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Prediction of the Fountain Heights in Fine Particle Spouted Bed Systems

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Abstract: New empirical correlations are proposed to predict the fountain heights in spouted bed systems operating with fine particles. These correlations can be used for predicting the total spouted bed vessel height which is composed of the maximum spoutable bed height and the fountain height. It is important to be able to predict the total vessel height from the fluid and particle proportions and the spouted bed gemotery since further detailed information may not be available in the initial design stage. The fountain height correlations are developed for particles in the size range of 0.30 to 0.45 mm. The total vessel height is predicted by means of these equations and the maximum spoutable bed height correlations developed earlier.

Key Words: Spouting, Fluidization, Fountain Heights.

Küçük Tanelerle Çalışan Taşkın Yataklarda Fıskiye Yüksekliğinin Hesaplanması

Özet: Küçük tanelerle çalışan taşkın yataklı sistemlerdeki fıskiye yüksekliğinin hesaplanması için yeni semi-ampirik bağıntılar geliştirilmiştir. Bu bağıntılar kullanılarak taşkın yataklı reaktör yüksekliğinin, maksimum taşkın yatak yüksekliği ve fıskiye yüksekliğinin toplamı olarak hesaplanması mümkündür. İlk tasarım esnasında başka bilgi genellikle bulunamadığından taşkın yataklı reaktör yüksekliği hesabında akışkan ve tanecik özellikleriyle birlikte taşkın yatağın geometrisinden faydalanmak zorunlu olmaktadır. Fıskiye yüksekliği bağıntıları 0.30-0.45 mm büyüklükteki tanecikler için çıkarılmıştır.

Anahtar Sözcükler: Akışkanlaştırma, Taşkın Yataklar, Fıskiye Yüksekliği

Introduction

Spouted bed systems have emerged as very efficient fluid-particle contactors and find many applications in the chemical and biochemical industry. Some important applications of spouted beds include coal combustion, biochemical reactions, drying of solids, drying of solutions and suspensions, granulation, blending, grinding, and particle coating. An extensive overview can be found in Mathur and Epstein (1974).

A schematic diagram of a spouted bed is given in Figure 1. In spouted bed systems, the fluid is introduced centrally through a nozzle rather than uniformly through a distributor plate as in fluidized beds. The fluid enters the bed in the form of a jet and causes the particles to circulate in a uniform manner. The fluid and the particles are in counter current flow in the annulus which makes up the major portion of the spouted bed. Flow of particles and fluid is co-current in the spout where velocities are high and residence times are short. The spouting action favors particles larger than about 1 mm, however, significant progress has been made in the spouting of finer particles, and the subject is gaining importance as draft tube spouted bed systems are findings many applications.

Fine particle spouting has been accepted to differ from coarse particle spouting in many ways. An overview with respect to spoutability, spouting stability, and flow regime maps is given by Çeçen et al. (1995). Chandnani and Epstein (1987) also qualitatively describe gas spouting characteristics of fine particles.

A major difference of the fine particle spouting systems becomes apparent when the maximum spoutable bed heights of these systems are compared to those of coarse particle systems. The maximum spoutable bed height is the bed height above which stable spouting is not possible without a draft tube. A well known correlation for the maximum spoutable bed height of coarse particle systems is the semi-empirical model of Littman et al. (1979), given in Equation (1).

$$m = 0.218 + \frac{0.005}{A}; \quad A > 0.02 \qquad (1)$$

Figure 1. Schematic diagram of a spouted bed

Equation (1) relates the maximum spoutable bed height to the column geomtery and the fluid-particle properties by means of the parameter A which is a measure of the inlet jet momentum per unit area to the spout pressure drop. Effects of the inlet tube diameter and the fluid-particle properties are contained in the parameter A given in Equation (2).

$$A= \frac{r_f}{r_p - r_f} \frac{U_{mF} U_T}{g d_i} \quad (2)$$

Coarse particle systems have values of A greater than 0.02 and Equation (1) predicts the maximum spoutable bed heights for both air and water spouted coarse particle systems very well. It has been noticed by several investigators (Littman et al., 1977, 1979; Whiting, 1981; Chandnani, 1984) that when the parameter A has a value less than 0.02, Equation (1) overpredicts H_m considerably. These cases consist of fine particle systems for which the value of A is much less than 0.02.

