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ANALYSIS OF THE FLUID-DYNAMIC BEHAVIOR OF FLUIDIZED AND VIBROFLUIDIZED BED CONTAINING GLYCEROL

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Abstract - The fluid-dynamic characteristics of fluidized and vibrofluidized beds of inert particles in liquids are being widely studied by researchers interested in understanding and modeling the paste drying process. In this work characteristic fluid-dynamic curves of pressure drop versus air velocity were obtained for fluidized and vibrofluidized beds with glycerol. Glycerol was used as a standard fluid to simulate a paste in the bed, and "ballotini" glass spheres were used as inert particles. The fluid-dynamic behavior as well as the quality of the fluidization regimes was analyzed through pressure drop versus air velocity and standard deviations of pressure drop versus air velocity curves and visual observation of the flow patterns in the beds. The results indicated that standard deviation curves are a useful tool for gaining an understanding of the fluid-dynamic behavior of a vibrofluidized bed. They allow detection of changes in the fluid-dynamic behavior which were not observed by analyzing only the pressure drop versus air velocity curves. For fluidized beds (Γ=0.00), it was also observed that analysis of curves of standard deviations of pressure drop may help in the estimation of more accurate values of minimum fluidization velocities.
Keywords: vibrofluidized bed dryer, fluidization, glycerol, drying of pastes, minimum fluidization velocity.

INTRODUCTION

The use of spouted, fluidized and vibrofluidized beds with inert particles in paste drying is a promising drying technique. An advantage of using the vibrofluidized bed instead of the fluidized or spouted bed is that mechanical agitation increases the heat and mass transfer coefficients, reduces the minimum fluidization velocity and can even reduce the pressure drop. The volume of dead regions as well as channeling and bubble formation may also be reduced. In addition, fluidization of cohesive, adhesive and pasty material becomes feasible in these beds (Gupta and Mujumdar, 1980a; Erdèsz et al., 1986; Della Tonia Jr. et al., 1990; Cardoso and Kieckbusch, 1999).

To characterize a vibrofluidized bed, it is important to quantify the vibration energy imposed on the system. This is usually done with the dimensionless vibration number, proposed by Chlenov and Mikhailov (1972) and given by the following equation:

$$\Gamma = \frac{A \cdot (2 \cdot \pi \cdot f)^2}{g} \qquad (1)$$

where A and f are respectively the amplitude and the frequency of vibration and g is the acceleration of gravity.

It is also important to analyze the conditions under which incipient fluidization occurs when both

*To whom correspondence should be addressed vibration and gas flow are present (Bratu and Jinescu, 1971). The velocity at which incipient fluidization takes place is generally called the minimum fluidization velocity (U_{mf}). In a conventional fluidized bed, a good estimate of minimum fluidization velocity is obtained from the intersection of two straight lines depicted in the experimental curves of pressure drop as a function of superficial air velocity. In this situation, the point at which the transition from a fixed to a fluidized bed occurs is well-defined and the uncertainty of the estimated value is very small. However, for a vibrofluidized bed, depending on the range of dimensionless vibration numbers studied, this transition is not clear and may be located anywhere within a wide range of air velocities. Thus, the use of the same definition as that applied to conventional fluidized beds may be questionable. In spite of this, some authors still apply this definition to estimate the minimum fluidization velocity in vibrofluidized beds.

This procedure was adopted, for instance, by Gupta and Mujumdar (1980b), who obtained the minimum fluidization velocity for vibrofluidized beds and observed that, in some cases, the values increased as the dimensionless vibration number, Γ, was increased keeping amplitude of vibration constant. These results are physically inconsistent, because minimum fluidization velocity should have decreased as Γ was increased. The authors inferred that the methodology applied was not adequate and that a new definition of minimum fluidization velocity in vibrofluidized beds should be applied. The concept of a minimum mixing velocity (U_{mm}), defined as the air velocity at which the solid particles in the bed begin to move with respect to each other, was then introduced. This velocity must be determined from visual observations, and the authors concluded that minimum mixing velocity decreased as frequency of vibration was increased, which was thus a physically consistent behavior. In this case, the problem is that the proposed methodology depends heavily on the observer and on the existence of a system which allows visual observation. Under these conditions, the need to develop more reliable methodologies to determine minimum fluidization velocity, particularly for vibrofluidized beds, is evident. Another difficulty in determining minimum fluidization velocity is observed when the inert particles are covered with a paste, because the presence of a liquid affects the particle dynamics in the bed. Although in this work the values of minimum fluidization velocities obtained experimentally are given in the captions of Figures 8 to 11, they will be used only as reference values. A detailed analysis of the values of minimum fluidization velocity will be presented in subsequent work, since additional tests are still required for achieving a better understanding of their behavior.

