A Model of Attrition in the Jetting Region of Fluidised Beds

M. Ghadiri and R. Boerefijn
Department of Chemical and Process Engineering
University of Surrey*

Abstract
Attrition causes material loss and environmental hazards in powder processing. In fluidised beds, the jetting region is the main contributor to attrition. The present paper reviews the recent investigations of the effects of the interaction between single particle properties and jet hydrodynamics. A model of attrition in the jetting region of fluidised beds is presented, based on the impact attrition propensity of single particles and on modelling of the particle flow patterns in the jetting region. The experimental work, carried out for the purpose of evaluation of the model, focused especially on the effects of orifice gas velocity and diameter. The experiments involve measurements of impact attrition of single particles and measurements of particle velocities and solids concentrations in fluidised bed jets. The test materials are fluid cracking catalyst and common salt, both representatives of widely used classes of composite and crystalline materials, respectively. Significant effects of orifice gas velocity and diameter were predicted, which corroborated the experimental data. Hence, the model successfully establishes a link between single particle properties and bulk behaviour in a fluidised jet.

1. Introduction
Attrition, the unintentional breakage of particulate solids during processing, handling and storage, causes material loss and environmental hazards. Fluidised bed operations have become increasingly popular in industrial particle processing, for the ease of solids handling, mixing and high rates of heat and mass transfer. These features are desirable for a number of processes, such as drying and reactor systems, e.g. fluid catalytic cracking and combustion. Unfortunately, the intensive particle motion in fluidised beds causes attrition at the same time. For example, material loss in fluidised catalytic cracking units can amount to several tonnes per day! Zenz and Kelleher [1] have identified the distributor region and the cyclone as important sites for attrition due to the presence of high local velocity gradients. The distributor region provides by far the largest contribution to attrition in fluidised beds, when compared to the bubbling bed and the freeboard above it. Several studies have been undertaken in the past to characterise the attrition propensity of particles in fluidised beds [2], but few take account of the material properties of particles, or attempt to decouple the interacting hydrodynamic parameters. The dependence of the attrition rate in the jet region on the design and operating parameters, such as the distributor orifice size and gas velocity, and particle size and properties has so far not been established satisfactorily.

A number of empirical correlations for the rate of attrition in fluidised beds, $R_a$, have been reported in the literature. These are summarised in Table 1. Focusing on two main design and operation parameters, the orifice size, $d_{or}$, and the gas velocity, $u$, the correlations are generally written in the form of a power law:

$$R_a \propto u^n d_{or}^h$$

(1)

where $u$ can be the orifice gas velocity ($u_o$), or the superficial ($u_g$) or excess gas velocity ($u_g - u_{mf}$), with values of $n$ ranging from 0.66 to 5.8 and of $h$ from 0 to 1.11, as reported by different authors. The exponential correlation of Lin et al. [6] appears to be an exception to this general form, but reploting their data shows that there is no need for an exponential correlation, and that a good fit is also achieved with a linear regression. Notwithstanding this basic similarity, each of these correlations has been obtained for different materials, experimental set-up and ope-
Table 1. Overview of studies of fluidised bed attrition