Recently, Çeçen (1994, 1995) developed new empirical correlations to predict the maximum spoutable bed heights of fine particles spouted with gases and with liquids.

These correlations are given in Equations (3) and (4), respectively. Details of the derivations of these correlations are given in aforementioned references.

$$mA= 0.99 \left(\frac{Ad_i}{D_c}\right)^{0.856}; \quad 0.5 \leq d_p \leq 1.5 \text{ mm} \quad \text{gas spouting} \quad (3)$$

$$mA= 24.60 \left(\frac{Ad_i}{D_c}\right)^{1.259}; \quad dp \leq 0.5 \text{ mm}$$

$$mA= 1.07 \left(\frac{Ad_i}{D_c}\right)^{0.862}; \quad dp < 1.85 \text{ mm} \quad \text{liquid spouting} \quad (4)$$

The fountain height is another important parameter in the design of a spouted bed because along with the spouted bed height it determines the total height of a spouted bed vessel. The maximum spoutable bed height is of secondary importance in determining the vessel height for design purposes and must be considered together with the fountain height on top of the annulus. Since the fountain height directly depends on the spouting fluid flowrate among other variables, the total vessel height must bu determined such that it will contain the fountain for all anticipated flowrates in the system.

There are few models available to predict the fountain height in spouted beds. A major one is a theoretical model based on a force balance analysis by Grace and Mathur (1978). Their simplified expression for the fountain heights is

$$H_f = \varepsilon^{1.46} \frac{V_{omax}^2}{2g} \frac{\rho_p}{\rho_p - \rho_g} \quad (5)$$

The experimental data is for large particles and the drag effects have been assumed negligible for large particles in deriving Equation (5). The authors caution that Equation (5) may not be applicable to small particles or for extreme values of V_{omax} where drag effects are likely to be important. Another major drawback of the Grace and Mathur (1978) model is that the voidage and the particle velocity at the top of the spout must be known to calculate the fountain height. This information is not available in the initial design stage.

Epstein and Chandnani (1987) observed that in fine particle systems for a given value of U_i/U_{ms}, the value of H_f decreased as H increasad for a fixed particle size. Also, according to Epstein and Chandnani (1987), H_f increased as the particle size increased.

Day (1990) developed an empirical correlation to predict the fountain heights of coarse particle systems based on the data of Grace and Mathur (1978) and Day (1986). This correlation given in equation (6) implies that H_f decreases with increasing bed height for a fixed particle size and increases with increasing inlet gas velocity.

$$\frac{H_f}{d_i} = 46.4\left(\frac{U_i}{U_{ms}} - 1\right)^{0.865}\left(\frac{H}{H_m}\right)^{-0.379} A^{213}\left(\frac{\rho_p - \rho_f}{\rho_f}\right)^{-0.892}\left(\frac{d_p}{d_i}\right)^{-3.49}\left(\frac{d_i}{D_c}\right)^{-2.75} \tag{6}$$

The effect of the particle size is not clear because the paremeter A is also a complex function of the particle size.

In this work, fountain height correlations for the fine particle spouting regime are proposed for a particle size range of 0.300 to 0.450 mm, and comparison is made to the coarse particle spouting regime.

Experimental Procedure

The fountain heights of spherical glass beads with average diameters of 0.30, 0.377, and 0.45 mm were obtained in a semi-cylindrical spouted bed column of 80 mm diameter with a flat base. Bed heights ranging from well below the maximum spoutable height to equal to the maximum spoutable height were used in the experiments. Experimental conditions and some particle properties are given in Table 1. The fountain heights were measured as the height of the fountain above the bed surface at the spout-annulus interface. The bed height, H, is measured as the height of the bed from the flat base to the top of the annulus. The minimum spouting velocity, U_{ms}, is measured by means of a rotameter as the inlet fluid velocity at which the spout collapses and the particle circulation stops. Below the minimum spouting velocity the bed acts as a packed bed. Therefore, the fountain heights were measured at velocities above the minimum spouting velocity.