According to Freire (1992), the drying of paste in beds with inert particles is a very complex operation, mainly due to the variety of pastes with different characteristics which may be used, even though a lot of research has demonstrated the technical feasibility of drying organic and inorganic pastes in these beds. Publications in the literature report on the influence of a liquid, usually glycerol, in the operation of spouted beds (Patel et al., 1986; Schneider and Bridgwater, 1993; Santana et al., 1997; Passos and Mujumdar, 2000; Spitzner Neto and Freire, 2001; Spitzner Neto, 2001), fluidized beds (Passos and Mujumdar, 2000; Passos and Massarani, 2000) and vibrofluidized beds (Malhotra et al., 1984; Daleffe et al., 2002; Daleffe, 2002). Glycerol is usually used to simulate a paste due to its low evaporation rate under the conditions studied. In most work, the liquid is fed into the beds in a batch mode.

Malhotra et al. (1984) studied the pressure drops in a rectangular vibrofluidized bed, using "ballotini" glass spheres with diameter of $3.53x10^{-4}$ and $6.67x10^{-4}$ m (Geldart B particles), dimensionless vibration numbers varying from 0 to 4 and ratios of mass of glycerol to mass of inert varying from 0.000 to 0.006.

Daleffe et al. (2002) reported a fluid-dynamic study of a rectangular vibrofluidized bed, using as inert "ballotini" glass spheres with a diameter of $1.85x10^{-3}$ m (Geldart D particles). The dimensionless vibration number varied from 0.0 to 1.5 and the degree of saturation of glycerol from 0.0000 to 0.0072. Daleffe (2002) analyzed curves of standard deviations of pressure drop versus air velocity under different operational conditions and also reported new data on minimum mixing velocities. The experiments were performed in the same experimental apparatus as that described in Daleffe et al. (2002), operated within the same range of dimensionless vibration numbers and degrees of saturation of glycerol. The inert were "ballotini" glass spheres, with diameters of $1.10x10^{3}$, $1.53x10^{-3}$ and $1.85x10^{-3}$ m. Daleffe (2002) also studied the effect of temperature on particle agglomeration between 40 and 60 °C.

Garim and Freire (1999) combined analysis of pressure drop versus air velocity curves and standard deviations of pressure drop versus air velocity curves to obtain a good characterization of the fluid-dynamics of fluidized and vibrofluidized beds.

Camargo and Freire (2002) also used the standard deviations of pressure drop curves to complement their analysis of the fluid-dynamics in these beds. In both cases, the beds were operated without a paste.

The purpose of this work is to study the fluid-dynamic behavior of fluidized and vibrofluidized beds containing a paste, focusing on the effects of inert particle diameter, degree of saturation of glycerol and dimensionless vibration number on the fluid-dynamics of the beds. Characteristic curves and standard deviations of pressure drop curves will be obtained under different operational conditions.

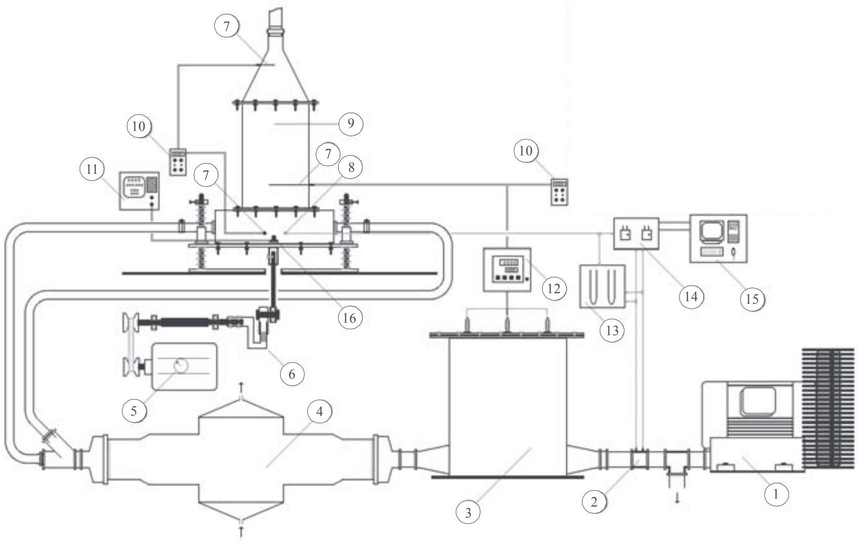
MATERIALS AND METHODS

Experimental Setup

The experimental apparatus is shown in Figure 1.

The vibrofluidized bed is composed of a rectangular chamber with a length of 0.200 m, a width of 0.115 m and a height of 0.300 m, made of galvanized iron. The air is provided by a blower and the airflow rate is obtained using a previously calibrated orifice plate. The orifice plate as well as the pressure tap located at the bottom of the bed are connected to pressure transducers linked to a data collecting system in a 486 DX computer with an A/D board. Air temperature is kept constant using an electrical resistance heater connected to a controller. A water cooler is used as auxiliary equipment to control temperature. An eccentric mechanism adjusts the amplitude of vibration and a mechanical controller located on the axle of the electric motor allows for adjustment of frequency of vibration. The acceleration, velocity and amplitude of vibration of the system generated by the imposed vibration is monitored by a piezoelectric accelerometer and frequency of vibration is measured with an optical tachometer.

