# Experimental Study of Attrition in the Spouted Bed and Spout-Fluid Bed with a Draft Tube

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## ABSTRACT

*The attrition of 300 μm natural zeolite particles was studied in a laboratory scale draft tube spouted bed (DTSB) and spout-fluid bed (DTSFB). It has been shown that the attrition rate decreases with time and reaches to an almost constant value. The results show that the prevailing attrition mechanism under the conditions of this work is the surface abrasion which occurs due to the collisions between particles. It has been found that increasing the cone angle from 30º to 60º in the DTSB, causes a decrease in the extent of attrition. In addition, by increasing the spouting air velocity and the height of the entrainment zone in the DTSB, the extent of attrition increases due to a more energetic collision between particles as well as the increased circulation rate of solids. Increasing the auxiliary air velocity in the DTSFB increases the rate of attrition. A comparison between the attrition in the DTSB and DTSFB has been conducted and has indicated that applying the auxiliary air flow causes up to a 6 % increase in the extent of attrition. An empirical correlation is derived for evaluating the extent of the attrition in the DTSB and DTSFB. This empirical correlation is in good agreement with the experimental data.*

## 1. Introduction

Spouted beds are versatile fluid-solid contactors, used especially for particles larger than 1 mm [1-3]. As stated by Estiati et al. [4], when these systems are operated with fine particles, situations can arise where the gas-solid contact is not fully satisfactory due to the bed instability. To alleviate these problems and to have better control of the solid circulation inside the system, the use of draft tube is proposed by several researchers [4-6]. However, studies on the investigation of hydrodynamics of these systems reveal that there is a dead zone in the annulus section, resuting in particle agglomeration and adhesion problems, which have negative effects on the operation [2, 7]. To mitigate these shortcomings, Chatterjee [8] proposed "hybrid" gas-solid contact reactors, called spout-fluid beds, which have the salient features of both spouted and fluidized beds [9]. In spout-fluid beds, in addition to supplying the spouting fluid through the central nozzle, as in conventional spouted beds, the auxiliary fluid is introduced through a porous or perforated surrounding distributor [2].

Draft tube spouted bed (DTSB) and draft

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tube spout-fluid bed (DTSFB) are being used in a wide variety of chemical processes, including drying [10-11], coating [12], coal gasification [13], combustion [14-15], pyrolysis of hydrocarbons [16], pneumatic conveying [17-20], pharmaceuticals [21] and solids mixing [22] systems. An overview of the characteristics of spouted beds with draft tube was presented by Hatate et al. [23]. Attrition is inevitable in these systems which include vigorous movements of particulate materials. Attrition results in the loss of solids through the removal of undersize particles, the need for recycling the lost solid product and the requirement for the additional filtration. In case of catalytic processes, this phenomenon can limit the useful life of catalyst particles [24]. In systems such as spouted beds, particles are normally required to remain in the bed for a considerable period. The attrition of particles to smaller sizes may affect the hydrodynamics of the bed as well as possibly causing the loss of fine materials by elutriation. Attrition can occur through two different mechanisms: abrasion and fragmentation. Abrasion causes very fine pieces to break away from the mother particle. Fragmentation is breaking the original particle into two or more smaller particles. The attrition in spouted beds with draft tube can occur due to the following reasons: (i) As particles get entrained into the jet and draft tube, they may collide with each other or with the draft tube. (ii) After particles reach the top of the fountain, they fall down on the dense phase in the annulus section. (iii) Particles that move toward the distributor may become abraded against each other, the draft tube or the wall of the bed.

There is a limited number of reports about the attrition in spouted beds. Mathur and Epstein [25] briefly addressed this subject.

Studies were carried out on the attrition of carbonaceous materials in spouted beds [26-27]. Moreover, the attrition of selected polymers [28], calcite [29] and sand [30] in spouted beds was briefly investigated. However, to the best of authors' knowledge, the effect of the auxiliary air flow, conical angle and distance between inlet and draft tube on the particles' attrition in spouted beds has not been yet investigated. On the other hand, although there are several correlations for estimation of the attrition in fluidized beds, no correlation exists for spouted beds. Therefore, in the present work, the equation of Pis et al. [31], which was initially developed for fluidized beds, has been modified to describe the attrition rate in spouted beds.

