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STUDY OF SOLIDS ENTRAINMENT INTO ATTRITION JETS IN FLUIDIZED BEDS

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Study of solids entrainment into attrition jets in fluidized beds

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Abstract:

Supersonic nozzles are applied to various fluidized bed processes, such as the production of pharmaceutical powders, fluid catalytic cracking, and fluid coking. In applications such as jet milling, it is essential to entrain a maximum flow-rate of solids from the fluidized bed into the jet cavity. Studies of solid entrainment rate into gas jets have been mostly conducted with subsonic jets and none with convergent-divergent nozzles. The purpose of this research is to study solids entrainment into jets issuing from supersonic convergent-divergent nozzles, and particularly the effects of nozzle size, nozzle mass flow-rate, injection gas properties and fluidization velocity. A novel accurate technique is developed to measure solids entrainment into jets.

Keywords: supersonic nozzle, Fluidized bed, solids entrainment, turbulent jet theory

Introduction

Supersonic nozzles, a type of convergent-divergent nozzles, are applied to various fluidized bed processes, such as the production of pharmaceutical powders, fluid catalytic cracking process, and fluid coking process (Figure 1). For instance, in fluid coking it is very important to control the size of coke particles because large particles will cause poor fluidization and reaction (Dunlop et al, 1958). Therefore, De Laval convergent-divergent nozzles are used to inject steam into fluid cokers, causing particle breakage and preventing net particle growth resulting from coke deposition. Predicting the effects of nozzle mass flow-rate, nozzle size, and gas properties on solids entrainment into supersonic jets is essential to optimize the attrition process and, especially, to minimize the consumption of attrition gas.

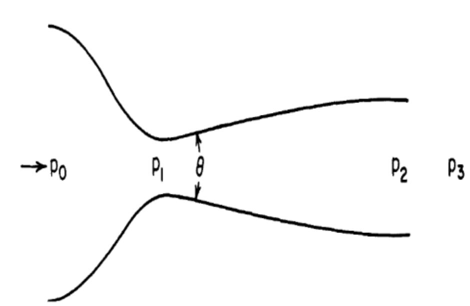

Figure 1 - Supersonic nozzle

(convergent-divergent nozzle)

In supersonic nozzles, the fluid reaches the sonic velocity at the throat, and supersonic velocity is obtained in the divergent section (Smith, 2005). The cross-sectional area, pressure and temperature vary with Mach number along the converging-diverging flow path according to (Liepmann, 1975, and Perry, 2008):

$$\frac{A}{A^*}=\frac{1}{M}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{(\gamma+1)/2(\gamma-1)}$$

$$\frac{p_0}{p}=\left[1+\frac{\gamma-1}{2}M^2\right]^{\gamma/(\gamma-1)}$$

$$\frac{T_0}{T}=1+\frac{\gamma-1}{2}M^2$$

The sonic mass flux through the throat is given by:

$$G=p_0\sqrt{\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}\left(\frac{\gamma M_w}{RT_0}\right)}(kg/m^2\cdot s)$$

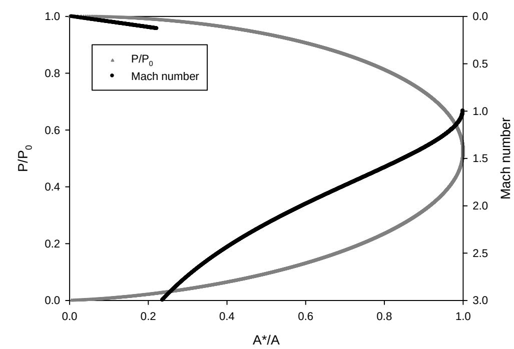

Figure 2 Effect of area ratio on the mach number and pressure ratio in a convergent-divergent nozzle

If A is set equal to the nozzle exit area, the exit Mach number, pressure, and temperature may be calculated. Expansion will be incomplete if the exit pressure exceeds the ambient discharge pressure; in this case, shock waves will occur downstream of the nozzle. If the calculated exit pressure is less than the ambient discharge pressure, the nozzle is over expanded and compression shocks will occur within the expanding section of the nozzle. The relation between area and any other flow data can be obtained through the Mach number, as shown in Fig. 2 .

