Types of Gas Fluidization

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Summary

The behaviour of solids fluidized by gases falls into four clearly recognizable groups, characterized by density difference \( \rho_s - \rho_f \) and mean particle size. The most easily recognizable features of the groups are: powders in group A exhibit dense phase expansion after minimum fluidization and prior to the commencement of bubbling; those in group B bubble at the minimum fluidization velocity; those in group C are difficult to fluidize at all and those in group D can form stable spouted beds. A numerical criterion, which distinguishes between groups A and B has been devised and agrees well with published data. Generalizations concerning powders within a group can be made with reasonable confidence, but conclusions drawn from observations made on a powder in one group should not in general be used to predict the behaviour of a powder in another group.

1. INTRODUCTION

It is impractical for most research workers, particularly those wishing to work on a reasonably large scale, to test a wide variety of powders, as this is only one of the variables to be studied. There is therefore a tendency to assume that conclusions drawn from data on the fluidization of one powder, e.g. cracking catalyst, are applicable to other powders having quite different particle sizes and densities. This can cause confusion, and as has been shown in a recent paper\(^1\), it is responsible for some of the apparent contradictions and differences of opinion which appear in published papers.

In this paper an attempt is made to group together those powders having broadly similar properties when fluidized by a gas, so that generalizations concerning powders within a group can be made with reasonable confidence.

Although a few of the characteristics of fluidized solids are common to all groups, many are not and intergroup predictions should therefore be avoided or made only with considerable caution. A simple criterion, which differentiates between the two largest groups of powders, is presented.

2. PREVIOUS WORK

Various attempts have been made to devise a criterion which would distinguish between bubbling (aggregative, heterogeneous) and non-bubbling (particulate, homogeneous) fluidization.

Some criteria are based on the concept of interparticle forces in the vicinity of bubbles and lead to dimensionless groups such as the Froude number\(^2\) or combinations of \( Fr \) with \( Re \) and other groups\(^3\). Whilst having the advantage of simplicity, these criteria do little more than distinguish correctly between liquid and gas fluidization. Zenz\(^4\) presented an empirical graphical plot of bed voidage against \( \rho_s/\rho_f \) with particle size as a parameter which indicates that bubbling and slugging become less likely as \( \rho_s/\rho_f \) decreases.

Other criteria\(^5-7\) are based on a consideration of the stability or rate of growth of disturbances. Despite being much more complicated, they make predictions which are no more accurate than the simple Froude criterion. Two other groups\(^8,9\) of workers have assumed that bubbles are always present but are not observable below a certain bubble–particle ratio. Simpson and Rodger's\(^9\) approach offers a way of estimating the size of bubbles likely to be present in a given system at different voidages. If the calculated bubble size is very small the system is said to be particulate. Unfortunately the correlations are rather complex and have been little used. Harrison, Davidson and de Kock's\(^8\) theory is based on the maximum size of bubble likely to be stable in a fluidized system. The mechanism of bubble collapse on which the theory is
based is almost certainly incorrect but it does, like the other theories, differentiate correctly between gas and liquid fluidization. Unlike the correlation of Simpson and Rodger, which predicts that a given system can exhibit both homo- and heterogeneous behaviour depending on the voidage (and therefore on the fluid velocity), the theory of Harrison et al. merely classifies systems into bubbling, transition and non-bubbling systems. In its present form it is not able to say whether a given system can exhibit more than one type of behaviour.

The most recent approach has been that of Verloop and Heertjes\(^\text{10}\), who use the occurrence of shock waves in the bed as a criterion for the transition between bubbling and non-bubbling. Their criterion shows that some systems can behave homogeneously at low voidages and heterogeneously at high voidages. It appears to give reasonable agreement with experimental data for liquid systems but, as will be shown later, its accuracy is poor in making predictions concerning gas-solid fluidization.

It is evident from this brief survey that as yet there is no easy and accurate method for predicting how a given powder will behave when fluidized by gas.

