An Overview of Attrition in the Jetting Region of Fluidised Beds

Mojtaba Ghadiri*, Wei Pin Goh

School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK

Abstract. The work on particle attrition in the jetting region of fluidised beds is reviewed. The rate of attrition is shown to depend on the orifice agas velocity to a power index, which could be much greater than the dependence of single particle attrition on impact velocity. This is predictable by coupling the extent of single particle impact breakage with jet hydrodynamics. More recent analyses by the use of CFD-DEM simulations, coupled with a model of the single particle breakage data, confirm the previous work and shed further light on the dependence of the effect of jet velocity, orifice size and transition velocity above which attrition is observed.

1. Introduction

Attrition in the jetting region of fluidised beds is a critical phenomenon governing particle lifetime, fines generation, and process efficiency. To provide a uniform gas distribution in fluidised beds, the distributor is designed to operate with a sufficiently high level of pressure drop, yielding a relatively high orifice gas velocity. This could cause significant surface damage even for strong particles, such as sand, and breakage for weak particles, such as spray-dried powders. A good example is particle attrition in Fluid Catalytic Cracking (FCC) operation in oil refining, where a few tons of debris are produced daily as a result of attrition.

There are numerous test methods developed for attrition testing, which are briefly reviewed here, followed by the characterisation of the attrition propensity of particles due to collision. This information is then used to analyse the rate of attrition in the jetting region of fluidised beds, by coupling with a hydrodynamic model of the jet region. Recent developments in the numerical simulation by Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM) quantify the effect of the important factors which affect the attrition rate therein.

Early comprehensive reviews have established that high-velocity collisions play a dominant role in dilute regions such as the jet [1] and propose that single-particle impact testing provides a fundamental measure of particle strength, offering a bridge between intrinsic material properties and bulk attrition behaviour. Boerefijn et al. [2] frame the process as a multi-scale problem involving particle properties, fluidised bed hydrodynamics, and operating conditions. The jet region is identified as a hotspot for impact-driven attrition due to elevated slip velocities and frequent particle acceleration. A predictive understanding requires coupling material response to impact with solids circulation patterns, an idea that underpins subsequent modelling efforts [1,2]. A range of experimental techniques has been developed to characterise attrition, though their relevance to jet-region conditions varies significantly. Jet cup testers [3] and air-jet apparatuses [4] are among the most representative, as they subject particles to high-velocity gas streams, similar to the jet environment. These methods capture both collision frequency and impact intensity, making them representative of the jet conditions. In contrast, standardised fluidised bed tests such as the ASTM method [5] provide reproducible benchmarks but often operate in bubbling regimes, where shear and low-energy collisions dominate, limiting their direct applicability to jet attrition.

Other devices probe complementary aspects of particle degradation. The UNC dustiness tester [6] and vortex shaker [7] primarily evaluate fines generation under dispersive or vibrational stresses, offering insight into particle fragility but not the high-energy impacts characteristic of jets. Similarly, stirred fluidisation systems [8] focus on dense-phase behaviour, where interparticle friction and shear prevail. While these methods are useful for broader attrition characterisation, they may underestimate breakage rates in jetting regions.

More targeted approaches have been developed to isolate impact-driven mechanisms. Particle jet impact studies [9] directly replicate high-velocity collisions, enabling controlled investigation of fragmentation thresholds and breakage modes. Likewise, impact breakage experiments [10] and plate impact tests [12] provide detailed information on energy–breakage relationships, which are essential for mechanistic modelling. Cyclone-based attrition testing [11] introduces repeated high-speed impacts and particle recirculation, offering a closer analogue to industrial systems, though with less control over individual collision events.

At the single-particle scale, the seminal work of Yüregir et al. [13] established the single particle impact tester as a robust tool for quantifying impact attrition. This method isolates particle strength and fracture behaviour, providing key parameters such as critical impact velocity and the extent of breakage. More recent developments,

* Corresponding author: m.ghadiri@leeds.ac.uk

such as the shear and impact tester by Ahmadian and Ghadiri [14], extend this capability by incorporating combined loading modes.

The integration of these experimental insights is formalised in the model proposed by Ghadiri and Boerefijn [15], which specifically addresses attrition in the jetting region. The model links single-particle impact data with solids flux and collision frequency, enabling prediction of attrition rates based on both material properties and hydrodynamic conditions. This framework provides an approach to scaling laboratory measurements to reactor performance.