The jet velocity is much higher than the superficial gas velocity. Previous studies have found that the transverse gas and solids velocity profiles in horizontal jets in fluidized beds are of the Schlichting or Tollmien type, as for homogeneous jets (Shakhova, 1968; Donadono *et al*., 1980; Filla *et al*., 1983; De Michele *et al.*, 1976). Hence, the theory of turbulent gas jets developed by Abramovich (1963) can be applied to solids entrainment with supersonic jets. De Michele et al. (1976) developed a modified model of the submerged turbulent theory to interpret mass transfer associated with gas injection, horizontal injection and large temperature differences between the bed and injected gases of various thermal properties. Xuareb et al. (1992) and Ariyapadi et al. (2003) have developed a model to predict gas and solids entrainment in horizontal jets. In previous studies by Briens et al. (2008) and Hulet et al. (2008a), a specific technique was employed to measure the solids entrainment into submerged gas and gas-liquid jets.

The objective of this work was to study the effects of nozzle mass flow-rate, nozzle size, injection gas properties, and superficial gas velocity of bed on solids entrainment, using supersonic nozzles in fluidized beds. A novel technique has been developed for the accurate measurement of solids entrainment into jets in fluidized beds.

Experimental setup

A fluidized bed with two compartments, shown in Figure 3, was used for the solids entrainment measurements. The fluidized bed is constructed of polycarbonate, has a rectangular cross-section of 1.2 m × 0.1 m, and is 2.3 m tall. The bed is divided into two equal compartments by a partition wall, with an opening fitted with a draft tube.

The fluidization velocity in each compartment is independently controlled by sonic nozzles and pressure regulators. Two differential pressure transducers are used to measure the pressure difference between the two compartments. A VTL (vertical transport line) unit is installed in the fluidized bed; it is comprised of a nozzle, a vertical riser, an elbow, a disengaging cyclone, and a downer with one 1 m length of sight glass and one pinch valve. A shroud installed around the VTL nozzle was used to maximize solids flow through the VTL (Hulet et al., 2008b). The bed solids could, thus, be pneumatically transported from the left side of bed to the right side through the VTL, while solids were conveyed back from the right side to left side by the supersonic nozzle through the draft tube connecting the two compartments. Coke particles, with a Sauter mean diameter of 135 µm and a density of 1450 kg/m^3, were used for the study. Several convergent-divergent supersonic nozzles, of various dimensions, were tested.

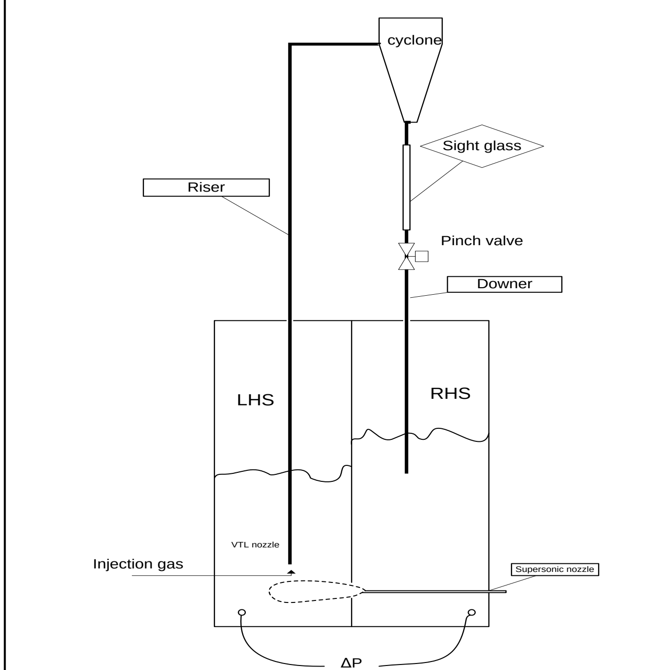

Figure 3- Fluidized bed with VTL unit

In each experiment, the gas flow through the VTL nozzle was adjusted until the bed levels in both compartments of the column became the same, as indicated by a zero differential pressure between the two compartments, and remained steady. The flowrate of solids entrained into the jet and carried from the right hand side compartment to the left hand side compartment was, then, equal to the solids flowrate through the VTL, which could be accurately measured by closing the pinch valve and monitoring the rise of the solids level through the sight glass, using a camera. In practice, it was difficult to exactly achieve a steady differential pressure of 0 between the two compartments. Several experiments were, therefore, conducted with different gas flows to the VTL

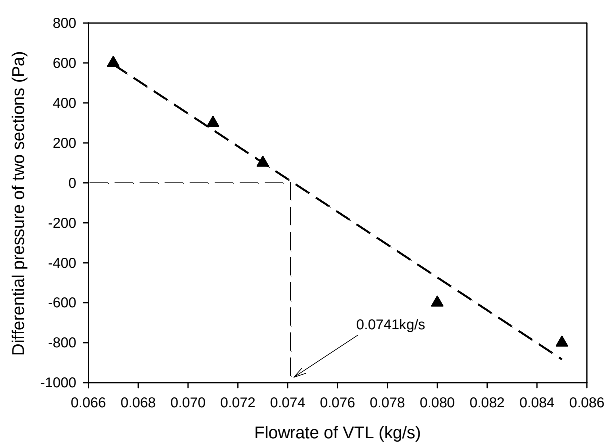

Figure 4 - Estimate of jet solids entrainment rate

and the resulting solids flowrate through the VTL was measured. The exact solids flowrate corresponding to a zero pressure differential was then obtained by interpolation, as shown by Figure 4.