3. DESCRIPTION OF POWDER GROUPS

Before attempting to develop a numerical criterion which can be used to predict how a given powder is likely to behave when fluidized by gas, a description of the properties of three clearly recognizable groups, and one other, will be given. This is based both on the published literature and on the present experimental work.

3.1 Group A

Materials having a small mean size and/or a low particle density (less than about 1.4 g/cm\(^3\)) generally exhibit the type of behaviour described below, some cracking catalysts being typical examples.

Beds of powders in this group expand considerably before bubbling commences\(^\text{11}\). When the gas supply is suddenly cut off the bed collapses slowly\(^\text{12}\), typically at a rate of 0.3--0.6 cm/s, this being similar to the superficial velocity of the gas in the dense phase\(^\text{13}\). Gross circulation of the powder\(^\text{14}\) (akin to convection currents in liquids) occurs even when few bubbles are present, producing rapid mixing. Bubbles in a two-dimensional bed appear to split and recocalesce very frequently. All bubbles rise more rapidly than the interstitial gas velocity, but in freely bubbling beds the velocity of small bubbles (<4 cm) appears to be about 30--40 cm/s regardless of bubble size\(^\text{15}\), suggesting that the gross circulation referred to controls the rise velocity. There is some evidence that the mean size of bubbles may be reduced in two ways, i.e. by having a wide particle size distribution and/or a small mean particle size\(^\text{16}\). A maximum bubble size does appear to exist\(^\text{11}\). Considerable back-mixing of gas in the dense phase occurs and gas exchange between bubble and dense phase is generally high\(^\text{18}\); however, the ratio (volume of cloud/volume of bubble) is negligible\(^\text{18}\). When the superficial gas velocity is sufficiently high to cause the formation of slugging conditions, the slugs produced are axi-symmetric; as the superficial gas velocity is further increased slug flow breaks down into a turbulent regime with "tongues of fluid darting zig-zag fashion up the bed"\(^\text{20}\). The velocity at which this occurs appears to decrease with particle size.

3.2 Group B

Group B contains most materials in the mean size and density ranges 40 \(\mu\text{m} < d_{\text{sv}} < 500 \mu\text{m}\), 4 g/cm\(^3\) > \(\rho_s > 1.4\) g/cm\(^3\), sand being the most typical powder. In contrast with group A powders, naturally occurring bubbles start to form in this type of powder at or only slightly above minimum fluidization velocity. Bed expansion is small and the bed collapses very rapidly when the gas supply is cut off. There is little or no powder circulation in the absence of bubbles and bubbles burst at the surface of the bed as discrete entities. Most bubbles rise more quickly than the interstitial gas velocity and bubble size increases linearly with both bed height and excess gas velocity \((U - U_0)\); coalescence is the predominant phenomenon\(^\text{21}\). There is no evidence of a maximum bubble size, although few studies\(^\text{22}\) have involved beds sufficiently deep or large enough to allow bubbles to reach the maximum size predicted by theory\(^\text{9}\). It has been shown recently\(^\text{1}\) that when comparisons are made at equal values of bed height and \(U - U_0\), bubble sizes are independent of both mean particle size and size distribution. Back-mixing of dense phase gas is relatively low as is gas exchange between bubbles and dense phase; the cloud volume/bubble volume ratio is generally not negligible. When the gas velocity is so high that slugging commences, the slugs are initially axi-symmetric, but with further increase in gas velocity an increasing proportion become asymmetric, moving up the bed wall with an enhanced velocity rather than up the tube axis. There is no evidence of the breakdown of slugging into turbulent flow\(^\text{20}\).
A numerical method for distinguishing powder groups will be discussed later, in Section 4.3.