| Authors          | Modelling Equation | Dim. of | Modelling | Material | Time of Operation (hr) | Range of \((u_a-u_m)\) (m s\(^{-1}\)) | Range of \(u_a\) (m s\(^{-1}\)) | Grid Type | Background Fluidisation | Attrition Debris Criterion |
|------------------|--------------------|---------|-----------|----------|------------------------|---------------------------------|--------------------------------|-----------|------------------------|---------------------------|
| Blinichev et al. [3] | \(R_s = \frac{90 \varphi \beta \sqrt{\frac{L_3}{m_3}}}{d_v^{1.3} \sigma_\varphi \beta_{0.3}} \) \(r^{0.8}\) | 3-5 mm NaCl, 3-5 mm nitrolosk, 3-5 mm silica gel | 1 | 0.11 | 20-240 | None | Elutriate |
| Merrick and Highley [4] | \(R_s = C M_1 (u_a-u_m)\) | kg s\(^{-1}\) | 3 types of coal 1.59 and 3.18 mm diameter | 100 | 0.67 | not indicated | not indicated | 0.67 | 0.24 m s\(^{-1}\) | Elutriate (smaller than 63 \(\mu\)m) |
| Chen et al. [5] | \(R_s = C \rho_i Q \left(\frac{2}{d_v} \varphi_{m}\right) f \left(d_v \varphi_{m}\right)\) \(\left(1-\varphi_{m}\right) f \left(1-\frac{d_v}{d_p}\right)\) | kg s\(^{-1}\) | 115-274 \(\mu\)m siderite iron ore and 210 \(\mu\)m lignite char | up to 24 | 0.2-0.5 | up to 300 | 1.47 | 3.18 mm single jet in porous plate | Variable |
| Lin et al. [6] | \(R_s = C \exp \left(0.162 (u_a-u_m)\right)\) | kg s\(^{-1}\) | mixtures of 133-354 \(\mu\)m silica sand and 10-113 mm char | 5 | 0.1-0.32 | up to 53.5 | 492 holes 0.24 cm wide in triangular pitch | None | Elutriate |
| Zenz and Kelleher [1] | \(R_s = C (u_a \cdot \varphi_{m}) \sqrt{d_v} \frac{d_v^2}{4}\) | kg s\(^{-1}\) | 200 mm FCC | 12-80 | not indicated | 33-303 | Downward pipe holes 0.8-19 mm wide | Variable | Elutriate |
| Donsi et al. [7] | \(R_s = C (u_a \cdot \varphi_{m}) \frac{W_1}{d_v}\) | kg s\(^{-1}\) | 0.4-3.0 mm coal in 0.2-1.0 mm sand | not indicated | 0.55-1.3 | 82-135 | 76 upward pipe holes, 1.5 mm wide | None | Elutriate and bed inventory |
| Kono [8] | \(R_s = C \rho_i \left(\frac{2}{d_v} \varphi_{m}\right)^{1.65}\) for \(u_a \leq 3.6\) m s\(^{-1}\) | kg s\(^{-1}\) | 0.97-4.00 mm Mullite Alumina-Silicates | 8-12 | 0.45-8.0 | 0.5-30 | 3.6-15.5 cm single tapered jet | None | Elutriate (smaller than 88 \(\mu\)m) |
| Sishtla et al. [9] | \(R_m = 1.6 \cdot 10^{-3} (u_a-u_m)^{0.96} (HGL)^{0.05}\) | km | 500-841 \(\mu\)m char | 14 | 0.3-0.6 | 67-134 | 6 bubble caps with 3 orifices, 0.24 cm wide, 30° downward | None | Elutriate and bed inventory (smaller than 500 \(\mu\)m) |
| Sevilla et al. [10] | \(R_s = C (u_a \cdot \varphi_{m})\) | kg s\(^{-1}\) | 1.18-2.80 mm sand agglomerates | up to 0.25 | 0.15 | 74-111 | 139 holes, 1.3 mm wide on 12 mm triangular pitch | None | Elutriate |
| Werther and Xi [11] | \(R_s = C \rho_i \left(\frac{2}{d_v} \varphi_{m}\right)^{1.3}\) | kg s\(^{-1}\) | 106 \(\mu\)m spent FCC, 125 \(\mu\)m fresh FCC | up to 260 | 0.2 | 25-100 | 0.5-2.0 mm single jet in porous plate | Variable | Elutriate (smaller than 35-35 \(\mu\)m) |
| Ghadiri et al. [12-15] | \(R_s = C u_a^{0.6} d_v^{0.5}\) \(h^{0.6}\) | kg s\(^{-1}\) | 425-600 \(\mu\)m NaCl, 90-106 \(\mu\)m FCC | 10-22 | 0.8-8.5 | 25-125 | 73, 110 and 375 mm holes in triangular pitch | None | Elutriate (all smaller than 355 \(\mu\)m FCC, all smaller than 75 \(\mu\)m) |
In this work, the attrition of common salt and fluid cracking catalyst (FCC) is considered, focusing in particular on the link between single particle properties and bulk attrition behaviour. These two material types, in addition to their own significance, may be considered as representatives of large classes of widely used materials, i.e. crystalline and composite structures. In this paper, the modelling approach will first be described. The experimental work supporting the development of the model is then presented.

2. Modelling Approach

In the present modelling approach, the impact breakage of single particles is coupled with a hydrodynamic model to predict the rate of attrition. The structure of the approach is represented schematically in Figure 1.

For impact attrition, Zhang and Ghadiri [16] have proposed the following correlation for the extent of attrition upon impact, $R_i$, based on the fracture mechanics of lateral crack formation:

$$ R_i = \alpha \frac{\rho_p u_i^2 H d}{K_c^2} $$

where $\rho_p$ is the particle density, $u_i$ the impact velocity, $H$ the hardness, $K_c$ the fracture toughness, $d$ a linear dimension of the particle, and $\alpha$ is a proportionality constant to be determined experimentally.

In practice, the value of the power index of $u_i$ may differ slightly from 2, depending on the complexity of the particle structure. It is therefore more general to consider:

$$ R_i \propto u_i^{2m} $$

where the power index $m$ may be obtained from particle impact tests.