Results and discussion

Figure 5 illustrates the configuration of a turbulent jet, in which a core of flow with undiminished velocity equals to U_0 reaches section 1-1, on the jet axis (Rajaratnam, 1976). This core is known as the potential core. Davies (1972) suggests that the length of potential zone is about 6.4 jet diameters, followed by a transition zone of about 8 jet diameters.

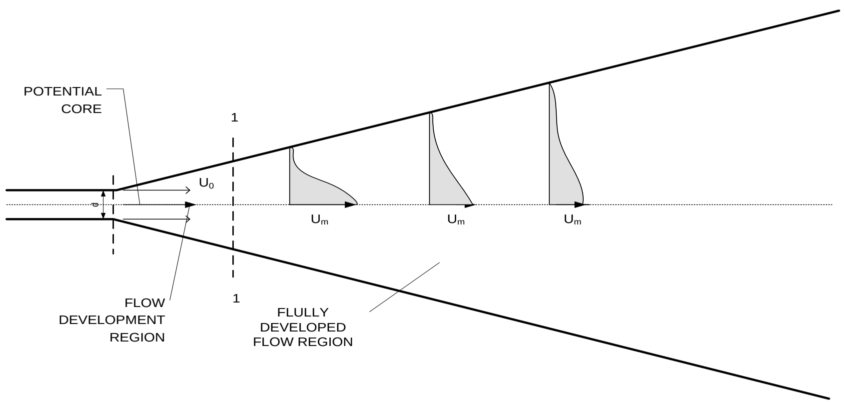

Figure 5 - Configuration of a turbulent jets (adapted from Rajaratnam, 1976)

As for turbulent jets in conventional fluids, jets in fluidized beds have a “potential” core within which gas momentum, temperature and composition are the same as at the mouth of the orifice. Merry suggested a scheme of the particle tracks in the vicinity of the jet, shown in Figure 6, with the majority of entrainment occurring near the nozzle tip in the potential zone region [Merry, 1971].

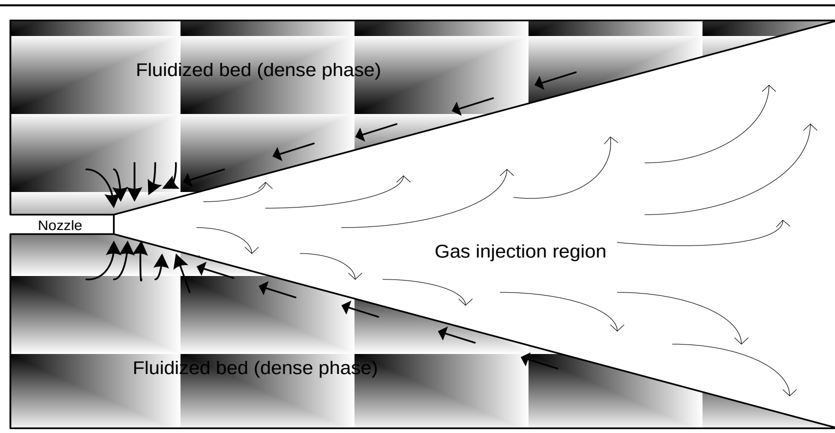

Figure 6 - Solid entrainment track in the injection region (adapted from Merry, 1971)

Briens et al. (2008) found that the superficial gas velocity has little effect on the solids entrainment rate into a sonic jet. Preliminary experiments in this work confirmed these results. The constant superficial gas velocity for both compartments was, therefore, set to a constant value of 0.11 m/s for all experiments.

Figure 7 shows that the maximum solids flowrate was obtained when the diameter of the connecting tube between the two compartments was between 0.0191 and 0.0254 m (3/4 and 1 inch). At smaller diameters, the jet was too constricted and could not carry all entrained solids through the tube. At larger diameters, the jet did not occupy the whole cross-section of the tube and solids could flow back near the wall of the tube.