Earlier studies on FCC catalysts [16,17] laid the groundwork by identifying the importance of particle size distribution evolution and attrition mechanisms in industrial units. These works underscore the practical significance of understanding jet-region attrition, particularly for maintaining catalyst activity and minimising fines losses.

In summary, the literature demonstrates that attrition in the jet region of fluidised beds is predominantly governed by high-energy impacts, which can be effectively characterised through a hierarchy of experimental techniques. While bulk tests provide useful benchmarks, single-particle and jet-based methods are essential for capturing the underlying physics. The coupling of these data with hydrodynamic models provides a predictive capability for optimising industrial processes.

2. Single Particle Impact Attrition

In our laboratory, we have characterised the single particle impact attrition of a wide range of particles, most notably FCC and reforming catalyst particles, common salt and ingots of NaCl, KCl and MgO, ammonium nitrate, spray-dried powders of detergents, coffee, burkeite, agglomerates and granules, pharmaceutical crystals of aspirin, paracetamol, and additively-manufactured agglomerates. The main mechanism of attrition is by the propagation of sub-surface lateral cracks, as shown in the SEM images in Figure 1.

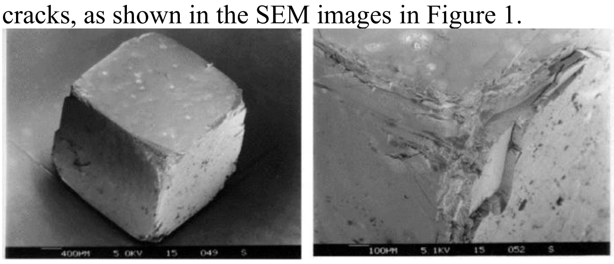

Figure 1. Attrition damage to an ingot of salt crystal [18].

The results for burkeite and MnO_2 particles, the latter used as a chemical looping catalyst (CLC), are shown in Figures 2 and 3, and in Table 1 for fresh and equilibrium FCC particles. The model of Ghadiri and Zhang [19] is used to analyse the results

$$\xi = \alpha\eta = \alpha \frac{\rho V^2 D H}{K_c^2} \qquad (1)$$

where ξ is the fractional loss from the mother particles.

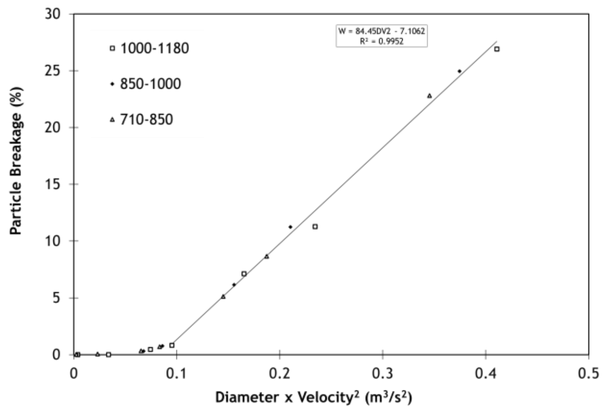

Figure 2. Impact attrition of spray-dried burkeite particles [20].

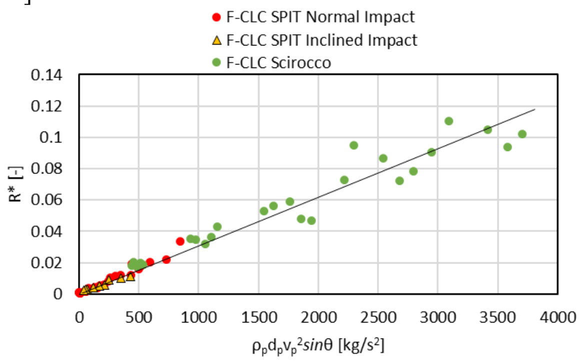

Figure 3. Impact attrition of crushed naturally-occurring MnO_2 particles [21].

Table 1. The attrition power index, *n*, for fresh and equilibrium FCC particles ($\xi = CV^n$) [1].

Material	Size range (μm)	C	n
F-cat	75-90	5×10^{-4}	1.93
F-cat	90-106	2.4×10^{-3}	1.79
F-cat	106-125	1.3×10^{-3}	2.06
E-cat	75-90	7.0×10^{-5}	2.03
E-cat	106-125	8.0×10^{-4}	1.79

3. Attrition in the Jetting Region of Fluidised Beds

Reported works in the literature show diversity in the dependence of jet attrition on the orifice gas velocity and size, as shown in Table 2, due to differences in the physical and mechanical properties of particles.