"Ballotini" glass spheres with a density of 2.500 kg/m^3 and diameters of $1.10x10^{-3}$, $1.55x10^{-3}$ and $1.85x10^{-3}$ m were used as inert. A mass of inert weighing 3 kg, corresponding to a static bed height of 0.08 m, was used in each test. The liquid used was glycerol with a minimum purity of 99.5%, which is a colorless fluid with a low vapor pressure and a density of 1.258 kg/m^3 (25 °C).



1 - Air Blower
2 - Orifice Plate
3 - Air Heater
4 - Air Cooler
5 - Frequency Variator
6 - Eccentric
7 - Thermocouple
8 - Pressure Tap
9 - Vibrofluidized Bed
10 - Signal Conditioner (Thermoc.)
11 - Signal Conditioner (Acceler.)
12 - Temperature Controller
13 - Manometer
14 - Pressure Transduce

Figure 1: Schematic diagram of the experimental setup.

Experimental Procedure

The same rectangular chamber could be operated with or without vibration, thus resulting in either a vibrofluidized or a fluidized bed. A screen was placed at the bed exit to avoid the entrainment of the particles from the equipment, particularly in cases of high airflow rates or irregular fluidization caused by particle agglomeration. The bed was operated at 40°C, a temperature chosen from preliminary tests, since fluid viscosity at this temperature was adequate to ensure uniform distribution of liquid on the particles, thus reducing problems caused by particle agglomeration.

Some tests were carried out in order to define a suitable operational range of dimensionless vibration numbers. To ensure the structural stability of the equipment, it was not possible to work with dimensionless vibration numbers greater than 1.5. The dimensionless vibration numbers studied were

0.00, 0.50, 1.00 and 1.50, and a constant amplitude of 3.0×10^{-3} m was adopted. The degree of saturation of glycerol (ϕ) was defined by the ratio of volume of glycerol (v_g) to volume of pores in the bed (v_p):

$$\phi = \frac{v_g}{v_p} \quad (2)$$

Loss by evaporation, the mass of liquid adhering to the walls and the mass of liquid dragged by the airflow were neglected. Degrees of saturation of 0.0000, 0.0009, 0.0018, 0.0036, 0.0054 and 0.0072 were used, and the liquid was fed into the bed in batch mode. For the highest degrees of saturation studied, high instabilities were observed in the fluidization.

The experimental procedure is described as follows: under fluidized conditions and once the steady state was reached, glycerol was added to the particles. To ensure that the inert were homogeneously covered by the liquid, the collecting of data was initiated after a time interval of 3 to 5 minutes. Then the pressure drop versus air velocity curves were obtained for either the fluidized or the vibrofluidized beds by measuring the pressure drops as a function of superficial air velocity, according to the classic methodology described in Bratu and Jinescu (1971). For every set of conditions for particle diameter, vibration and degree of saturation of liquid, the pressure drop was obtained as air velocity was reduced. The values for standard deviation of pressure drop were recorded by the data collecting system. Each value of pressure drop was obtained from the arithmetic average of the 300 points collected in a time interval of 3 seconds.

In this work, estimates of the minimum fluidization for fluidized and vibrofluidized beds operating with a paste were obtained from the classic methodology defined for conventional fluidized beds. Under each condition, minimum velocity was obtained from the intersection of two straight lines depicted in the pressure drop versus air velocity curve, one of which is the slope of the curve obtained in the fixed-bed region and the other the slope of the curve obtained in the fluidized bed region. For the vibrofluidized beds, in addition to the pressure drop versus air velocity curves, visual observation was used to detect the point at which the particles started moving with respect to each other, as described in Gupta and Mujumdar (1980). Visual observation was possible throughout the upper part of the bed, since the bed walls were not transparent. Some tests were repeated to verify the reproducibility of the data.

RESULTS AND DISCUSSION

The reproducibility of the pressure drop versus air velocity and of the standard deviations of pressure drop versus air velocity curves was verified for a particle of $d_p = 1.55\times10^{-3}$ m. The results are depicted in Figure 2 for the fluidized bed (Γ= 0.00) and in Figure 3 for the vibrofluidized bed, both operating with glycerol. It can be noted in Figure 2 that the pressure drop and standard deviation data show good reproducibility, with the deviations within the range of experimental errors. The curves are typical of a fluidized bed, with a well-defined transition from the fixed to the fluidized regime. Note that in the range of air velocities at which the bed behaves as a fixed-bed, the standard deviations are very low (below 25 N/m^2), increasing significantly as incipient fluidization begins.

In Figure 3, with the bed operating under vibration and with glycerol, the curves also show good agreement and deviations smaller than the experimental error (which is estimated as being around 6 %). In Figure 3 it can be observed that, under vibrating conditions, a change in the behavior of the standard deviation curve can not be directly related to the point at which fluidization begins.