3.3 Group C

Powders which are in any way cohesive belong in this category. "Normal" fluidization of such powders is extremely difficult; the powder lifts as a plug in small diameter tubes, or channels (rat-holes) badly. \( i.e. \) the gas passes up voids extending from distributor to bed surface. This difficulty arises because the interparticle forces are greater than those which the fluid can exert on the particle, and these are generally the result of very small particle size, strong electrostatic charges or the presence in the bed of very wet or sticky material. Particle mixing and consequently heat transfer between a surface and the bed is much poorer\(^{23}\) than with powders of groups A or B.

Fluidization can generally be made possible or improved by the use of mechanical stirrers\(^{24}\) or vibrators which break up the stable channels, or, in the case of some powders, by the addition of a fumed silica of sub-micron size. Where agglomeration occurs due to excessive electrostatic charging some improvement can generally be effected by humidification of the incoming gas, or by making the equipment walls conducting, for example, by coating glass with a very thin layer of tin oxide\(^ {25}\). An equally effective but less permanent technique is to coat the particles with a conducting substance such as graphite\(^ {26}\).

3.4 Group D

The justification for this further category of powders, confined to large and/or very dense particles, is not so readily apparent as in the other three cases since relatively little published information is available\(^ {27,28}\).

Certainly all but the largest bubbles rise more slowly than the interstitial fluidizing gas, so that gas flows into the base of the bubble and out of the top, providing a mode of gas exchange and by-passing different from that observed with group A or B powders. The gas velocity in the dense phase is high, solids mixing relatively poor; consequently back-mixing of the dense phase gas is small. The flow regime around particles in this group may be turbulent, causing some particle attrition with rapid elutriation of the fines produced\(^ {29}\). Relatively sticky materials can be fluidized since the high particle momentum and fewer particle-particle contacts minimize agglomeration. There is some evidence that bubble sizes may be similar to those in group B powders at equal values of bed height and \( U - U_0 \) but that bubble formation does not commence until about 5 cm above the distributor\(^ {30}\). However, it does appear that if gas is admitted only through a centrally positioned hole, group D powders can be made to spout.

4. CRITERIA FOR CLASSIFYING POWDERS INTO GROUPS

4.1 The bubble point

The most easily observed difference between powders in groups A and B is whether or not the bed bubbles at or very close to minimum fluidization. If there is an appreciable bed expansion before bubbling commences, then the powder belongs to group A and is likely to have the other properties associated with that group. Calling the superficial gas velocity at which the first bubble appears \( U_{MB} \), the minimum bubbling point, we can define group A powders as those in which \( U_{MB}/U_0 > 1 \). Correlations for \( U_0 \) are well established, but the only simple and accurate correlation for \( U_{MB} \) available is that published in brief by the writer\(^ {31} \) in 1967, which is now discussed in a revised form.

4.2 Experimental work

Three low density powders were used: fresh and spent cracking catalyst, and Diakon, a plastic moulding powder having spherical particles. All had a wide size distribution as received. The powders were carefully separated by sieving into the size fractions shown in Table 1. Each fraction was sized by performing a microscope count of at least 650 particles per fraction. A 5-cm-diam. glass column having a filter paper distributor was used to fluidize 200-g powder fractions, giving bed heights of approximately 20 cm. The minimum fluidization velocity was measured in the usual way using the pressure drop-gas velocity curve\(^ {11} \) and the air velocity increased until the first clearly recognizable bubble, usually about 0.5 cm diam., was observed to break the surface of the bed. This velocity was noted. Further increase in air velocity caused many bubbles and the air flow was then reduced until only one or two small bubbles were visible; this velocity was also noted. This procedure was repeated several times for each fraction and an average value of the minimum bubbling velocity was then calculated. The results are presented in Table 1.
### TABLE 1