Results and Discussion

The results of the fountain height measurements are analyzed and plotted as H_f/d_i and as H_f/H versus U_i/U_{ms} for each bed height and the particle sizes studied. The fountain height data has been correlated in terms of the U_i/U_{ms} and H/H_m parameters for the three particle sizes investigated. These correlations are obtained by means of a regression analysis and are given in Equations (7), (8), and (9).

For 0.450 mm particles, the fountain height correlates as

$$\frac{H_f}{H} = 1.046\left(\frac{U_i}{U_{ms}} - 1\right)^{0.829}\left(\frac{H}{H_m}\right)^{-0.242} \tag{7}$$

Whereas for a particle size of 0.377 mm, the fountain height correlates as

$$\frac{H_f}{H} = 1.594\left(\frac{U_i}{U_{ms}} - 1\right)^{0.347}\left(\frac{H}{H_m}\right)^{0.089} \tag{8}$$

and for 0.300 mm particles, the fountain height can be determined from

$$\frac{H_f}{H} = 0.603\left(\frac{U_i}{U_{ms}} - 1\right)^{0.895}\left(\frac{H}{H_m}\right)^{0.595} \tag{9}$$

The analysis of the results can be discussed in terms of the effects of the fluid inlet velocity, the bed height, and the particle size.

Figure 2 is a plot of the dimensionless fountain height, H_f/H, versus the dimensionless fluid inlet velocity, U_i/U_{ms}, and combines all data for the particle sizes studied. A common trend observed in Figure 2 for all particle sizes is that the fountain height increases with the inlet gas velocity for all particle sizes and also for all bed heights. A striking result immediately obvious from Figure 2 is that the fountain heights for the 0.377 mm particles are the highest irrespective of the bed height. It is also worth noting that the dimensionless fountain height as seen in Figure 2 for the 0.377 mm particles shows a rapid increase fom zero as the inlet fluid velocity ratio, U_i/U_{ms}, is varied from 1 to about 1.1. For the 0.450 mm particles, however, the fountain height increases without such a sudden jump. The data for the 0.300 mm particles are too few for a clear conclusion, yet it can be seen that the fountain height increases smoothly with the inlet fluid velocity.

Figure 3 is a plot of the dimensionless fountain height, H_f/H, versus the dimensionless inlet fluid velocity, U_i/U_{ms}, for the 0.450 mm particles for various bed heights. It is obvious from the plot that as the bed height is increased, the fountain height also varies. This effect does not look significant when the fountain height is scaled by the bed height H. The variation of the fountain height with respect to be height for a given fluid inlet velocity is best seen in Figure 4