## 2. Experiments

Figure 1 provides a schematic of a semi-circular DTSB. Two half conical spouted beds with different cone angles (30° and 60°) have been used in this work. The conical parts were made of Delrin whereas the cylindrical columns were of plexiglass. The half bed allows for the visualization of the bed hydrodynamics during the operation. Table 1 gives dimensions of both columns in detail. The spouting air at room temperature was introduced into the bed through a semi-circular inlet nozzle of 10 mm diameter. The air flow rate was controlled by a mass flow controller (ALICAT, MCR-1500SLPM-D). A stainless steel porous plate was employed at the top of the nozzle to prevent the particles falling back to the inlet pipe. In order to operate the spouted beds under the spout-fluid bed condition, a gas feed reservoir was installed around the conical section of the bed for the auxiliary (fluidizing) air supply as illustrated in Figure 1. Holes with 1 mm

diameters were uniformly drilled on the lateral side of the conical section. The number of holes are presented in Table 1. The percentage of the open area on the lateral surface was decided as 0.4 % to ensure that

the air was introduced to the bed uniformly. A filter cloth was used around the conical section to prevent the particles blocking the holes.
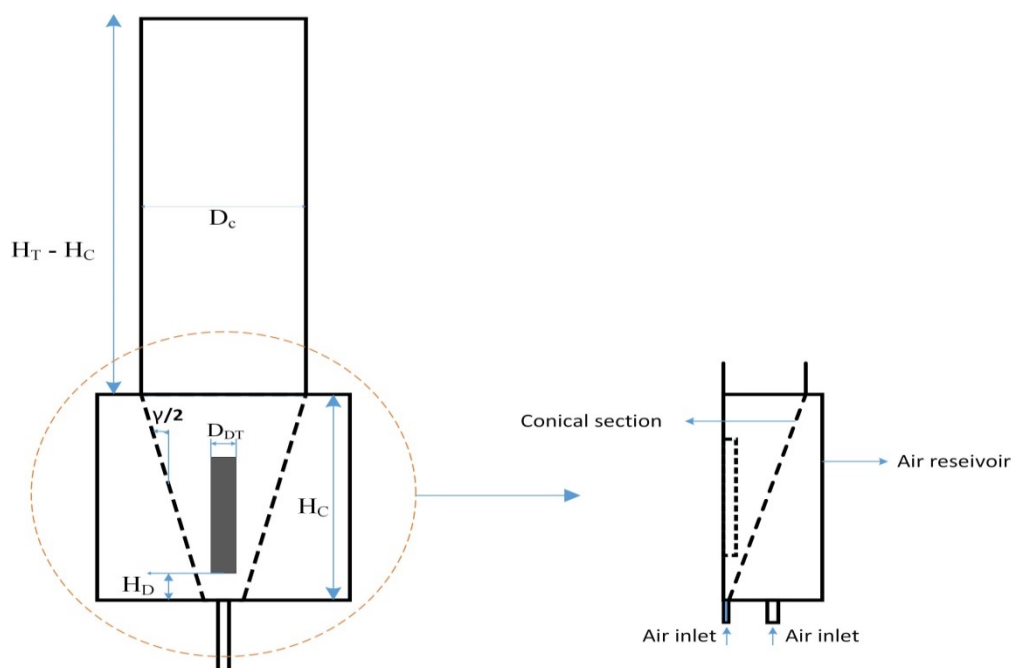


**Figure 1.** Schematic of the semi-circular spout-fluid bed and its side view.

**Table 1**
Characteristics of 30° and 60° half conical spout-fluid beds with draft tube.

| Column part | Parameter | 30° | 60° |
|---|---|---|---|
| Conical section | Holes diameter (mm) | 1 | 1 |
| | Number of holes | 169 | 90 |
| | Open area fraction (%) | 0.4 | 0.4 |
| | Vertical height, $H_C$ (mm) | 230 | 100 |
| Cylindrical section | Height, $(H_T - H_C)$ (mm) | 940 | 940 |
| | Diameter, $D_C$ (mm) | 150 | 150 |
| Draft tube | Height, $H_{DT}$ (mm) | 130 | 80 |
| | Diameter, $D_{DT}$ (mm) | 23 | 23 |
| | Distance from gas inlet, $H_D$ (mm) | 30, 50 | 30 |

Attrition tests were performed by using natural zeolite particles with an average size of 300 µm and density of 2470 kg/m$^3$ as the bed material. In each experiment, 158 g of zeolite was charged into the bed. With that amount, the bed height ($H_b$) was about 130 mm in the 30° spouted bed and 80 mm in the

60° bed. The duration of all the experiments was 6 hours. The air supply was turned off after each one hour and particles were taken out, weighed, and put back into the bed. The particle size distribution before and after the tests were determined by sieve analyses.