Experimental results on Group A powders

<table>
<thead>
<tr>
<th>Powder</th>
<th>Nominal size range (μm)</th>
<th>Actual size (μm)</th>
<th>$U_0$ (cm s$^{-1}$)</th>
<th>$U_{MP}$ (cm s$^{-1}$)</th>
<th>$e_{MB}$</th>
<th>$H_{MB}$</th>
<th>$H_0$</th>
</tr>
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<tbody>
<tr>
<td>Diakon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho_s = 1.18$ g cm$^{-3}$</td>
<td>105–125</td>
<td>118</td>
<td>0.82</td>
<td>1.17</td>
<td>0.496</td>
<td>1.065</td>
<td></td>
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<tr>
<td></td>
<td>125–150</td>
<td>141</td>
<td>0.96</td>
<td>1.34</td>
<td>0.481</td>
<td>1.040</td>
<td></td>
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<tr>
<td></td>
<td>150–180</td>
<td>155</td>
<td>1.43</td>
<td>1.60</td>
<td>0.465</td>
<td>1.012</td>
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<tr>
<td></td>
<td>180–210</td>
<td>190</td>
<td>2.44</td>
<td>2.51</td>
<td>0.452</td>
<td>1.003</td>
<td></td>
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<tr>
<td></td>
<td>210–250</td>
<td>220</td>
<td>3.11</td>
<td>3.11</td>
<td>0.444</td>
<td>1.000</td>
<td></td>
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<tr>
<td></td>
<td>250–300</td>
<td>263</td>
<td>4.11</td>
<td>4.11</td>
<td>0.444</td>
<td>1.000</td>
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<tr>
<td></td>
<td>300–350</td>
<td>318</td>
<td>6.45</td>
<td>6.45</td>
<td>0.444</td>
<td>1.000</td>
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<tr>
<td>Fresh catalyst</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>$\rho_s \approx 1.0$ g cm$^{-3}$</td>
<td>10–20</td>
<td>25</td>
<td>0.08</td>
<td>0.25</td>
<td>0.645</td>
<td>1.43</td>
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<tr>
<td></td>
<td>20–30</td>
<td>39</td>
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<td></td>
<td>45–53</td>
<td>53</td>
<td>0.23</td>
<td>0.59</td>
<td>0.645</td>
<td>1.28</td>
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<tr>
<td></td>
<td>53–63</td>
<td>68</td>
<td>0.29</td>
<td>0.68</td>
<td>0.645</td>
<td>1.21</td>
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<td></td>
<td>63–75</td>
<td>75</td>
<td>0.33</td>
<td>0.73</td>
<td>0.638</td>
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<td></td>
<td>75–90</td>
<td>100</td>
<td>0.46</td>
<td>0.90</td>
<td>0.627</td>
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<td></td>
<td>90–105</td>
<td>108</td>
<td>0.44</td>
<td>0.93</td>
<td>0.630</td>
<td>1.19</td>
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<tr>
<td></td>
<td>as received</td>
<td>65</td>
<td>—</td>
<td>0.64</td>
<td>0.630</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>Spent catalyst</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho_s \approx 1.5$ g cm$^{-3}$</td>
<td>−45</td>
<td>45</td>
<td>0.13</td>
<td>0.51</td>
<td>0.675</td>
<td>1.41</td>
<td></td>
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<tr>
<td></td>
<td>45–53</td>
<td>62</td>
<td>0.18</td>
<td>0.60</td>
<td>0.630</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>53–63</td>
<td>75</td>
<td>0.22</td>
<td>0.68</td>
<td>0.635</td>
<td>1.31</td>
<td></td>
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<tr>
<td></td>
<td>63–75</td>
<td>87</td>
<td>0.26</td>
<td>0.73</td>
<td>0.600</td>
<td>1.25</td>
<td></td>
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<tr>
<td></td>
<td>75–90</td>
<td>95</td>
<td>0.35</td>
<td>0.82</td>
<td>0.610</td>
<td>1.18</td>
<td></td>
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<td></td>
<td>90–105</td>
<td>115</td>
<td>0.4</td>
<td>0.84</td>
<td>0.610</td>
<td>1.14</td>
<td></td>
</tr>
</tbody>
</table>

#### 4.3 Criterion for groups A and B

It is interesting to note that the two largest sizes of Diakon bubbled at the incipient fluidization velocity and the 210–250-μm fraction at a velocity very close to $U_0$. According to the criterion ($U_{MB}/U_0 > 1$ for group A powders) these largest fractions should be classified as belonging to group B.