In a fluidised bed with a jetting distributor region, the contribution of the bubbling zone to the attrition rate is usually very small compared to that of the jetting region [13]. The attrition mechanism in a fluidised bed jet involves the entrainment of particles into a dilute jet core, followed by the acceleration of the particles, whereafter they impact on the dense phase on top of the jet. Intense interparticle collisions are considered to cause attrition, at a rate that can be estimated from impacts of single particles on a rigid target, at an impact velocity, $u_i$, corresponding to the particle velocity, $u_p$, in the jet.

The number of particles engaged in the attrition process scales with the rate at which solids become entrained from the bulk into the dilute jet core. A hydrodynamic model may be used to obtain the dependence of $W_s$ and $u_p$ on the orifice gas velocity. This can be done by power-law correlations [12]:

$$ u_p \propto u_o^l $$

$$ W_s \propto u_o^k $$

Ghadiri et al. [12] proposed that the attrition rate in the jetting region is linearly related to the single particle impact attrition and the solids entrainment rate. Thus, substituting Eq. (4) into Eq. (3), and multiplying by the solids entrainment rate, $W_s$, the attrition rate in a single jet may be given as:

$$ R_a \propto W_s R_i \propto u_i^k u_p^m \propto u_o^{k + lm} $$

In this way, a descriptive and predictive model is established, which incorporates the single particle attrition characteristics. The results of this approach will be presented in section 4.

The dependence of the attrition rate $R_a$ on the orifice size, as reported in the literature, is inconsistent. The power index $h$ in Eq. 1 given by Kono [8] and Ghadiri et al. [15] is of order unity, between 0.44 and 1.11. For comparison with other correlations that are expressed in different dimensions, e.g. those of Werther and Xi [11], and Zenz and Kelleher [1], it is necessary to normalise the correlations, e.g. by dividing the rate of attrition by the mass flow rate of fluidising gas. Following this approach, the correlations of Werther and Xi [11] and Zenz and Kelleher [1] indicate that the attrition rate does not depend on the orifice size.

For the analysis of the effect of the orifice size
of the attrition rate $R_a$, Ghadiri et al. [15] have employed a similar approach as described above for the effect of orifice gas velocity. Normalising the solids entrainment rate with respect to the gas flow rate, $W_s$, its dependence on the orifice diameter, $d_{or}$, can be expressed in a power law [15]:

$$W_s / W_g \propto d_{or}^2$$  \hspace{1cm} (7)

and similarly for the dependence of the particle velocity:

$$u_p \propto d_{or}^1$$  \hspace{1cm} (8)

Following the same approach as for the effect of velocity (Eq. 6), the attrition rate in the jet can expressed as:

$$R_a \propto (W_s / W_g) R_i \propto d_{or}^s u_p^m \propto d_{or}^s + t^m$$  \hspace{1cm} (9)

Thus, the dependence of the attrition rate on the orifice size can be established by quantifying the power indices. This is described in section 4.

Independent studies of the hydrodynamics of fluidised bed jets by Massimilla and co-workers, firstly introduced by De Michele et al. [17], have provided comprehensive models of particle flow patterns in the jetting region [18]. With these hydrodynamic models, particle velocities and solids entrainment rates can be readily obtained for different orifice velocities and sizes. However, the application of these models requires knowledge of the relevant input parameters, describing the jet geometry, such as the jet penetration length, the jet divergent angle, and the solids concentration in the jet. These have to be obtained from separate experiments, which are described in sections 3.2 and 3.3.

3. Experimental

Several tests have been employed in the evaluation of the jet attrition model. The experiments involve firstly single particle impact tests for the determination of the impact attrition of single particles as a function of the impact velocity, as shown in Eq. 2. This is described in section 3.3. Secondly, the attrition rate in a fluidised bed with several gas distributors has been measured in order to compare these results with predictions from the attrition model. This is described in section 3.2. In order to quantify the power indices given in equations (6) and (9), it is first necessary to specify a number of hydrodynamic parameters, such as the jet angle.

This is described in section 3.3.

3.1 Single particle impact test

Single particle impact tests have been carried out in an impact test rig developed previously [19] and shown in Figure 2. It consists of a funnel-shaped inlet section guiding the particles into an eductor tube, which ends in a collection chamber, where particles impact on a rigid horizontal target plate made of sapphire. The particle velocity before impact is measured with dual light diodes or with a laser Doppler velocimeter.