## 3. Results and discussion

Prior to attrition tests, a study was conducted to characterize the hydrodynamic regime inside the systems and to determine the minimum stable spouting velocities ($U_{mss}$) under different conditions in 30º and 60º beds using the same zeolite particles. The minimum spouting velocities were determined by simultaneous visual observations and pressure drop measurements, using the increasing velocity procedure. The measurement of the bed pressure drop was conducted by a differential pressure transducer connected to the bed's internal wall at the base of the conical section. The other line of the transducer was left open to atmosphere. Figure 2 represents the variation of the bed pressure drop with the inlet spouting gas velocity measured in 30º and 60º DTSBs. It was visually monitored that with the introduction of the spouting gas, the pressure drop increased linearly to its peak value as the bed was under the fixed bed condition. The point indicated by (A) in Figure 2 is where the fixed bed resistance breaks and the bed materials begin their entrainement into the draft tube from the annulus section. In fact, the fluidization of particles through the draft tube with occasional spouts just begins at this point. This behavior continues throughout the region indicated by (i). The point indicated by (B) is where the spouting is first observed, albeit in an unstable fashion. This point is the minimum spouting velocity ($U_{ms}$). Throughout the region (ii) an unstable spout, marked by a constantly changing fountain height, exists. This unstable behavior ends at point (C) and a stable spout, denoted by (iii), can be observed throughout the region. In this region, the fountain height does not change considerably. Point (C) indicates the minimum stable spouting velocity ($U_{mss}$). As it can be seen in Figure 2, applying the auxiliary air (fluidizing air) to the bed results in levelling off the peak of the pressure drop. This is attributed to the decrease in the flow resistance with the expansion in the annulus as the the fluiding air is introduced. The minimum stable spouting velocities measured in both units are tabulated in Table 2. As it can be seen in Table 2, the application of the auxiliary gas flow to the bed decreases the minimum stable spouting velocity. $U_f=0$ corresponds to the spouted bed condition whereas if $U_f> 0$, the spout-fluid condition occurs.

### 3.1. Effect of the spouting gas velocity

Figure 3 illustrates the weight loss of the bed material due to the attrition during the tests at various spouting air velocities in a 30º draft tube spouted bed. The weight loss occurs rapidly at the beginning of the test. The total mass of particles in the bed reaches a constant value after 4 hours. The dependency of the attrition rate to time and velocity was also reported for fluidized bed systems in literature [30, 32-34]. The dependency of the weight loss to time can be explained by rounding off and surface abrasion of particles that happens gradually [35]. The rate of attrition increases by increasing the gas velocity, since the impacts of particles (on each other, the wall, and the draft tube) are more intense at higher gas velocities. Therefore, the amount of elutriated fines is higher at the beginning of each test and decreases as the time passes. Since the movement of particles in the annulus section is very slow, most of the particles' attrition is expected to occur in the draft tube, especially at the entrance. On the other hand, an increase in the gas velocity increases the height of the fountain.

Therefore, the impacts of particles falling down and those in the annulus on one another are augmented which result in the breakage of more particles.
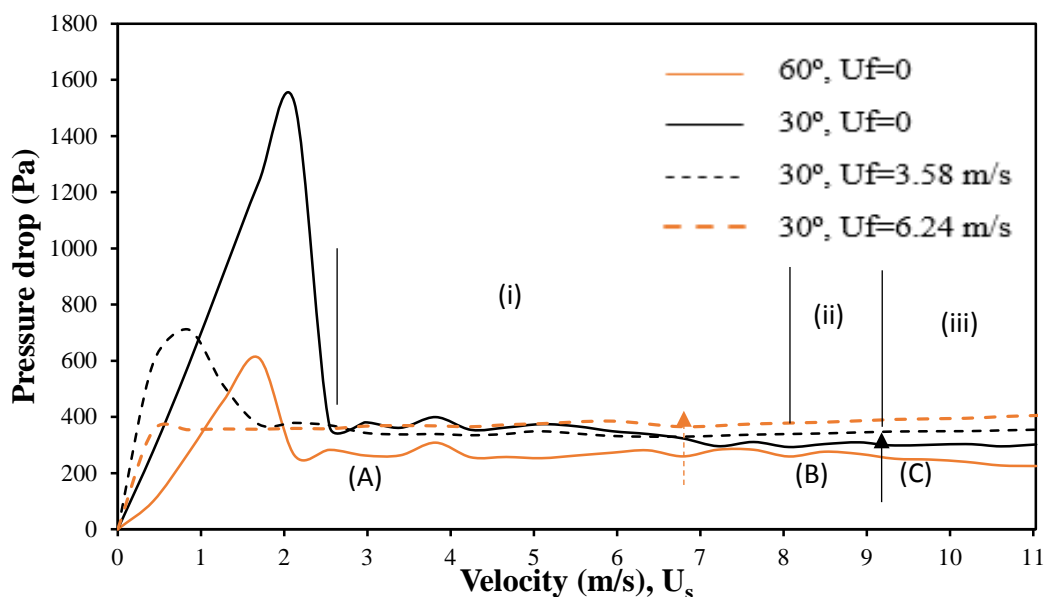


**Figure 2.** Evolution of the pressure drop with the spouting gas velocity (arrows show minimum stable spouting velocities).