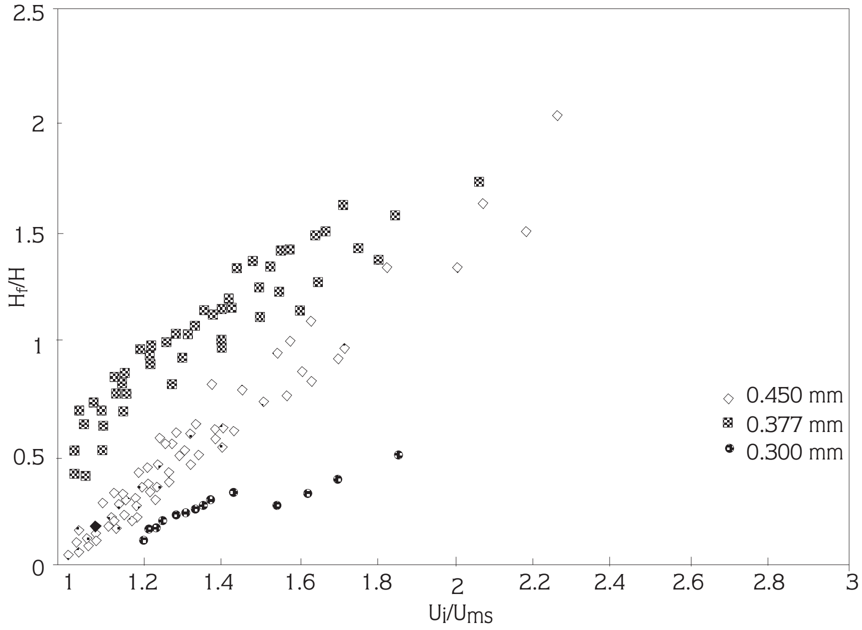

Figure 2. Variation in the dimensionless fountain height (H_f/H) with respect to the spouting fluid velocity ratio U_i/U_{ms}.

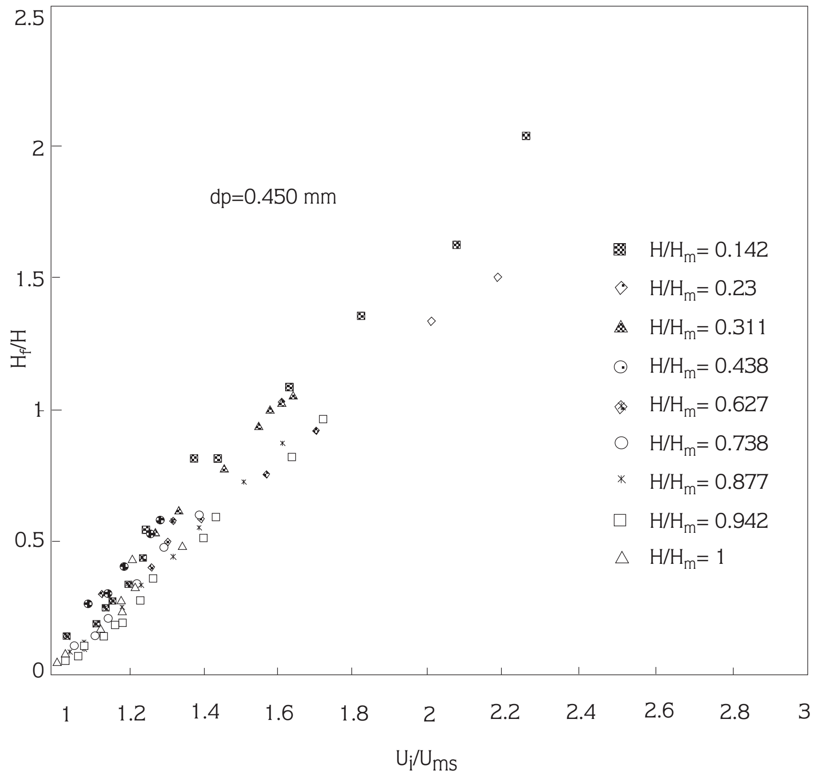

Figure 3. Variation in the dimensionless fountain height (H_f/H) with respect to the spouting fluid velocity ratio U_i/U_{ms} for dp= 0.450 mm for various H/H_m values.

where H_f/d_i is plotted with respect to U_i/U_{ms} for the 0.450 mm particles. An important conclusion drawn from Figure 4 is that the fountain height increases when the bed height is increased for any fluid inlet velocity ratio. Specifically, as Equation (7) implies, H_f is proportional to $H^{0.758}$ for the 0.450 mm particles. This is opposite to the trend observed with coarse particles, in that case the fountain height decreases with increasing bed height as seen in Equation (6) for coarse particles (i.e. H_f is proportional to $H^{-0.379}$). The trend in H_f with respect to U_i/U_{ms} is similar to that of coarse particles where H_f is proportional to $(U_i/U_{ms}-1)^{0.865}$.