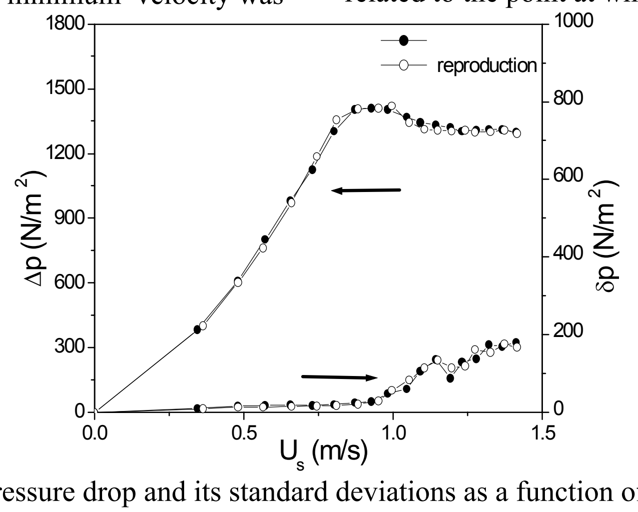


Figure 2: Pressure drop and its standard deviations as a function of superficial air velocity; (reproducibility tests), Γ = 0.00; ϕ = 0.0000.

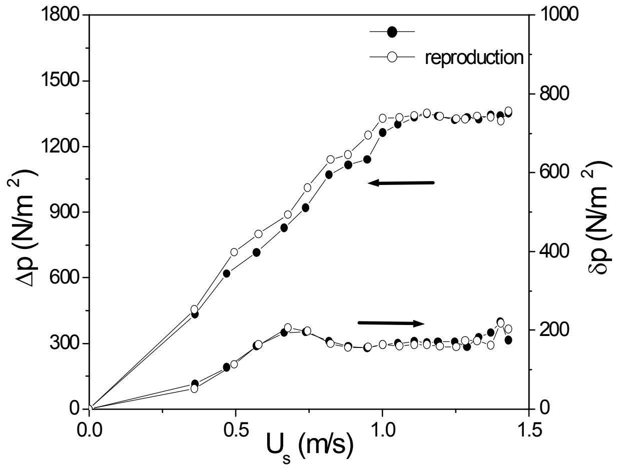


Figure 3: Pressure drop and its standard deviations as a function of superficial air velocity; (reproducibility tests), $\Gamma = 1.00$; $\phi = 0.0018$.

Figures 4 and 5 show data on pressure drop versus air velocity for different particle diameters. For comparison, data reported by Malhotra et al. (1984) are presented along with the results obtained in this work. In spite of the fact that the parameters used are not the same in both studies, their ranges of magnitude are similar and the comparison shows consistent behavior in the results. To allow a comparison, the degree of saturation of glycerol (ϕ), as defined in this work, was converted to a weight fraction of glycerol (X) to adopt the same definition as that used by Malhotra et al. (1984). In the remainder of this work, the original definition of degree of saturation of glycerol (ϕ) was kept because it is more commonly used in the specialized literature.

Figure 4 shows that, when the system is operated under vibration, an expansion of the bed occurs in the region of fixed-bed behavior. At the transition to a fluidized bed a sharp peak appears in the pressure drop, which is probably caused by the sudden rupture of particle agglomerates which are formed due to the stickiness of the glycerol. From this region on, the pressure drops in both works are practically constant, a typical behavior of the fluidized regime.

It can be seen in Figure 4 that the pressure drop obtained under vibration by Malhotra et al. (1984) is greater than that obtained in the fluidized bed. This result differs from that obtained in this work, and this difference may probably be attributed to the different particle diameters, since Malhotra et al. (1984) used particles of the Geldart B group and in this work Geldart D particles were used. Comparing the results, it can be noted that the curves obtained in this work for the largest particle diameter shift downwards but the qualitative behavior is similar for both diameters.

Figure 5 shows data from Malhotra et al. (1984) on particles with a diameter almost three times smaller than those used in this work. Again, since the curves obtained by Malhotra et al. (1984) show a qualitative behavior similar to that in the data in this work, it can be inferred that the shift in the curves can be attributed to the differences in particle size.

A comparison of the results from Figures 4 and 5 indicates that in both cases the curves in the transition region become smoother under vibration. In systems with no paste, the fluid-dynamic data are consistent with those for this condition presented in the literature, such as in Strumillo and Pakowski (1980).

The effect of particle diameter on bed dynamics is depicted in Figure 6. A well-defined and stable fluidization curve is obtained for the smallest particle diameter. For the two largest particle diameters, under this saturation condition, fluidization started only at an air velocity close to the blower's limiting capacity. In this case, the action of the viscous forces combined with the weight of the particles prevented the onset of fluidization, thus keeping the bed agglomerated. In the standard deviation of pressure drop curves it is possible to note that the increase in particle diameter reduced the values of the standard deviations, with the maximum standard deviation being smaller than 50 N/m^2. Because for larger particle diameters air velocity did not reach a high enough value to fluidize the bed, the low values obtained for the standard deviations are explained.