**Table 2**
Variation of the minimum stable spouting velocity ($U_{mss}$) with the auxiliary air velocity ($U_f$) in 30º and 60º spout-fluid beds with draft tube.
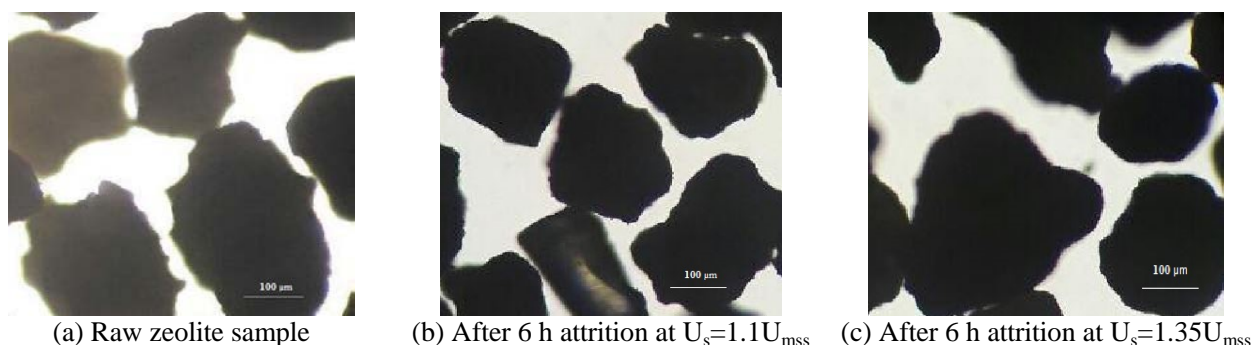
| Test No. | Experimental conditions | | |
|---|---|---|---|
| | $U_f$ (m/s) | $U_{mss}$ (m/s), 30º bed | $U_{mss}$ (m/s), 60º bed |
| 1 | 0 | 9.2 | 9.2 |
| 2 | 3.6 | 7.4 | 7.6 |
| 3 | 4.9 | 6.8 | 7 |
| 4 | 6.2 | 6.6 | 6.4 |
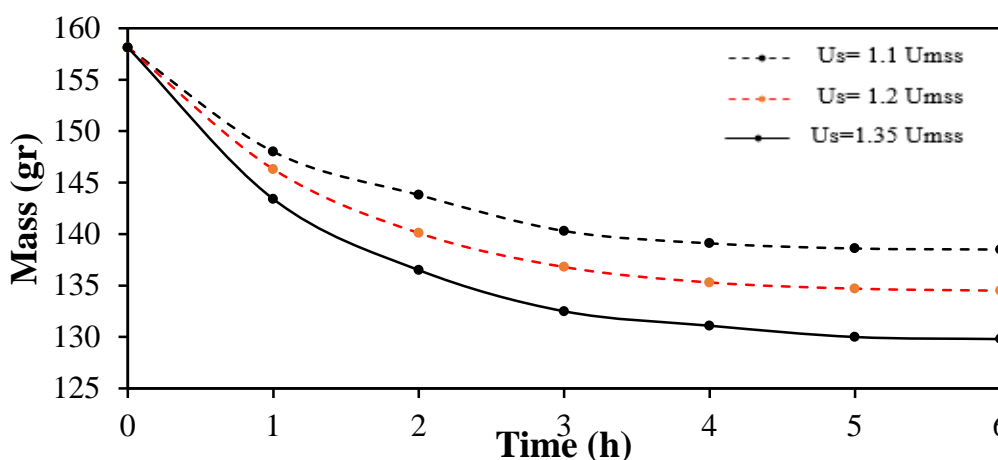


**Figure 1.** Mass loss of bed materials in a 30° draft tube spouted bed at various air velocities ($H_b$ = 130mm, $d_p$= 300µm), in all experiments $U_f$= 0.

The particles' attrition leads to change in the fractional size distribution of the bed material which affects the hydrodynamic behavior of the bed. The size distribution of bed materials was measured by sieving before and after the tests. The comparison between the size distributions of particles before and after the tests shows that larger particles abrade and break to fine particles during the tests. An optical microscope was used for inspecting the surface of particles before and after the tests. Figure 4 shows the rough and irregular surface of the parent particles as well as the abraded surface of the particles after 6 hours of the operation at two different gas velocities. Due to the more severe collisions between particles at a higher gas velocity, solids surfaces are rougher in the experiment at $1.35U_{mss}$ compared to that at $1.1U_{mss}$.

| (a) Raw zeolite sample | (b) After 6 h attrition at $U_s=1.1U_{mss}$ | (c) After 6 h attrition at $U_s=1.35U_{mss}$ |

**Figure 4.** Micrographs of solids at the beginning and after the tests in a 30° draft tube spouted bed (a) before the test (b) after 6 h at $U_s=1.1U_{mss}$ and $U_f= 0$ (c) after 6 h at $U_s=1.35_{mss}$ and $U_f= 0$.