When the minimum bubbling velocities of all the other fractions, as well as that of the wide size range fresh catalyst (i.e. all the group A powders), are plotted against mean particle size $d_{SV} (=1/\Sigma x/d_{SV})$ it can be seen (Fig. 1) that a very simple relationship exists between $U_{MB}$ and $d_{SV}$, namely

$$U_{MB} = K_{MB} d_{SV} \tag{1}$$

$k_{MB}$, which has units of s$^{-1}$, has a value of 100 when $U_{MB}$ is in cm s$^{-1}$ and $d_{SV}$ in cm. Thus

$$U_{MB} = 100 d_{SV} \tag{2}$$

Some data of Davies$^{11}$, Godard$^{15}$, de Jong$^{35}$ and Rietema$^{32}$ are also represented well by eqn. (2). Data fit equally well whether derived from narrow cuts or wide size range material.

It is curious that the bubble point can be correlated by means of an equation which involves a term ($K_{MB}$) having units of frequency. Hiby$^{33}$ has noted
that gas-fluidized beds of low height show a tendency to spontaneous vertical oscillation of the particles with frequencies in the range 7–25 s⁻¹. He suggested that this might act as a triggering mechanism for bubble formation, and at first sight this seems a plausible explanation for the frequency term in the bubble point equation. However, as Hiby's experimentally measured frequencies were considerably lower than 100, we shall not pursue this line of thought further. We are pleased that such a simple equation describes the experimental data so well and shall proceed to use it.

Let us replot eqn. (2) on log-log paper (line MB, Fig. 2) together with an equation for the minimum fluidization velocity¹¹

\[ U_0 = \frac{8 \times 10^{-4} g d_{SV} (\rho_s - \rho_t)}{\mu} \]  

(3)

using two selected values of \( \rho_s - \rho_t \) and \( \mu \) for air at room temperature.

Consider particles of density difference 1 g cm⁻³ and mean particle size 100 μm. Entering the graph at the left along the 100-μm line we strike first the theoretical minimum fluidization velocity for these particles at 0.43 cm s⁻¹ and then the minimum bubbling point velocity at 1 cm s⁻¹, giving a value of \( U_{MB}/U_0 = 2.33 \) indicating a bubble-free expansion region and a group A powder. In contrast 100-μm sand (\( \rho_s = 2.7 \) g/cm⁻³) has a \( U_0 \) of 1.2 cm s⁻¹, which is larger than the bubbling velocity of 1 cm s⁻¹. It will therefore bubble at minimum fluidization and fall into group B as will particles of density difference 1 g cm⁻³ larger than about 250 μm.

Thus for a powder to belong to group A,

\[ \frac{U_{MB}}{U_0} \geq 1 \]  

(4)

Substituting in this equation from eqns. (1) and (3) we have the following criterion:

For a powder to belong to group A,

\[ \frac{8 \times 10^{-4} g d_{SV} (\rho_s - \rho_t)}{K_{MB} \mu} \leq 1 \]  

(5)

Now for air at room temperature and pressure \( K_{MB} = 100 \) and \( \mu = 1.8 \times 10^{-4} \) poise. Replacing \( d_{SV} \) (cm) by \( d' \) (the particle size in μm) we have

\[ (\rho_s - \rho_t) d' \leq 225 \]  

(6)

Equation (6) has been plotted on Fig. 3 as XY together with particle density/mean size data from a wide variety of authors who have commented on the behaviour of the powders with which they worked. The open points represent powders which the authors remarked were extremely difficult to fluidize (group C), the half-closed points represent powders where bubble-free bed expansion was noted (group A) and the solid points where it was specifically mentioned that bed expansion was low and/or bubbling occurred at or very close to minimum fluidization velocity. The division between groups C and A is represented by the shaded area PQ which has been drawn so as to separate empirically open and half-closed points.