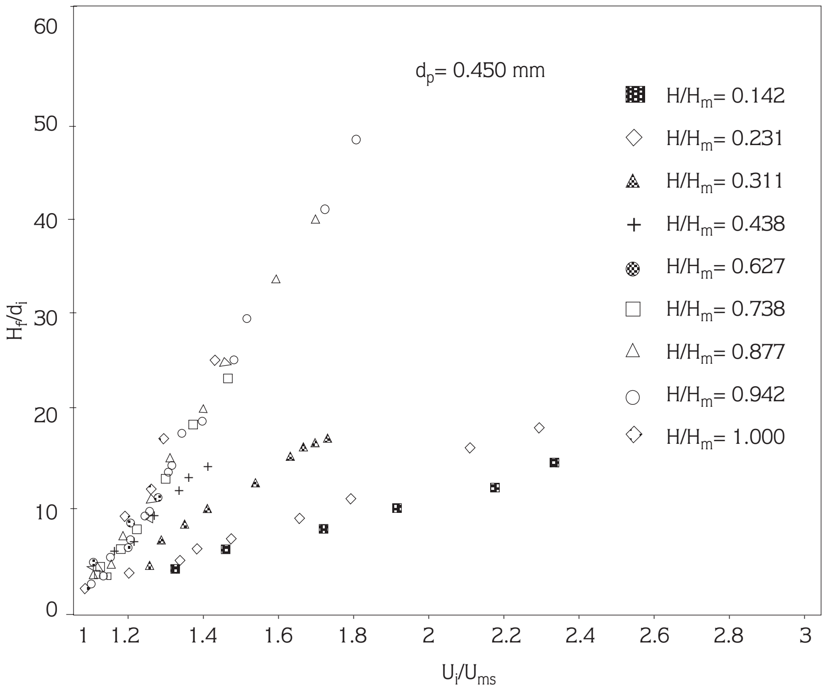

Figure 4. Variation in the dimensionless fountain height (H_f/d_i) with respect to the spouting fluid velocity ratio U_i/U_{ms} for dp= 0.450 mm for various H/H_m values.

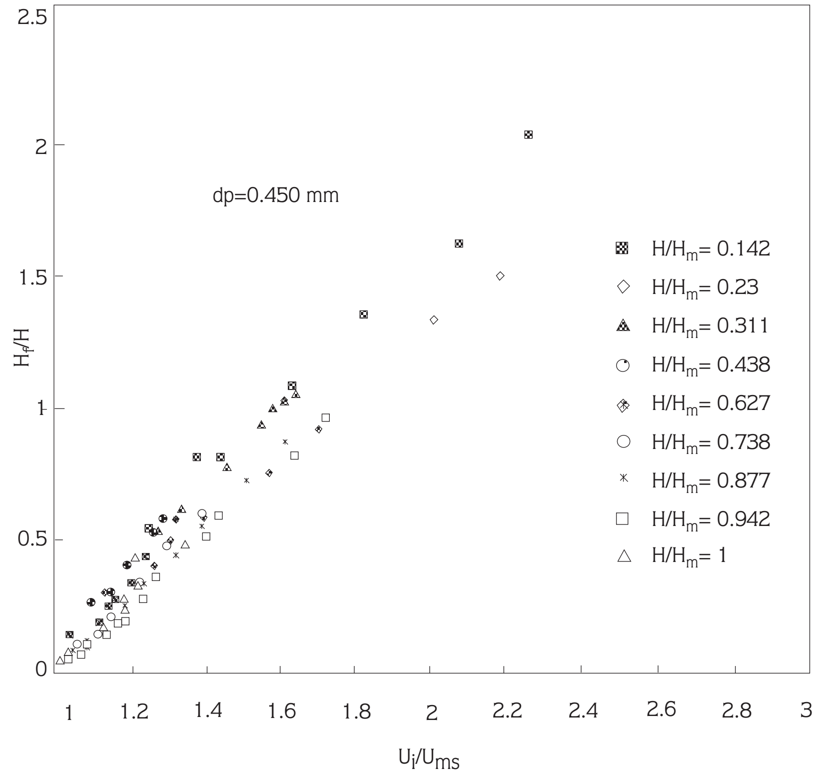

Figure 5. Variation in the dimensionless fountain height (H_f/H) with respect to the spouting fluid velocity ratio U_i/U_{ms} for dp= 0.377 mm for various H/H_m values.