### 3.2. Effect of the auxiliary air flow

Figure 5 demonstrates the effect of the auxiliary air flow rate on the bed weight changes under the conditions presented in Table 2. As illustrated in Figure 5, the extent of attrition increases with the application of the auxiliary gas. Furthermore, increasing the auxiliary gas flow rate has a direct effect on the attrition rate. Introducing the auxilary gas flow into the annulus yields a better solid-gas contact and improves mixing, as well as reducing some common limitations of the spouted bed, such as the particle aggmoloration, reaction dead zones or adhesion to the wall or base of conventional spouted bed reactors [36]. On the other hand, at a higher auxiliary gas flow rate, a substantial increase in the solid circulation rate is realized at the same total gas flow rate. In other words, particles move faster in the annulus section of a spout-fluid bed compared to the same in a conventional spouted bed [37]. Thus, by increasing the auxiliary gas flow rate, the collisons between particles and particles as well as particles and the wall become more effective for the abration and beakage of particles.

### 3.3. Effect of the cone angle

Figure 6 shows the gas-solid flow patterns in a 60° DTSFB during the tests with various auxiliary air velocities. In Figure 6 (a), dead zones in the 60° bed without the auxiliary air flow are shown by oval shapes. In Figure 6 (b)-(d), the disappeareance of the dead zones with the application of the auxiliary air can be observed. In addition, bubbling occurs in the annulus region as the rate of the auxiliary gas flow increases. As a result, particles collisions become more vigorous and the rate of attrition increases with time. The same trend was also observed in the 30° bed.
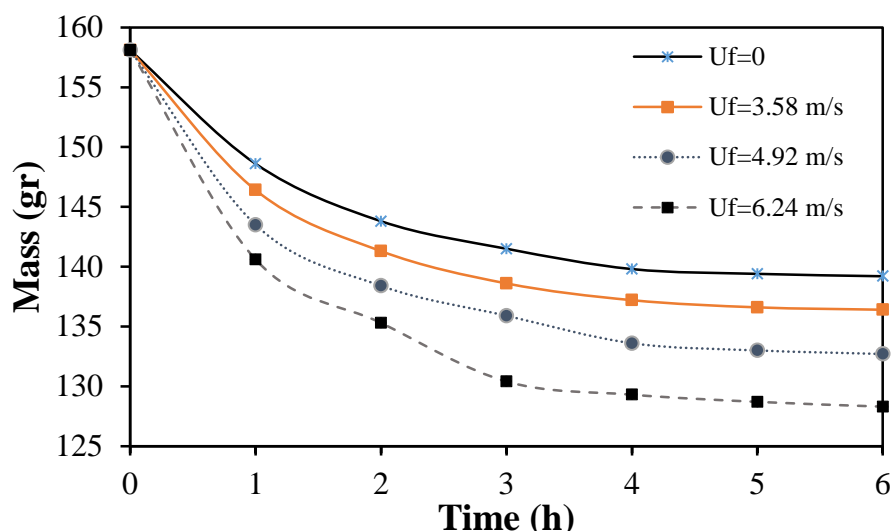
**Figure 2.** Mass loss of bed materials in a 30° spout- fluid bed with the draft tube at various auxiliary air velocities ($H_b$ = 130mm, $d_p$ = 300µm).