The impact product is analysed gravimetrically. As a criterion for attrition, the mass of debris passing through a sieve, with a size of two BS410 sieve sizes below the lower limit of the original size, is chosen. In the low range of impact velocities, where mainly surface damage (chipping) occurs, the fines produced will be far smaller than the original mother particles. Cleaver et al. [20] have shown that the attrition results are in this case insensitive to the specific criterion applied, as long as the sieve size, used for the separation of debris from the mother particles, lies in between the particle size distributions of the Fine Product and Coarse Product, as shown schematically in Figure 3. The attrition rate is then simply defined as the ratio of the mass of fine product to the initial sample mass of mother particles:

$$R_i = \frac{M_{\text{fine product}}}{M_{\text{mother particles}}}$$

Fig. 2 Air eductor single particle impact rig.
3.2 Fluidised bed attrition test

Fluidised bed attrition tests have been carried out for the determination of the variation of attrition with orifice gas velocity and size.

Two materials have been investigated, Pure Dried Vacuum (PDV) NaCl salt, produced by ICI plc, mean particle size $d_p = 418 \mu m$, with a density of 2180 kg m$^{-3}$, and FCC, $d_p = 106 \mu m$, with a density of 1500 kg m$^{-3}$. For FCC, the data of Werther and Xi [11] were used. The experimental set-up used for fluidised bed attrition tests of salt is shown in Figure 4. A detailed description can be found elsewhere [13]. Three different perforated plate distributors were used, with 73, 110, and 175 holes of 1 mm diameter, i.e. each with a different free area. This enabled the decoupling of the effect of superficial and orifice gas velocity on the attrition rate, since the bed could be operated at the same superficial velocity for three different orifice gas velocities. According to the correlation of Fakhimi and Harrison [21], all grid holes were active in all conditions, so that good distribution of air across the distributor was ensured.

The contributions of the jetting region and of the bubbling part of the bed to the attrition rate have been decoupled by operating the bed at different loading, yielding different bed heights. By plotting the attrition rate against bed height and extrapolating to a height equal to the jet height, the contribution of the jetting region to attrition has been quantified.

The effect of distributor orifice diameter on the attrition rate has been investigated by Ghadiri et al. [15] using salt as the test material in a 58 mm diameter cylindrical Perspex bed of 0.9 m height, otherwise similar to the set-up shown in Figure 4. The results are presented in section 4.

3.3 Measurement of jet parameters

In the hydrodynamic jet model of De Michele et al. [17], which is employed here, the particle flow patterns in the jet are calculated on the basis of Schlichting similarity profiles, following the turbulent jet theory of Abramovich [22]. These profiles scale with the actual geometry of the jet, as it extends axially and expands radially into the bulk of the bed. To establish these profiles for a given orifice size and velocity, several parameters, such as the jet angle and height, and the initial solids concentration at the jet exit need to be specified. All these parameters are difficult to measure, especially in a three-dimensional bed. A number of measurements have been carried out in two-dimensional and three-dimensional (cylindrical) fluidised beds, using various measurement techniques [12-15, 23-25]. The measurements with two-dimensional beds are only used for input in the two-dimensional version of the hydrodynamic model. However, comparison of the model predictions with the experimental data from two-dimensional configurations can be used to check the validity of the current approach.

Measurements of jet angles in the cylindrical fluidised bed, described in section 3.2, have been carried out using an X-ray facility using salt, $d_p = 418 \mu m$, and alumina particles, $d_p = 107 \mu m$ [25].

Digital analysis of video images taken from a two-dimensional fluidised bed, shown in Figure 5, has been used for measurements of jet half angles with FCC catalyst, $d_p = 90 \mu m$. In this apparatus, the gas jet is produced by slots, sandwiched between two porous plates for background fluidisation [23].

In this two-dimensional set-up, a strong dependence of the jet angle on orifice gas velocity has
Fig. 5 Two-dimensional fluidised bed for high-speed video imaging of jets.

been found, even with a narrow orifice of 0.5 mm, where the jet half angle decreases in a linear fashion from 11.5° ($u_0 = 9.4$ ms$^{-1}$) to 7° ($u_0 = 54$ ms$^{-1}$). The trends for different orifices behave like tangents to a single hyperbolical curve, as shown in Figure 6. There is, however, a certain overlap in the gas velocity range, where the trendlines for neighbouring jet sizes cross over each other, indicating a distinct effect of the orifice size, rather than just a velocity effect. Similar effects, but to a different extent, were observed in the three-dimensional set-up [25].

Measurements of the initial solids concentration in the jet have been made using the two-dimensional fluidised bed, shown in Figure 5, which was equipped with optical glass walls for the specific purpose of video recordings with a high resolution camera [23]. Results of these measurements are shown in Figure 7. The solids concentration at the nozzle exit appears to increase with decreasing orifice size. This is supported by our visual observations [24] that with wide orifices, the jet core is clear of solids, whereas with narrow orifices the jet core is occupied by a significant amount of solids, even at high $u_0$.

