the bed pressure drop.

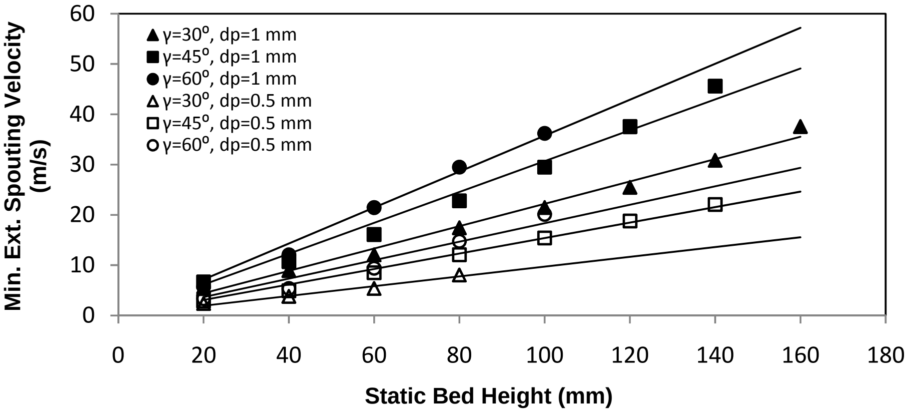

Figure 6. Effect of the static bed height on the minimum external spouting velocity.

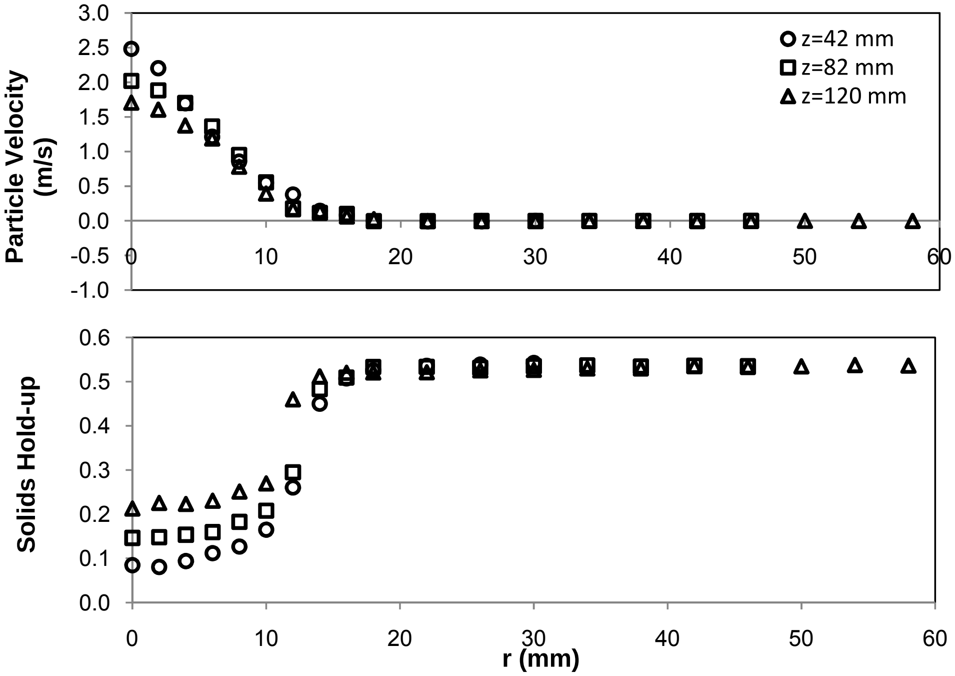

Figure 7. Radial profiles of local time-mean particle velocities and solids hold-up at different axial locations.

CONCLUSIONS

The purpose of this study was to understand the hydrodynamic characteristics of spouted bed nuclear fuel coaters. Experiments were performed in a 15 cm ID conical spouted bed at different static bed heights and cone angles (30°, 45°, 60°) with zirconia particles (d_p = 0.5, 1 mm; ρ_p = 6050 kg/m^3) to simulate the particle properties in hot bed conditions. Bed pressure drop, local instantaneous particle velocities and solids hold-ups were measured. The main conclusions are summarized below:

- The minimum external spouting velocity increases with cone angle, particle diameter and static bed height.

- The average bed pressure drop decreases with cone angle.
- A very large slip is obtained between gas and particle velocities in the spout region. The spout widens with height. At the axis, the particle velocity decreases from 2.5 m/s to 1.6 m/s, whereas the solids hold up increases from 0.08 to 0.20 with height.
- The solids hold up increases sharply at the interface between the spout and the annular zones. The annulus is characterized by slowly downward moving particles with velocities of approximately -0.003 m/s at almost loosely packed conditions.

ACKNOWLEDGEMENT

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NOTATION

γ	Angle of the conical section, degree
ρ_p	Particle density, kg/m^3
τ	Delay time between two signals from two light receivers, sec
d_p	Particle diameter, mm
D_i,D_o,D_c	Diameter of the bed bottom, gas inlet, column, respectively, mm
H_c,H_b	Height of the conical section, static bed, respectively, mm
L_e	Effective distance between two bundles of optical fibers, mm
r	Radial distance from the bed axis, mm
U_{ms},U_p,U_o	Min. external spouting velocity, particle velocity, inlet gas velocity, m/s
z	Axial location, mm

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