For the smallest particle diameter, the fluidization regime was reached and the standard deviation data show an initial increase at an air velocity higher than 0.78 m/s, which is the minimum fluidization velocity. The standard deviation data show an oscillatory behavior for air velocities higher than this. In this region an intense mixing of particles in the bed could be visually observed, which probably prevented the formation of large particle agglomerates in this case. It can be observed in Figure 6 that minimum fluidization velocity increases with the increase in particle diameter, an expected behavior, since the larger the particle diameter, the higher the air velocity required to keep the particles suspended in the bed.

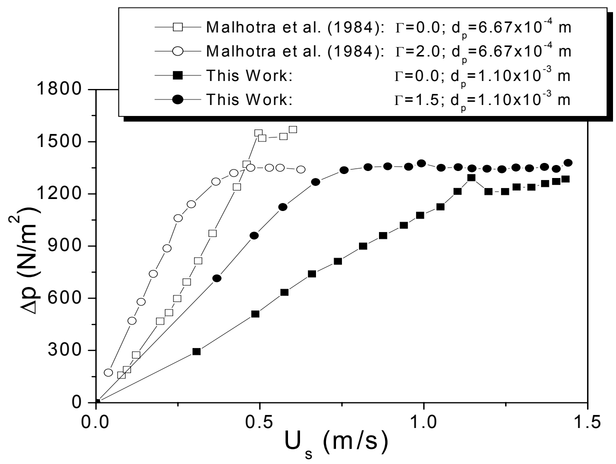


Figure 4: Pressure drop in the bed as a function of superficial air velocity; Malhotra et al. (1984): $H_0 = 0.095$ m, $X = 0.003$; this work: $H_0 = 0.080$ m, $X = 0.002$.

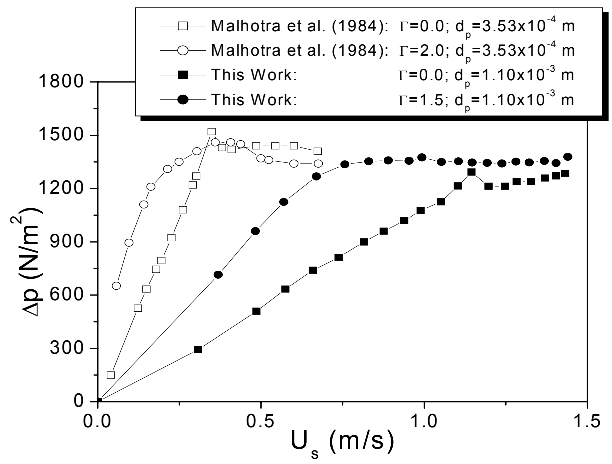


Figure 5: Pressure drop in the bed as a function of superficial air velocity; Malhotra et al. (1984): $H_0 = 0.095$ m, $X = 0.006$; this work: $H_0 = 0.080$ m, $X = 0.002$.

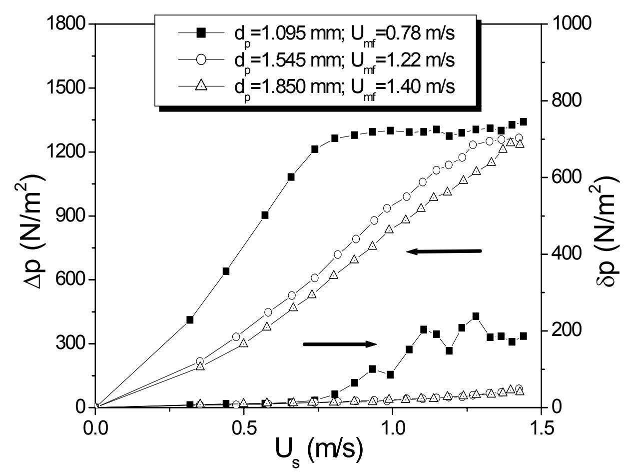


Figure 6: Pressure drop in the bed and its standard deviations as a function of superficial air velocity; $\Gamma = 0.00$; $\phi = 0.0009$.

In Figure 7 the mean values of pressure drops versus air velocity and their standard deviations for the vibrofluidized bed operating with glycerol are depicted. For all the particle diameters studied, the curves have an initial region of steep increase in the pressure drops at the lowest air velocities. As air velocity continues to be increased, the fluidized regime is reached and the pressure drops remain constant. In this case, a fluidized regime was reached for all the particle diameters. For the smallest diameter (d_p=1.095 mm) the transition between the fixed and fluidized regimes occurred at lower air velocities than for the particles with larger diameters. In the systems with vibration depicted in Figure 6, it can be noted that this transition is gradual and smooth. The pressure drops for d_p=1.095 mm are greater than those obtained for the other diameters, indicating that a more compact bed of particles was obtained. For the two largest diameters, the pressure drop curves might be described as sequences of linear sections, each one with a different slope (see Figure 7). This behavior is caused by the vibration and also by the effect of the variation in air velocity on particle dynamics, which are significant even if the particles are covered with a liquid. It can be noted from Figure 6 that the initial regions of steep increase in the pressure drops are also observed in the fluidized bed. In general, the transition from the fixed to the fluidized regime is sharp in the fluidized beds and smooth in the vibrofluidized ones.