| $U_f$=0 | $U_f$=3.58 (m/s) | $U_f$=4.92 (m/s) | $U_f$=6.24 (m/s) |
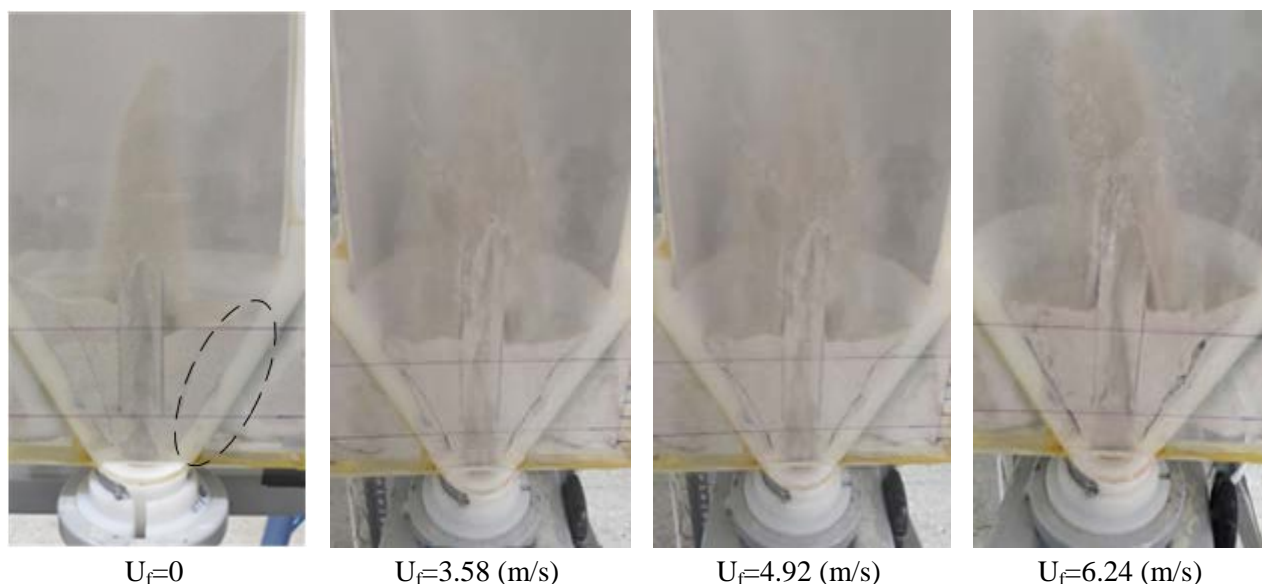
**Figure 3.** Disappearance of dead zones by introducing the auxiliary gas flow in a 60° spout-fluid bed with a draft tube ($H_b$ = 80mm, $d_p$ = 300µm) the oval shape shows dead zone, $U_s$= $U_{mss}$.

The extent of attrition in the 60° conical draft tube spouted bed is compared with that in the 30° bed in Figure 7. This figure demonstrates that under the same operating condition (both beds are at $U_{mss}$ and the same amount of bed material is used in both beds), the attrition in the 30° bed is higher than the same in the 60° bed. This trend can be explained by the fact that there are dead zones in the 60° conical draft tube spouted bed, but the dead zones in the 30° draft tube spouted bed are almost negligible. Therefore, less particles participate in the circulation in the 60° bed as a result of the larger dead zone. Another reason is the lower circulation rate observed in the 60° bed compared to the same in the 30° bed which is also reported by other researchers [38]. Consequently, the number and intensity of contacts between particles are less in the 60° bed compared with that in the 30° bed.
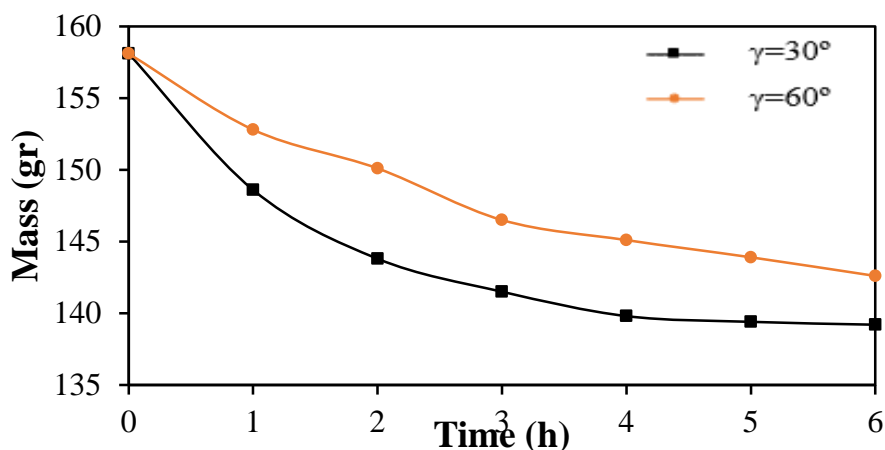
**Figure 4.** Effect of the cone angle on the change of mass of particles in spouted beds operating at the minimum stable spouting velocity ($U_{mss}$ for both 30° and 60° beds = 9.2 m/s), in both beds $U_f$= 0.