### 4.4 Criterion for groups B and D

The distinction between groups B and D is not as clear-cut as that between A and B, but it can be made on two grounds, one theoretical, one empirical. The first criterion is based on the different mode of gas by-passing described in Section 3.4.

We can calculate the density/particle size combinations of powders in which bubbles less than a given size would rise more slowly than the interstitial gas velocity by using eqn. (7):

\[ \left( \frac{g d_{pB}}{2} \right)^{\frac{1}{2}} \leq \frac{8 \times 10^{-4} (\rho_s - \rho_t) g d_{SV}}{\mu e_0} \]  

(7)

It is clear that when considering groups B and D we are really looking at a continuum, and it is not diffi-
cult to envisage a transition within a large deep fluidized bed in which, near the distributor, small bubbles travel more slowly than the interstitial gas and faster than the interstitial gas velocity higher up the bed.

Bubble sizes greater than 25 cm have rarely been reported, so let us choose $d_B = 25$ cm. The choice is not critical since in eqn. (7) we are considering $\sqrt{d_B}$. For large-particle systems $d_B \approx 0.4$ and for air $\mu = 1.8 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$. If we insert these numerical values and substitute $d'$ (μm) for $d_{SV}$ (cm) we obtain, for group D,

$$ (\rho_f - \rho_i)(d')^2 \geq 10^6 $$

The use of eqn. (3) on the right-hand side of eqn. (7) is not strictly justified for these large particles since the flow regime is transitional, not laminar. However, the arbitrary (though reasonable) choice of $d_B$ and the nature of the other assumptions do not warrant the adoption of a more complicated (though more accurate) equation for $U_0$.

The second possible criterion is based on a recent suggestion from Baeyens$^{37}$ that group D powders are capable of maintaining a stable spout in a bed more than 30 cm deep. Experimental investigations are in progress on this and will be reported in due course, but for the present, the density–size combinations of powders which have been reported as spoutable$^{38}$ are shown on Fig. 3 as crosses. It can be seen that, with the exception of the 350-μm powder (reported to be the smallest size ever spouted), the crosses fall near or to the right of the line. This does give some validity to eqn. (8).

5. COMMENTS ON THE CRITERIA

It can be seen from Fig. 3 that eqn. (6) does represent a realistic boundary between groups A and B for ambient conditions. However, further data are required in selected areas—notably high-density small particles and low-density large particles. It is particularly desirable to choose series of size fractions which cross over the line representing eqn. (6). This was achieved with Diakon and it was possible to demonstrate that, depending on mean size, the material could behave either as group A or B (Table 1). There is probably also a gradual change in properties across group A. For example, experimental evidence (Table 1 and refs. 11 and 15) suggests that as we move diagonally away from XY towards the left, the maximum dense phase expansion $e_{MB}$ increases.

5.1 Effects of gas density and viscosity

Godard and Richardson$^{15}$ showed that an increase in pressure, and therefore of gas density, increased the minimum bubbling velocity. Although
there are too few results available to correlate their data, the overall effect must be to increase the magnitude of \( K_{MB} \) in eqn. (5). This increases the size of the constant on the right-hand side of eqn. (6) and thus moves \( XY \) (Fig. 3) to the right. An increase in pressure could therefore have two effects:

(a) Some powders which have group B properties in air at ambient pressure and temperature may now behave as members of group A.

(b) Those already in group A could now behave as though they have a smaller size and density since their distance from \( XY \) has been increased, i.e. they may exhibit increased bed expansion and the transition from slug flow to turbulent fluidization could now occur at a lower velocity, giving the appearance of smoother fluidization.

It has been reported by several workers that operation at higher pressure on an industrial scale produces smoother fluidization and less slugging. It may be significant that the powder used by Lee et al. (240 \( \mu \)m, \( \rho_s = 0.9 \text{ g cm}^{-3} \)) falls very close to the line \( XY \) at ambient conditions.