The values for standard deviations of pressure drop are also shown in Figure 7. The values for the systems with vibration are higher than those obtained for the fluidized beds, as can be seen by a comparison with data shown in Figure 6. Vibration tends to increase the oscillation in pressure drops, resulting in higher standard deviation values. For the smallest diameter (d_p=1.095 mm), the standard deviations show an initial region of steep increase up to an air velocity of 0.46 m/s. For air velocities higher than this, the standard deviation data initially decrease and then remain almost constant for a range of air velocities from about 0.50 to 1.00 m/s. Visual observation of the flow indicated that the decrease observed in the standard deviations probably occurred due to the establishment of preferential channels for the flow and because the particles are kept suspended by the airflow, thus stabilizing the fluidization. After this region of constant values some fluctuations appear in the standard deviation values, probably caused by intensification of the fluidization. For the two largest particles, the standard deviations are smaller than those observed for the 1.095 mm particles in almost the whole range of air velocities. The curves are qualitatively similar for these particles, indicating that under these conditions the standard deviations are not affected by the increase in air velocity, probably because the effect of the mixing of particles caused by vibration is not important in these cases.

To analyze the effect of adding a specific amount of liquid on the fluid-dynamic behavior of the beds, the pressure drops and standard deviations obtained for both a fluidized and a vibrofluidized bed at different degrees of saturation are shown in Figures 8 and 9, respectively. It can be observed in Figure 8 that the increase in the saturation degrees causes a reduction in the pressure drops, but for values of ϕ higher than 0.0018, the curves are not significantly affected by the increase in ϕ. The reduction in the pressure drops observed up to ϕ=0.0018 is because, as the volume of glycerol in the bed increases, the wetted particles tend to agglomerate. Particle agglomerations generate an irregular airflow pattern due to the phenomenon of channeling, which favors the percolation of air through the bed of particles. This effect is dominant up to the point at which the air velocity is high enough to break up the agglomerates and prevents the passage of air through the preferential channels, where the curves are no longer affected by the degree of saturation. For degrees of saturation higher than 0.0018, the beds are strongly agglomerated and the curves are not affected by an increase in the values of ϕ.

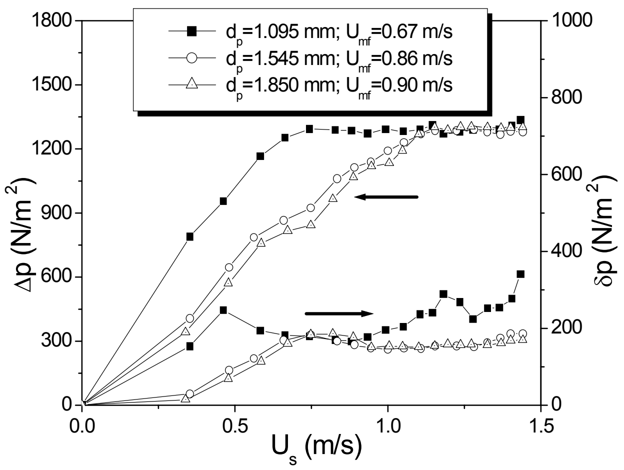


Figure 7: Pressure drop in the bed and its standard deviations as a function of superficial air velocity; Γ = 1.00; ϕ = 0.0018.

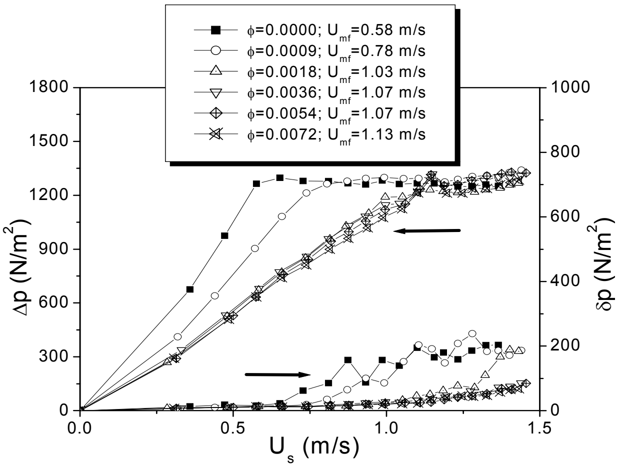


Figure 8: Pressure drop in the bed and its standard deviations as a function of superficial air velocity; $\Gamma = 0.00$; $d_p = 1.095 \times 10^{-3}$ m.

Analyzing the standard deviation curves, it can be noted that in the fixed-bed region, the curves are not affected by degree of saturation. This occurs because with the increase in the volume of glycerol in the bed, the stickiness of the particles tends to be accentuated, increasing particle agglomeration and preventing the onset of fluidization. For values of ϕ higher than 0.0018 and until an air velocity of 1.25 m/s is reached, the curves do not depend on degree of saturation, because in this range of air velocities the bed of particles is strongly agglomerated and an increase in ϕ has little effect on fluid-dynamic behavior. Therefore high air velocities are required to start the fluidized regime, extending the region of fixed-bed regime. The flow regime under this condition is characterized by poor and irregular fluidization, with the formation of channeling. For values of ϕ up to 0.0009, the curve is very similar to that obtained for the bed with no glycerol.