In order to compare the hydrodynamic model predictions with the actual solids flow patterns, measurements of particle velocities have been carried out in the two-dimensional bed equipped with optical glass walls, for the FCC and the NaCl salt. The results are shown in Figure 8 and 9 [23, 24]. These measurements have been obtained, using digital image analysis of video images of the particle flow, recorded with a Kodak high speed video camera at frame rates up to 40500 frames per second.

For FCC (Figure 9), a good agreement is shown between experimental data and predictions from the hydrodynamic model. For NaCl (Figure 8), the agreement is fair, but the data are more closely matched for large orifice diameters. Considering the observation that NaCl particles do not accelerate significantly along the jet height for narrow orifices, because of the increased solids concentration, this feature suggests that there is a distinct effect of the ratio of
particle-to-orifice diameter on the flow pattern, which is currently not accounted for in the model.

![Graph](image1)

**Fig. 6** Jet angles in a fluidised bed jet of FCC ($d_p = 90 \mu m$) as a function of $u_o$ for different orifices.

![Graph](image2)

**Fig. 7** Solids concentration in a fluidised bed of FCC ($d_p = 90 \mu m$) at the orifice exit as a function of $u_o$ for different orifices.

![Graph](image3)

**Fig. 8** Comparison of numerical predictions (lines) and experimental measurements (markers) of particle velocities of NaCl particles in jets from different nozzles.

- $d_{or} = 8.0 \text{ mm}$; ○, $d_{or} = 5.0 \text{ mm}$; ▲, $d_{or} = 0.5 \text{ mm}$; ▲, $d_{or} = 0.2 \text{ mm}$.

![Graph](image4)

**Fig. 9** FCC particle velocity in the jet from a 0.5 mm jet nozzle.

4. Attrition model application and evaluation

4.1 Effect of velocity on single particle impact attrition

The first step in the application of the attrition model is the establishment of the power index $m$ in Eq. (3). The single particle impact tests show a slight variation from the theoretical value of 2 for some materials. Table 2 shows measured values of $m$ for melt-grown and solution grown NaCl crystals, and for FCC. The solution grown NaCl crystals contain polycrystals and crevasses, which contribute to the deviation of $m$ from 2. The index $m$ is sensitive to internal and surface defects and structure, the presence of polycrystals, work-hardening and fatigue [13, 14, 16, 26].

| Material          | $m$  |
|-------------------|------|
| NaCl melt-grown   | 2.0  |
| NaCl solution-grown | 2.6  |
| FCC               | 2.34 |

4.2 Effect of distributor orifice size and velocity on fluidised jet attrition

The measurement of the fluidised bed jet attrition as a function of orifice velocity and size involved decoupling of a number of concurrent processes, such as the attrition in the jetting region and in the bubbling part of the bed. As described in section 3.2, experiments with different bed heights have been carried...
out to enable the establishment of a correlation between the bed height and the attrition rate, from which the attrition in the jetting region may be inferred. The result of this operation is shown in Figure 10, where the data points are accompanied by a trendline of a best fit with a power index yielding a value of \( n \) in Eq. (6), as reported in Table 3.

The entrainment rate and particle velocity in the jet, as predicted by the hydrodynamic jet model, are shown in Figures 11 and 12 for NaCl for a 1.0 mm orifice diameter. From the curve fits, values of the power indices \( k \) and \( l \), for the particle velocity and the solids entrainment rate, respectively, as given in Eqs (4) and (5), may be obtained. These are given in Table 3, together with the value of \( m \), from Eq. (3), for the NaCl particles. The overall attrition index \( n \) (Eq. 6) is then calculated and is given in Table 3.

The predicted results compare favourably with experimental data for NaCl and FCC, also shown in Table 3. The experimental value of \( n \) for FCC is that given by Werther and Xi [11]. Zenz and Kelleher [1] report a slightly lower value of 2.5 for larger FCC particles. Values of \( k \) and \( l \) for FCC have been obtained using the experimental parameters given by Werther and Xi [11] and \( m \) has been obtained by single particle impact testing [1] using the same material as used by Werther and Xi [11].

The predicted dependence of the attrition rate on the orifice diameter is shown in Table 4, where the values of \( s \), \( t \) and \( h \) have been given (see Eqs (7)-(9)). The values of \( h \) compare reasonably well with the experimental values of Kono [8] and Ghadiri et al. [15], but contradict with the absence of any effect of the orifice size, as indicated by Werther and Xi [11] and Zenz and Kelleher [1]. Variations in the level of background fluidisation may be responsible for this difference (see Table 1).