Equation (5) predicts that an increase in viscosity alone should also move \( XY \) to the right and produce similar improvements in fluidization. However, some caution is needed before this is accepted at its face value, because the effect of changing only viscosity is not easy to study. The viscosity of a gas can be changed in two ways—by using a different gas and/or by increasing the temperature—but both methods normally also involve changing the gas density. As far as is known, the effect on the minimum bubbling velocity of changing viscosity alone has not been studied nor has the effect of operating at low gas densities (i.e. reduced pressure). It is therefore difficult to decide whether or not operation at high temperature would produce a net movement of \( XY \) to the right, since although the gas viscosity would increase, we do not know the effect on \( K_{MB} \) of simultaneously reducing the gas density, this being another area for further research.

5.2 Comparison with other criteria

It is possible to compare two other criteria with the one already presented and expressed as eqn. (5). Verloop and Heertjes suggest that heterogeneous (i.e. bubbling) fluidization will occur immediately if

\[
\frac{(gd^3)(\rho_s - \rho_t)}{\mu} > 5000
\]

Oltrogge finds that his data correlate with the same group on the left-hand side of eqn. (9), but that for bubbling at \( U_0 \),

\[
\frac{(gd^3)(\rho_s - \rho_t)}{\mu} > 400
\]

Using the nomenclature of powder groups given earlier, it is apparent that eqns. (9) and (10) could also be used to identify group B powders. Obviously both cannot be correct, and in fact that of Verloop and Heertjes lies much too far to the right and is not shown on Fig. 3. Equation (10), however, (line O-O on Fig. 3) agrees with published results about as well as eqn. (5), and this is most interesting since the thinking behind eqn. (5) is quite different from that leading to eqn. (10).

CONCLUSIONS

(1) The behaviour of powders fluidized by gases falls into four categories characterized by density difference (\( \rho_s - \rho_t \)) and mean size. Powders in group A exhibit dense phase expansion after minimum fluidization and prior to the commencement of bubbling; those in group B bubble at the minimum fluidization velocity; those in group C are difficult to fluidize at all and those in group D are of large size and/or density and spout readily.

(2) A criterion which distinguishes between groups A and B has been devised and is shown to agree well with published data. It also predicts that a change in pressure and/or gas viscosity may cause a change in the behaviour of particles. A tentative criterion is also suggested for group D.

LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d' )</td>
<td>particle size in microns (( \text{cm} \times 10^4 ))</td>
</tr>
<tr>
<td>( d_{SV} )</td>
<td>surface/volume diameter of particle (cm)</td>
</tr>
<tr>
<td>( d_B )</td>
<td>frontal diameter of bubble (cm)</td>
</tr>
<tr>
<td>( g )</td>
<td>gravitation constant (981 cm s(^{-2}))</td>
</tr>
<tr>
<td>( K_{MB} )</td>
<td>constant in eqn. (1) (s(^{-1}))</td>
</tr>
<tr>
<td>( U_0 )</td>
<td>superficial velocity of gas at minimum fluidization (cm s(^{-1}))</td>
</tr>
<tr>
<td>( U_{MB} )</td>
<td>superficial velocity of gas at minimum bubbling condition (cm s(^{-1}))</td>
</tr>
<tr>
<td>( x )</td>
<td>weight fraction of particles in each size range</td>
</tr>
<tr>
<td>( \varepsilon_0 )</td>
<td>bed voidage at minimum fluidization velocity</td>
</tr>
<tr>
<td>( \mu )</td>
<td>viscosity of fluidizing gas (g cm(^{-1}) s(^{-1}))</td>
</tr>
<tr>
<td>( \rho_t )</td>
<td>density of fluidizing gas (g cm(^{-3}))</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>density of particle (including any internal porosity) (g cm(^{-3}))</td>
</tr>
</tbody>
</table>
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