### 3.4. Effect of the height of the entrainment zone

The effect of the height of the entrainment zone, which is the distance between the gas inlet and the draft tube ($H_D$), on the extent of the weight loss has also been investigated in this study. For that purpose, two sets of experiments, in which the height of entrainment zones of 3 cm and 5 cm, were conducted. The minimum stable spouting velocities of those tests were measured as 9.2 and 10.2 m/s respectively. Figure 8 illustrates the weight loss of bed materials with time during experiments with two different heights of the entrainment zone in which the gas velocity was set to the minimum stable spouting velocity in each case. As shown in the figure, attrition increases slightly by increasing the height of the entrainment zone. By increasing the distance between the gas inlet of the bed and the draft tube, the fraction of the flow that goes through the annulus section increases and more solid particles can be entrained by the gas due to the increase in the contact area of the entrainment zone, resulting in the increase in the circulation rate [39]. In addition to a higher gas velocity, it was visually observed that the fountain height increased by increasing the height of the entrainment zone. These phenomena cause stronger particle collisions for the higher entrainment zone that would lead to an increase in the extent of attrition.
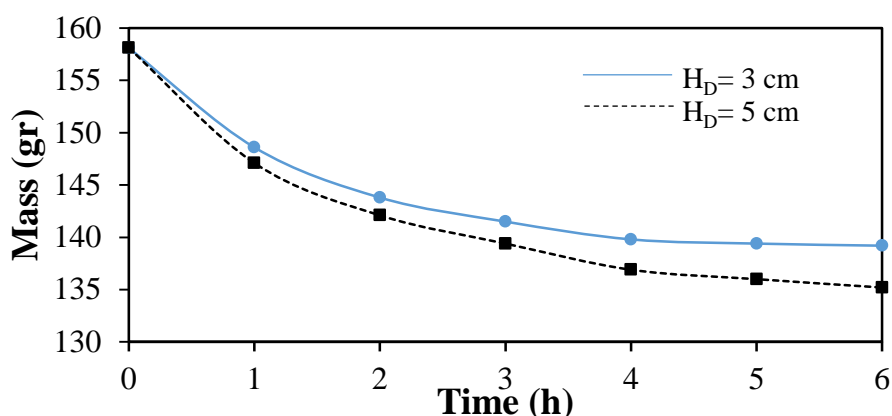


**Figure 5.** Mass changes of bed materials in a 30° spouted bed with a draft tube at different entrainment zone heights ($H_b$ = 130mm, $d_p$ = 300µm), in both experiments $U_s$= $U_{mss}$ and $U_f$= 0.

## 3.5. Empirical correlation

The following empirical equations, which are available in litearture for the evaluation of the percent of attrition in fluidized beds, have been first evaluated as candidates for the representation of the exent of attrition in spouted beds in this study:

$$A = a_1 + b_1 t - a_1 e^{-c_1 t} \quad [40] \tag{1}$$

$$A = a_2 + b_2 t - \frac{a_2}{1+c_2 t} \quad [31] \tag{2}$$

where A is the percent of attrition and a, b and c are coefficients of which the values depend on the test condition, characteristics of experimental set-up and bed material. A comparison between the performances of these two correlations is given in Table 3. Based on the correlation coefficients reported in this table, it can be concluded that the experimental data obtained in the spouted bed fit better to the equation of Pis et al. [31].

**Table 3**

Coefficients of equations (1) and (2) and corresponding correlation coefficients.

| Test condition | Equation No. | *a* | *b* | *c* | Correlation coefficient |
|---|---|---|---|---|---|
| $H_D = 3$ cm, $U = U_{mss}$ | (1) | 92.71 | 0.143 | -0.001 | 0.973 |
| | (2) | 12.37 | -0.0078 | 0.0057 | 0.999 |
| $H_D = 3$ cm, $U = 1.1U_{mss}$ | (1) | 93.99 | 0.1481 | -0.0011 | 0.974 |
| | (2) | 14.0235 | -0.0095 | 0.0052 | 0.997 |
| $H_D = 3$ cm, $U = 1.2U_{mss}$ | (1) | 107.9 | 0.177 | -0.0012 | 0.974 |
| | (2) | 18.45 | -0.0135 | 0.0049 | 0.998 |
| $H_D = 3$ cm, $U = 1.35U_{mss}$ | (1) | 116.8 | 0.205 | -0.0012 | 0.969 |
| | (2) | 18.73 | -0.0116 | 0.0059 | 0.999 |
| $H_D = 5$ cm, $U = U_{mss}$ | (1) | 91.86 | 0.149 | -0.0014 | 0.997 |
| | (2) | 9.885 | -0.0014 | 0.0079 | 0.994 |
| $H_D = 5$ cm, $U = 1.2U_{mss}$ | (1) | 106.1 | 0.167 | -.0015 | 0.977 |
| | (2) | 11.13 | 0.0003 | 0.0073 | 0.993 |

Equation (2) was further improved to obtain a more general correlation which would take into account the inlet gas velocity and the height of the entrainment zone by introducing the dimensionless time as follows:

$$\tau = \frac{tU}{H_D} \tag{3}$$

where $U = U_s + U_f$.