In Figure 9, for Γ=1.00, the behavior of the pressure drop curves obtained with glycerol are very similar to that of the curve obtained for ϕ=0.0000, indicating that vibration dominates bed dynamics, even at high degrees of saturation. Under vibrofluidized conditions, the pressure drops increase slightly as the degree of saturation increases. The increase in the volume of liquid, combined with the compacting effect of the vibration makes the percolation of air through the bed even more difficult. The slight oscillations observed in the curves for vibrofluidized beds are caused by fluctuations in the pressure drops produced by the vibration and by bubble coalescence.

A comparison of the standard deviation data shown in Figures 8 and 9 indicates that vibration (Figure 9) attenuates the effect of the degree of saturation on the curves of standard deviations of pressure drop versus air velocity.

The effect of the dimensionless vibration number, Γ, on the bed operating without glycerol is shown in Figure 10. The curves are qualitatively similar to those obtained by Bratu and Jinescu (1971). In this particular case, the variation in Γ does not significantly affect the behavior of the pressure drop versus air velocity curves, except that in vibrating beds, the regions of transition from the fixed to the fluidized regimes are smoother.

The curves in Figure 10 show that, under most conditions, the values of standard deviations increase as air velocity is increased. For dimensionless vibration numbers from 1.00 to 1.50, the standard deviation values increase as Γ is increased, particularly in the ranges of air velocities from 0.00 to 0.30 m/s and from 0.80 to 1.50 m/s. For Γ=0.50, the standard deviation curve is similar to that obtained for the fluidized bed, with an increase in behavior for the whole range of air velocities. For air velocities higher than 0.80 m/s the curves show no dependence on vibration number, because the high air velocities attenuate the effects of vibration on the bed of particles.

The behavior of the curves of pressure drops versus air velocity and standard deviation versus air velocity becomes quite different with glycerol, as can be seen in Figure 11, with data obtained for a degree of saturation of ϕ=0.0072. Contrary to what was observed in Figure 10 for the dry bed, the curve of the fluidized bed has lower values of pressure drops for the whole range of air velocities. At this degree of saturation, the action of cohesive forces results in agglomeration of particles and formation of preferential channels, which in turn results in poor and irregular fluidization. With channeling, the pressure drops in the bed are reduced. At high air velocities, the liquid bridges linking the agglomerates are broken and the fluidization regime is attained. Now, for the vibrofluidized beds, it can be seen that vibration increases the pressure drops, because under vibration the formation of channeling and bubble coalescence in the bed are hindered. Thus, more compacted beds are formed, resulting in more homogeneous fluidization and higher pressure drops. The increase in dimensionless vibration numbers from Γ=0.50 to 1.50 does not affect the curves.

Regarding the standard deviation curves (Figure 11), the shift between the curves for the fluidized and the vibrofluidized beds is larger than that observed for the systems without glycerol (Figure 10). The variation in the standard deviation values with air velocity for the fluidized bed is small, even in the fluidized regime. Again, this is caused by the poor fluidization obtained due to channeling. For the vibrofluidized beds, the standard deviations increase as the vibration number is increased, but the dependence on air velocity is weaker than that observed in the curves in Figure 10. Because the addition of liquid favors particle agglomeration, it can be observed that as air velocity is increased, the standard deviations are reduced, because the whole bed of particles is suspended by the airflow; even in the vibrating beds the formation of channeling can be observed, thus weakening the intensity of fluctuations in the flow. The oscillations observed in the curves at the highest air velocities appear due to the bubbles and clusters in the bed.

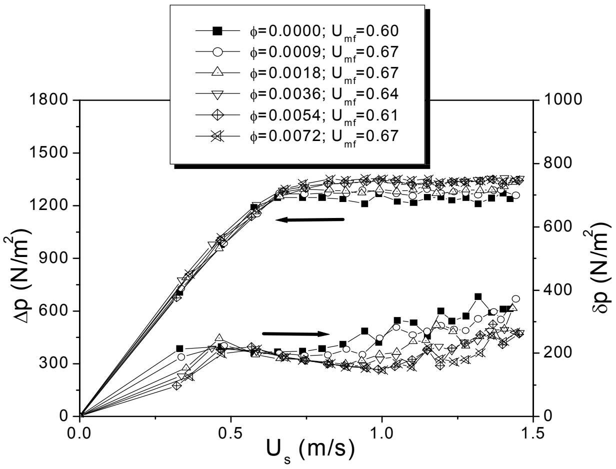


Figure 9: Pressure drop in the bed and its standard deviations as a function of superficial air velocity; Γ = 1.00; $d_p = 1.095x10^{-3}$ m.