Table 4. Hydrodynamic and attrition parameters for the effect of the orifice diameter

| Parameter | FCC | NaCl |
|-----------|-----|------|
| \( u_o \) | -0.006 | 0.41 | 0.95 | -0.004 | 0.44 | 1.11 |
| \( v \) | 0.06 | 0.3 | 0.76 | 0.11 | 0.28 | 0.84 |
| \( h = s + t \cdot m \) | 0.17 | 0.182 | 0.6 | 0.18 | 0.1 | 0.44 |
5. Discussion

The model of jet attrition combines a model of particle breakage with a hydrodynamic model of particle flow in a jet in order to predict the rate of attrition. The experimental observations of particle velocity and concentration profiles suggest that there is an influence of the orifice-to-particle size ratio, and this is currently not taken into account in the hydrodynamic model.

For orifices much larger than the particle size, the core of the jet is almost entirely clear of particles, whereas for orifices of size comparable to or smaller than the particle size the solids concentration in the jet was observed to be high. This strongly influences the particle-particle interactions. For the latter, at high orifice velocities, the particles will shear against each other, causing abrasion, whereas for the former, particles may accelerate freely, causing more integral damage, thus increasing the probability of fragmentation. Further refinement of the model is necessary to incorporate the effect of the ratio of orifice diameter to particle size.

There are several simplifying assumptions in the attrition model, whose validity may have to be assessed for particles of interest. These are as follows.

i) It is assumed that the dependence of interparticle impact damage on impact velocity follows the same trend as the impact of a particle on a rigid target. The latter may provide a more extensive damage as the target is rigid. However, the effect of impact velocity is not expected to be different from interparticle collisions.

Generally, the collision frequency in a fluidised bed is very high. The high speed video recordings of NaCl particles showed that particles in fact accelerate along the jet axis, which is almost clear of particles, and subsequently impact on the dense phase on top of the jet. The particles often scour the jet boundary as if they had been launched into a pin ball machine. However, most of the momentum is dissipated during the first impact, and the subsequent collisions take place at a velocity similar to the recirculation velocity of particles in the bulk. Therefore, the actual process of attrition will be contained in the first particle-bulk collision, and the similarity between the single impact and the jet impact is preserved.

ii) The influence of time is shown in Figure 13 for NaCl particles. This effect has not been considered in several investigations, where tests have been performed for one hour only [3, 27], or even shorter periods [10]. Cairati et al. [28] have shown that molybdate catalyst particles do not reach steady state equilibrium within one hour in the Forsythe-and-Hertwig test [27], and the present NaCl particles reach steady state only after five hours.

iii) Impact breakage studies have shown that repeated impacts at the same velocity may progressively either weaken or strengthen the particles, causing the attrition rate to vary with the number of impacts [29]. Plastic deformation of semi-brittle particles may cause work-hardening, which eventually leads to an increase in the attrition rate. On the other hand, the first few impacts may cause weaker particles to break, whence the remainder would appear to be more resistant to attrition.

iv) In the analysis of attrition, Ghadiri et al. [12-15] have carried out a complete analysis of the bed inventory, accounting for the debris in the bed. In a number of previous investigations, the attrition rate is quantified by the amount of fines elutriated from the bed. This process ignores the quantity of the debris [30] which is in dynamic equilibrium in the bed [31]. This may be a source for discrepancies in the trends reported in the literature.

The power index $m$ for single particle impact damage does not vary widely from its theoretical value of 2 for FCC and different types of NaCl. However, the overall attrition index varies from 3 to about 5! It is interesting to note that the present approach is capable of identifying the relevant hydrodynamic parameters to predict the actual power index for attrition in the processing environment.

6. Conclusions

The model of attrition in fluidised bed jets provides a realistic prediction of the effect of a number of important design and operating parameters such as orifice size and gas velocity. The model takes account of the particle properties and hydrodynamic conditions of the jet. The procedure established to estimate the attrition rate in the jetting region of fluidised beds is to obtain a measure of the attrition propensity of single particles by impact testing and to couple this process with the rate of solids entrainment into the jetting region by the use of hydrodynamic modelling. The model has been successfully applied to two very different types of material, FCC powder and NaCl crystals. Further testing with materials such as weakly-bonded agglomerates and resins would be useful to establish the range of the applicability of the model.
7. Acknowledgement

Financial support from the University of Surrey and Shell Research B.V. is gratefully acknowledged. The authors are grateful to EPSRC and Mr Peter Goodyer for providing quick access to the high speed video and photography facilities from EPSRC’s equipment pool. Dr W. Duo is thanked for his valuable comments on the manuscript.