The gas velocity was also made dimensionless through Reynolds number:

$$Re_s = \frac{U_s D_i}{\nu} \tag{4}$$

Cosideringg these dimensionless numbers and the effect of the cone angle, the new correlation can be presented as follows:

$$A = 1.26 \left(\frac{Re_s}{Re_{mss}}\right)^{1.454} \left(7.88 - \frac{7.88}{1+6e-07\tau}\right) \tan(\gamma)^{-0.182} \tag{5}$$

The correlation coefficient for Equation (5) is found to be 0.87. This equation can be further improved to include the effect of the auxiliary air flow of gas in the DTSFB:

$$A = 1.26 \left(\frac{Re_s}{Re_{mss}}\right)^{1.454} \left(7.88 - \frac{7.88}{1+6e-07\tau}\right) \tan(\gamma)^{-0.182} e^{1.536 \frac{U_f}{U_{mss}}} \tag{6}$$

The parity plot of the experimental and

calculated percentages of attrition (A) is presented in Figure 9. This figure shows that Equation (6) provides a good prediction of the experimental results. In addition, the correlation coefficient for this equation is 0.95 which also confirms that Equation (6) fits the experimental values properly.
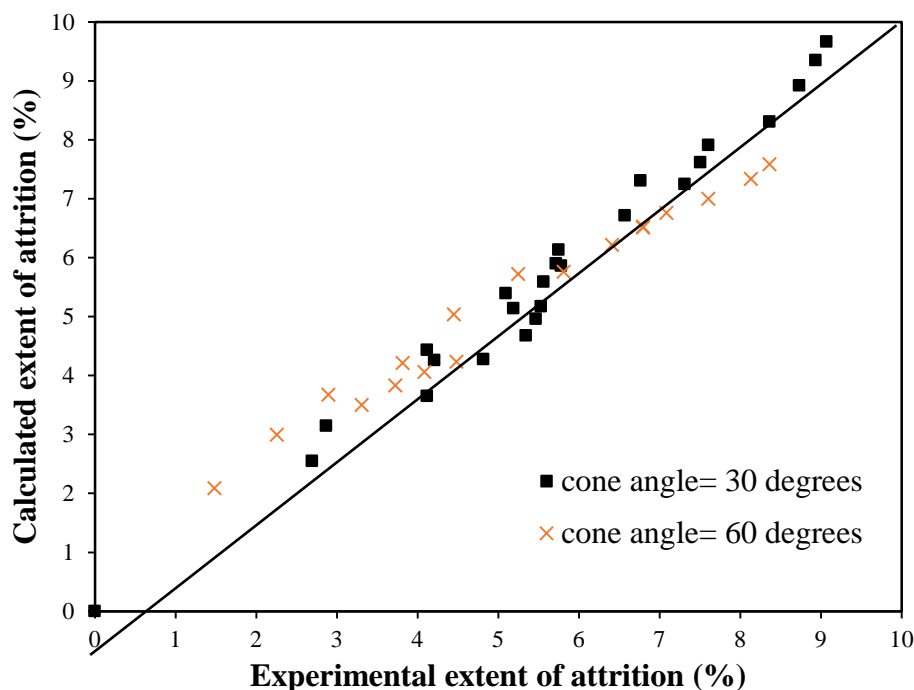


**Figure 6.** Comparison of the calculated and experimental extents of attrition.

## 4. Conclusions

A study was carried out on the attrition of natural zeolite in draft tube spouted and spout-fluid beds. It was shown that the attrition rate would decrease with time and reach an almost constant and significantly low value. Moreover, it was found that the extent of attrition increased by increasing the air velocity and auxiliary air flow rate. The effect of the cone angle and the distance between the inlet and draft tube on attrition was also investigated and it was shown that the extent of attrition was higher in beds with smaller cone angles and larger entrainment zones. An empirical equation was proposed for the calculation of the attrition rate. The effects of the auxiliary gas flow rate and cone angle were taken into account in the proposed correlation. It was shown that the new correlation could properly predict the attrition extent in both the presence and absence of the auxiliary air.

## Nomenclature

| | |
|---|---|
| $A$ | percent of attrition [%]. |
| $D_c$ | diameter of cylindrical part [m]. |
| $D_i$ | inlet diameter [m]. |
| $D_{DT}$ | draft tube diameter [m]. |
| $H_b$ | static bed height [m]. |
| $H_C$ | height of conical part [m]. |
| $H_D$ | distance between inlet and draft tube (entrainment zone) [m]. |
| $H_{DT}$ | height of draft tube [m]. |
| $H_T$ | total height of spouted bed [m]. |
| $L_D$ | draft tube length [m]. |
| $U$ | cumulative inlet velocity [m/s]. |
| $U_s$ | inlet spouting velocity [m/s]. |

| | |
|---|---|
| $U_f$ | inlet fluidizing (auxiliary) air velocity [m/s]. |
| $U_{mss}$ | minimum stable spouting velocity [m/s]. |
| $W_{min}$ | minimum weight of parent particles in bed [kg]. |

**Greek letter**

| | |
|---|---|
| $\gamma$ | cone angle [°]. |

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