3.1. Jetting Hydrodynamic Model of Donsi *et al.* [22]

The jet model of Donsi *et al.* [22] gives the functional dependence of particle velocity, concentration, and hence the particle flux, in the jet region, as a function of particle properties and orifice size, i.e.

$V_p = f(uo, d)$; $C_p = h(uo, d)$ Flux, $W_s = g(uo, d)$

Therefore:

- **Effect of Orifice velocity: (constant d)**

$$V_p \propto u_0^{\alpha} \text{ and } W_S/W_g \propto u_0^{\beta}$$

- **Effect of Orifice size: (constant u_0)**

$$V_p \propto d^n \text{ and } W_S/W_g \propto d^m$$

Table 2. Dependence of the overall and jet attrition rate on the orifice size and superficial/orifice gas velocity [1].

Author	Material	Attrition rate W (kg hr⁻¹)	Attrition rate W (kg hr⁻¹)
Blinichev et al. (1968)	Salt granules	$W_{overall} \propto U^{5.8}$	$W_{overall} \propto d^3$
Kono (1981)	Alumina-Silica	$W_{overall} \propto U^{2\text{-}3}$	
Patel et al. (1986)	Urea	$W_{overall} \propto U$	
Contractor et al. (1989)	Catalyst particles	$W_{jet} \propto U^{2\text{-}4.5}$	
Ayazi Shamlou et al. (1990)	Glass agglomerates	$W_{overall} \propto (U - U_{mf})$	
Seville et al. (1992)	Sand agglomerates	$W_{jet} \propto (U - U_{mf})$ $W_{bed} \propto (U - U_{mf})$	
Ghadiri et al. (1992)	NaCl Salt	$W_{jet} \propto U^{5.1}_{or}$	
Werther & Xi (1993)	FCC	$W_{jet} \propto U^3_{or}$	$W_{jet} \propto d^2$

3.2. Analysis of Jet Attrition: Effect of Orifice Velocity

Coupling the flux in the jet region with the single particle attrition, we get the attrition rate in the jet region, Aj, as follows:

$$A_j \propto W_s \times Ap \propto u_0^k$$

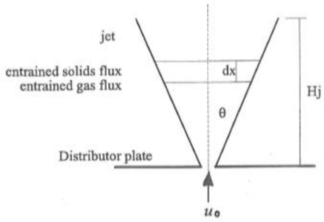

Figure 4. Schematics of the jet geometry and its features.

The results of the analysis by Ghadiri et al. [23] is shown in Table 3. The power index of the orifice gas velocity, *k*, is predicted to vary with orifice size. This has not been acknowledged in the previous works. The prediction is very sensitive to the jet half-angle θ.

Table 3. Prediction of the dependence of the jet attrition on the orifice velocity and size [23].

			Prediction based on Hj from Yates et al.			Prediction based on max particle velocity		
Material	Orifice diameter (mm)	Jet half-angle (°)	n	m	k	n	m	k
FCC	0.5	8	1.23	1.03	3.91	1.30	1.07	4.11
FCC	1.0	9	1.00	1.21	3.55	1.06	1.27	3.75
FCC	2.0	9	0.86	1.30	3.31	0.65	1.56	3.08
NaCl	1.0	6	1.00	0.92	3.52	1.86	0.42	5.26
NaCl	2.0	6	0.88	1.10	3.34	1.79	0.60	5.26
NaCl	3.0	6	0.81	113	3.24	1.63	0.68	4.92

3.3. Analysis of Jet Attrition: Effect of Particle to Orifice Size Ratio

Ghadiri *et al.* [23] carried out a systematic investigation of attrition of FCC powder in the jetting region of a fluidised bed, quantifying the dependence of the attrition rate on the orifice velocity and size. Boerefijn [24] subsequently showed that the orifice size dependency arises from differences in the mechanics of interparticle interaction arising in turn from the size ratio of the orifice to the particles, as schematically illustrated in Figure 5: (a) small dor/dp, fresh FCC; (b) small dor/dp, used FCC; (c) large dor/dp, fresh FCC, (d) large dor/dp, used FCC.