8. Nomenclature

\( C \) : Constant (see Table 1)
\( d \) : linear particle dimension (m)
\( d_{or} \) : distributor orifice size (m)
\( d_p \) : mean particle size (m)
\( d_{p0} \) : initial mean particle size (m)
\( f \) : distributor free area (\( -/- \))
\( h \) : power index (Eq. 1) (\( -/- \))
\( H \) : hardness (Pa)
\( HGI \) : Hardgrove Grindability Index (kg)
\( k \) : power index (Eq. 5) (\( -/- \))
\( K_c \) : fracture toughness (N m\(^{-3/2}\))
\( l \) : power index (Eq. 4) (\( -/- \))
\( m \) : power index (Eq. 3) (\( -/- \))
\( M \) : mass (kg)
\( M_b \) : total bed weight (kg)
\( n \) : power index (Eq. 1) (\( -/- \))
\( Q \) : volumetric orifice gas flow rate (m\(^3\) s\(^{-1}\))
\( R_a \) : fluidised bed jet attrition (\( -/- \))
\( R_{bed} \) : fluidised bed bulk attrition (\( -/- \))
\( R_i \) : single particle impact attrition (\( -/- \))
\( s \) : power index (Eq. 7) (\( -/- \))
\( t \) : power index (Eq. 8) (\( -/- \))
\( u_i \) : particle impact velocity (m s\(^{-1}\))
\( u_{mf} \) : minimum fluidisation velocity (m s\(^{-1}\))
\( u_o \) : orifice gas velocity (m s\(^{-1}\))
\( u_p \) : particle velocity in the jet (m s\(^{-1}\))
\( u_s \) : superficial gas velocity (m s\(^{-1}\))
\( W \) : residue bed weight (kg)
\( W_c \) : carbon loading (kg)
\( W_s \) : solids entrainment rate (kg s\(^{-1}\))
\( W_g \) : gas mass flow rate (kg s\(^{-1}\))
\( z \) : number of grid jet holes (\( -/- \))
\( \beta \) : correction factor (\( -/- \))
\( P_f \) : fluid density (kg m\(^{-3}\))
\( P_s \) : solids density (kg m\(^{-3}\))
\( \sigma_{br} \) : crushing strength (Pa)
\( \tau \) : processing time (s)
\( \varphi_s \) : particle sphericity (\( -/- \))
\( \varphi_{10} \) : initial particle sphericity (\( -/- \))

9. References

1) Zenz, F.A. and E.G. Kelleher: J. Powder & Bulk Solids Technol., 4 (2/3), 13 (1980)
2) Bemrose, C.R. and J. Bridgewater, Powder Technol., 49, 97 (1987)
3) Blinachev, V.N., V.V. Strel’tsov and E.S. Lebedeva: Intern. Chem. Engng, 8 (4), 615 (1968)
4) Merrick, D. and J. Highley: AIChE Symp. Series, 137 (70), 366 (1974)
5) Chen, T.P., C.I. Sishtla, D.V. Punwani and H. Arastoopour, “A Model for Attrition in Fluidized Beds”, in Fluidization, J.R. Grace and J.M. Matsen eds, Engineering Foundation, New York, 445 (1980)
6) Lin, L., J.T. Sears and C.Y. Wen: Powder Technol., 27, 105 (1980)
7) Donsi, G., L. Massimilla and M. Miccio: Combustion and Flame, 41, 57 (1981)
8) Kono, H.: AIChE Symp. Series, 205 (77), 96 (1981)
9) Sishtla, C., J. Findlay, I. Chan and T.M. Knowlton: “The Effect of Temperature and Gas Velocity on Fines Generation in Non-Reactive Fluidized Beds of Coal Char”, in Fluidization VI, J.R. Grace, L.W. Shemilt and M.A. Bergougnou eds, Engineering Foundation, New York, 581 (1984)
10) Seville, J.P.K., M.A. Mullier, L. Hailu and M.J. Adams: “Attrition of Agglomerates in Fluidised Beds”, Proc. VIIth Intern. Conf. on Fluidization, Queensland, Engineering Foundation, New York, 587 (1992)
11) Werther, J. and W. Xi: Powder Technol., 76, 39 (1993)
12) Ghadiri, M., J.A.S. Cleaver and V.G. Tuponogov: “Modelling Attrition Rates in the Jetting Region of a Fluidised Bed”, Proc. Symposium of Attrition and Wear in Powder Technology, Utrecht (NL), 79 (1992a)
13) Ghadiri, M., J.A.S. Cleaver and K.R. Yüreğir: “Attrition of Sodium Chloride Crystals in a Fluidized Bed”, Proc. VIIth Intern. Conf. on Fluidization, Queensland, Engineering Foundation, New York, 603 (1992b)
14) Ghadiri, M., J.A.S. Cleaver, V.G. Tuponogov and J. Werther: Powder Technol., 80, 175 (1994)
15) Ghadiri, M., J.A.S. Cleaver and V.G. Tuponogov: "Influence of Distributor Orifice Size on Attrition in the Jetting Region of Fluidized Beds", Preprints VIIIth International Symposium on Fluidization, Tours (F), Engineering Foundation, 799 (1995)