The effect of the fluid inlet velocity and bed height on the fountain height for the 0.377 mm particles are shown in Figures 5 and 6, respectively. For this particle size H_f/H increases less strongly with U_i/U_{ms} than with the 0.450 mm particles. The effect of the bed height is not clear on Figure 5 because the data are close to each other, however, as an overall trend it can be concluded that as the bed height increases H_f/H also increases slightly. It is clearly visible in Figure 6 that the fountain height increases with increasing bed

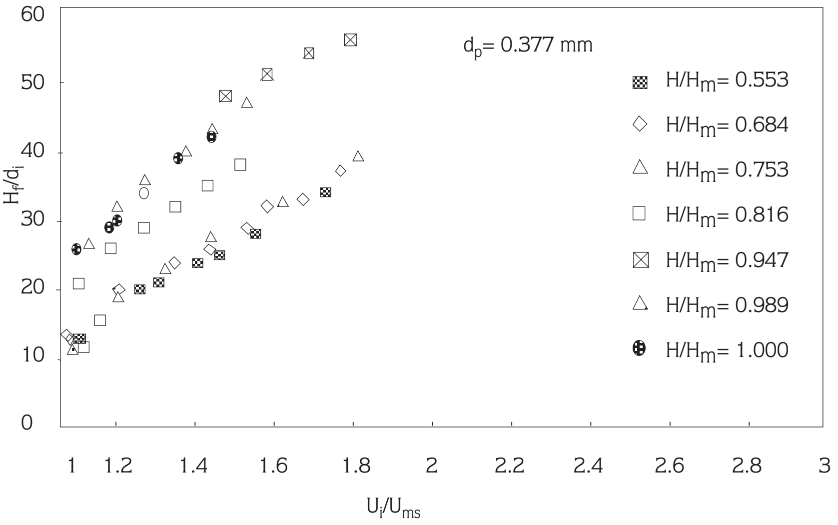

Figure 6. Variation in the dimensionless fountain height (H_f/d_i) with respect to the spouting fluid velocity ratio U_i/U_{ms} for dp= 0.377 mm for various H/H_m values.

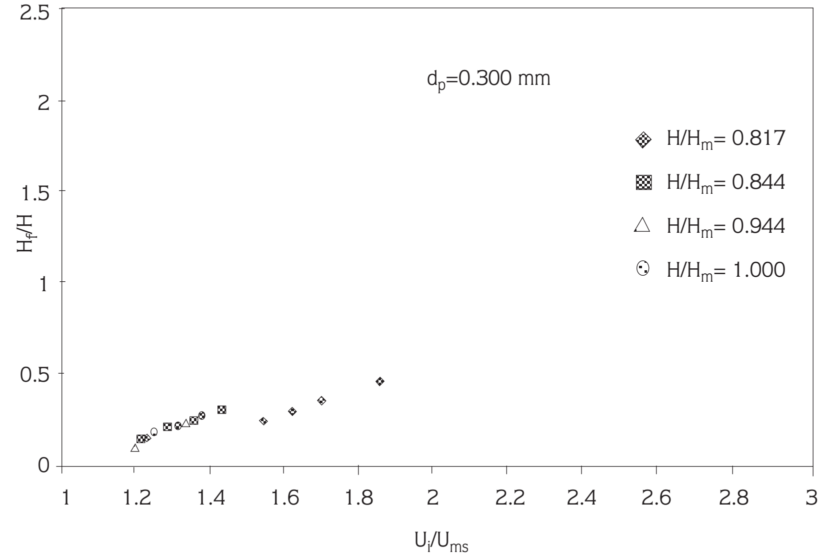

Figure 7. Variation in the dimensionless fountain height (H_f/H_i) with respect to the spouting fluid velocity ratio U_i/U_{ms} for dp= 0.300 mm for various H/H_m values.

height. The highest fountain heights are observed at bed heights around the maximum spoutable bed height. For the 0.377 mm particles, H_f is proportional to $H^{1.089}$ and $(U_i/U_{ms}-1)^{0.347}$. The deviation of this proportionality from Equation (6) for the coarse particle spouting regime, where H_f is proportional to $H^{-0.347}$, is obvious.