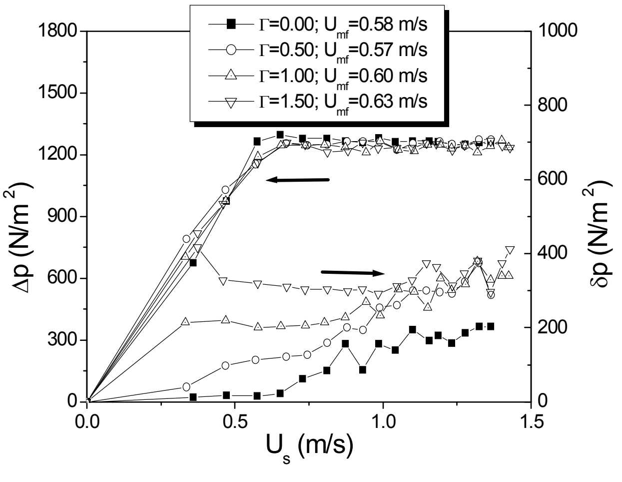


Figure 10: Pressure drop in the bed and its standard deviations as a function of superficial air velocity; ϕ = 0.0000; $d_p = 1.095x10^{-3}$ m.

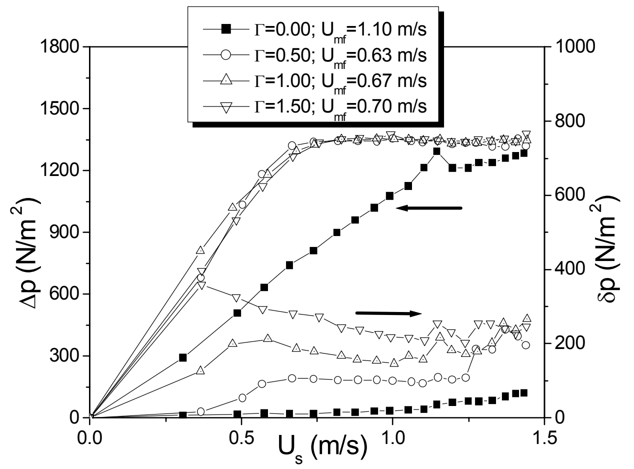


Figure 11: Pressure drop in the bed and its standard deviations as a function of superficial air velocity; ϕ = 0.0072; d_p = 1.095x10^{-3} m.

CONCLUSIONS

For both the fluidized and the vibrofluidized beds containing glycerol, the formation of particle agglomerates, which caused the formation of channeling and led to poor and irregular fluidization patterns, was usually observed. In these cases, vibration improved particle mixing and the transport characteristics, helping to break up the agglomerates and attenuating the channeling. The dependence of the pressure drops on the intensity of vibration was not significant, except in the regions of transition between the fixed and the fluidized regimes. On the other hand, the degree of saturation of liquid and particle diameter significantly affected the behavior of the pressure drop versus air velocity curves.

The variation in degree of saturation of liquid affected the fluidized and the vibrofluidized beds differently. An increase in the degree of saturation of liquid caused a reduction in the pressure drops for the fluidized beds as an effect of the poor fluidization patterns. For the vibrofluidized beds, the presence of vibration attenuated the effect of the paste and the pressure drops were not affected by the increase in degree of saturation.

A reduction in particle diameter usually caused an increase in the pressure drops, a result that agrees well with that reported by Malhotra et al. (1984).

Comparing data from this work with those reported by Malhotra et al. (1984), qualitatively similar behaviors were observed for the pressure drop versus air velocity curves. A few discrepancies observed between the results of this work and those reported by Malhotra et al. (1984) were attributed to the difference in particle diameters tested, since that author used particles of the Geldart B group, while in this work Geldart D particles were used.

Analysis of the standard deviations of the pressure drop indicated that, for either a fixed or a totally agglomerated bed, the pressure deviations were very small as a result of the air flowing through preferential channels in the bed. Under fluidization, the instabilities in the movement of particles generate fluctuations in the pressure drops, which were particularly observed at the highest air velocities and are intensified by vibration.

The results indicate that analysis of fluid-dynamic behavior in fluidized and vibrofluidized beds can be improved by the measurements in the standard deviations of pressure drop versus air velocity curves. They allow detection of changes in the bed's behavior that could not be observed by only analyzing the pressure drop versus air velocity curves. In addition, the values for standard deviations of pressure drop may provide a useful tool in the estimation of more accurate values for minimum fluidization velocities in fluidized beds (Γ=0), although further study is still needed.

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NOMENCLATURE

A	amplitude of vibration,	m

dp	mean particle diameter,	m
f	frequency of vibration,	Hz
g	acceleration of gravity,	m/s2
Us	superficial air velocity,	m/s
Umf	minimum fluidization velocity,	m/s
Umm	minimum mixing velocity,	m/s
vg	volume of glycerol,	m3
vp	pore volume in the bed,	m3
X	glycerol mass by particle mass,	-
Δp	pressure drop in the bed,	N/m2
δp	standard deviation of pressure drop in the bed,	N/m2
ϕ	degree of saturation of glycerol,	-
Γ	dimensionless vibration number,	-

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