16) Zhang, Z. and M. Ghadiri: "Effect of Particle Size on Attrition", Proc. First International Particle Technology Forum, AIChE, Denver, Colorado, 247 (1994)

17) De Michele, G., A. Elia and L. Massimilla: Ing. Chim. Ital., 12 (11-12) 155 (1976)

18) Massimilla, L.: "Gas Jets in Fluidized Beds", in Fluidization, 2nd ed., J.F. Davidson, R. Cliff and D. Harrison eds, Academic Press, New York, 133 (1985)

19) Ghadiri, M., and K.R. Yüregir: "Impact Attrition of NaCl Particles", in Tribology in Particulate Technology, B.J. Briscoe and M.J. Adams eds, Adam Hilger, Bristol (1987)

20) Cleaver, J.A.S., M. Ghadiri and N. Rolfe: Powder Technol., 76, 15 (1993)

21) Fakhimi, S. and D. Harrison: Inst. Chem. Eng. Symp. Ser., 33, 29 (1971)

22) Abramovich, G.N.: "The Theory of Turbulent Jets", MIT Press, Cambridge Massachusetts (1963)

23) Boereefijn, R. and M. Ghadiri: "Attrition of Fluid Cracking Catalyst in Fluidised Beds", Proc. 5th World Congress on Chem. Engng/2nd Intern. Particle Technol. Forum, San Diego, 273 (1996a)

24) Boereefijn, R. and M. Ghadiri: "Motion Analysis of Fine Particles in Jets in Two-Dimensional Fluidised Beds", Proc. IChemE Research Event/2nd European Conference for Young Researchers in Chemical Engineering, Leeds/Bradford, 1048 (1996b)

25) Cleaver, J.A.S., M. Ghadiri, V.G. Tuponogov, J.G. Yates and D.J. Cheesman: Powder Technol., 85, 221 (1995)

26) Papadopoulos, D.G. and M. Ghadiri: Adv. Powder Technol., In Press (1996)

27) Forsythe Jr, W.L. and W.R. Hertwig: Ind. & Engng Chem., 41 (6), 1200 (1949)

28) Carati, L., L. Di Fiore, P. Forzatti, I. Pasquon and F. Trifiro: Ind. Eng. Chem. Process Des. Dev., 19, 561 (1980)

29) Zhang, Z., PhD Thesis, Univ. of Surrey, 1994

30) Ayazi Shamlou, P., Z. Liu and J.G. Yates: Chem. Engng Sci., 45 (4), 809 (1990)

31) Donsi, G., G. Ferrari, B. Formisani, and G. Longo: Powder Technol., 61, 75 (1990)

32) Yang, W.-Y. and D.L. Kearns: AIChE Symp. Series, 205 (77), 28 (1981)

Authors' short biography

Professor Mojtaba Ghadiri

Mojtaba Ghadiri graduated in Chemical Engineering from the University of Tehran, and subsequently obtained an MSc from Imperial College and a PhD from the University of Cambridge. He then worked for Unilever Research as a scientist for two years before joining the University of Surrey in 1983. Mojtaba Ghadiri holds the Chair of Particle Technology at the University of Surrey. His current research activities are on attrition and comminution of particulate solids, fluidisation, and electrical effects in bulk particulate systems. He has developed a specialised facility for mechanical testing of fine particulate solids and has worked extensively on linking the material properties with particle behaviour in attrition and comminution processes.

Ir Renee Boereefijn

Renee Boereefijn graduated in Mechanical Engineering from the University of Twente in 1994. For his Diploma Thesis, he spent a year at the University of Naples, where he worked on the hydrodynamics of fluidised beds and developed a special probe for measurement of voidage waves. His current research activities are focused on the interactions between the hydrodynamics of fluidised bed jets and attrition in fluidised beds, using state-of-the-art digital image processing and high-speed video techniques, as well as laser doppler anemometry, as part of his PhD dissertation. Additionally, his recent work includes the impact fracture behaviour of various types of particulate solids.