The finest particle size studied, 0.300 mm, also shows a similar behavior with respect to the fluid inlet velocity and the bed height as can be seen from Figure 7. Here, the limited spoutability of these fine particles also restricted the amount of data that could be collected. For this size, the fountain height is more sensitive to the inlet fluid velocity and the bed height than the other two larger sizes as can be seen from Equation (9). The impaired spoutability of this particle-size is accompanied by the channeling phenomena during spouting. By the formation of a channel, the momentum is preserved in the spout instead of diffusing into the annulus, explaining the stronger dependence of the fountain height on the fluid inlet velocity and the bed height. Once a channel is formed, the extra momentum supplied can be transferred to the fountain so that the fountain height increases faster with the fluid inlet velocity. However, it is not possible to assume that H_f/H should be higher than that for other particle sizes because some fraction of the momentum supplied to the system is used to sustain the channel itself. As yet, it is not clear how large this fraction is, but it must be fairly large because the spoutability of this particle size is rather limited. This fact is also seen by comparing the maximum spoutable bed heights in Table 1.

Table 1. Experimental Conditions and Some Fluid and Particle Properties.
Column Diameter: 80 mm.
Fluid: Air at room temperature
ρ_f= 1.165 kg/m^3, μ_f= 18.427 10^{-6} Ns/m^2

d_p (mm)	ρ_p (kg/m^3)	d_i (mm)	H_m(mm)	U_{mF}(m/s)
0.450	2491	5	260	0.149
0.377	2495	5	190	0.098
0.300	2495	3	180	0.058

The fact that the three particle sizes which are not extremely different from each other display such different behavior with respect to fountain height is related to their spouting characteristics. It is certain that spoutability deteriorates for particles smaller than about 0.300 mm and spouted bed applications are then possible only with the aid of a draft tube.

The resulting fountain height correlations in this work used together with the maximum spoutable bed height correlations developed earlier (Çeçen, 1994), make it possible to determine the total height of a spouted bed vessel operating with small particles. For this purpose, Equation (3) can be used the calculate H_m from reactor geometry and basic fluid-particle properties, and the fountain height can be predicted from Equations (7-9) depending on the closest particle size.

Conclusions

The differences in the fountain height relations for fine particles and coarse particles emphasize fine particle spouting and coarse particle spouting as two distinct spouting regimes. This fact is of extreme importance for the design of spouted bed systems because appropriate relations must be used for the two different spouting regimes. With the aid of the fountain height correlations developed in this work, it is recommended that the total vessel height in spouted beds operating with fine particles is predicted by the use of Equations (7,8,9) and Equation (3). The prediction of the total spouted bed vessel height from the above mentioned equations is very practical because these relations are based on the particle properties and the reactor geometry which are known in the initial design stage.

Nomenclature

A = dimensionless parameter defined in Equation (2)
d_i = inlet tube diameter, mm
D_c = column diameter, mm
d_p = particle diameter, mm
g = gravitational acceleration, mm/s^2
H = bed height, mm
H_f = fountain height, mm
H_m = maximum spoutable bed height, mm
$m = H_m d_i/D_c^2$
U_i = inlet fluid velocity, m/s
U_{mF} = minimum fluidization velocity, m/s
U_{mS} = minimum spouting velocity, m/s
U_T = terminal fall velocity of a particle, m/s
V_{omax} = particle velocity at the top of the spout, m/s

Greek Symbols:

ε = voidage at the top of the spout
ρ_f = fluid density, kg/m^3
ρ_g = gas density, kg/m^3
ρ_p = particle density, kg/m^3
μ_f = fluid viscosity, Ns/m^2

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