4. Analysis of Jet Attrition by CFD-DEM Method

Fulchini [25] carried out such an analysis using the EDEM software package. The input data are shown in Table 4. A snapshot of the simulations is shown in Figure 6, showing the maximum particle velocity of about 2 m/s for an orifice velocity of 40 m/s. Spherical particle shape is used, but other properties are for two types of MnO_2 material, fresh F-CLC and equilibrium E-CLC particles. The attrition results are shown in Table 5 and Figure 7.

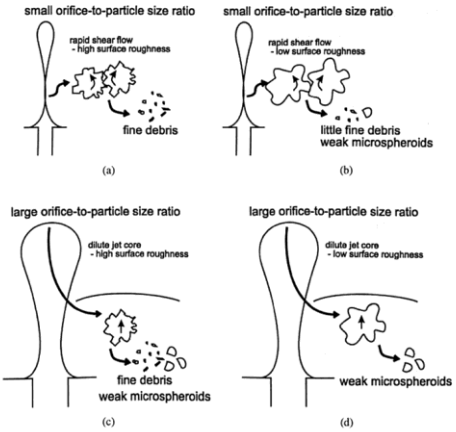

Figure 5. Schematics of interparticle interactions depending on the size ratio of orifice and particles [1].

5. Conclusions

Coupling jet hydrodynamics and attrition kinetics provides a means to identify the influence of material properties and operating conditions on attrition in the jetting region of fluidised beds. The attrition rate in a jet per unit mass of gas flowing through the orifice depends on the orifice diameter as well as velocity. This dependency may be a contributory factor for the existence of differences in reported results in the literature. Numerical simulations by CFD-DEM confirm the mechanics model of jet attrition.

Table 4. CFD-DEM simulation input data [25].

Particle size [μm]	925
1. Particle shape	Spherical
Particle density [kg/m³]	3300
Bed dimensions [mm×mm×mm]	100×10×600
Orifice to particle size ratio	12
Number of particles [-]	20000
Air velocity inlet [m/s]	40
Temperature [°C]	25
Mesh cell size [mm]	2.5
Number of cells	38400
Turbulent model	k-ε
Drag model	Gidaspow
CFD-DEM coupling	4-way
Contact model	Hertz-Mindelin (no slip)

Acknowledgement

This paper is dedicated to the memory of the late Professor Giorgio Donsi, a great friend and inspiring scientist, whose model of jet penetration in fluidised beds was coupled with the Ghadiri and Zhang model of single particle impact attrition to predict particle attrition in the jet region. The work was conducted with some ten scholars, with support from BP Research, Shell Research, FCC manufacturers, and Total, in collaboration with Institut Francaise du Petrole in Lyon.

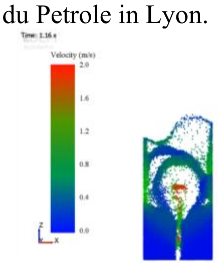

Figure 6. A snapshot of simulations showing the particle velocity range in the jet region [24].

Table 5. Simulation results showing the dependence of the attrition rate on the orifice velocity and size, according the notation of Equation 2 [24].

Jet attrition			
Symbol	description	F-CLC	E-CLC
c_{jet}	Jet attrition index	5.5 X10^{-7}	1.4 X10^{-9}
u_{jet}^	Jet velocity power index	2	6
d_{or}^	Orifice size power index	1.7	3.6
$u_{jet,0\ m/s}$	Jet transition velocity	13.5	4.2

$$\dot{R}_{jet} = \alpha \frac{H}{K_c^2} c_{jet} n_{or} \rho_p u_{jet}^x d_{or}^y \qquad (2)$$

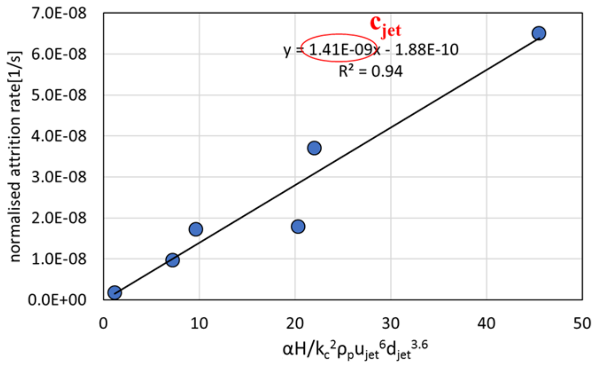

Figure 7. Attrition rate of a single jet in a fluidised bed [24].

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