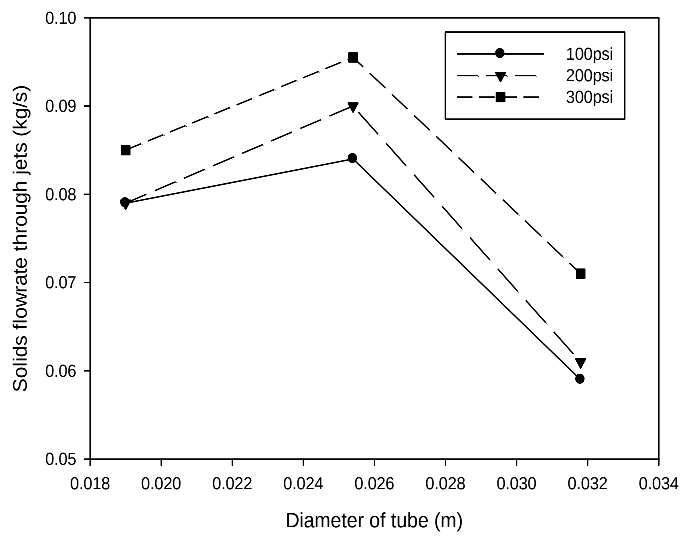

Figure 7 - Effect of connecting tube diameter on measured solids flowrate

Figure 8 shows that the solids entrainment rate was affected by the nozzle gas flowrate. It also shows that the solids entrainment rate into the jet steadily increases with increasing distance between nozzle tip and connecting tube. However, most of the entrainment occurred at short distances, since doubling the distance x/d_0 from 9.5 to 19 only increased the solids flow by about 15%. This confirms that most of the entrainment occurs in the region corresponding to the potential core and the transition zone.

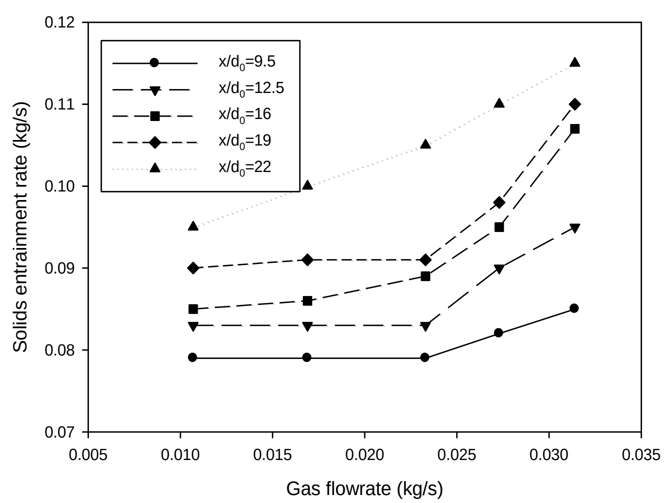

Figure 8 - Effect of nozzle air flowrate on solids entrainment rate for varying distance x from the nozzle (2.4mm nozzle, air, 19mm orifice).

Because a prime objective is to reduce the consumption of nozzle gas, the dimensionless entrainment efficiency is defined as:

$$entrainment\ efficiency = \frac{solids\ entrainment\ (kg/s)}{flowrate\ of\ \ gas\ injection\ (kg/s)} = \frac{W_s}{W_g}$$

A comparison of Figures 8 and 9 shows that while increasing the gas flowrate through the nozzle increases the solids entrainment rate, it dramatically reduces the entrainment efficiency. Increasing the gas flowrate through the nozzle does not greatly increase the size of the jet cavity, which suggests that the entrainment rate may be limited by phenomena occurring at the jet-bed interface.

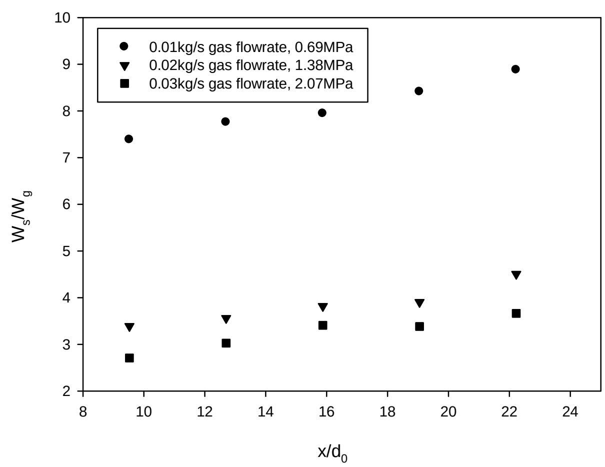

Figure 9 - Effect of nozzle air flowrate on the entrainment efficiency at varying distance from the nozzle (2.4mm nozzle, air)

In order to study the effect of the nozzle size, two different nozzle sizes were tested. A comparison of Figures 9 and 10 demonstrates that smaller nozzles are much more efficient at entraining solids: reducing the nozzle diameter by a factor of two increases the entrainment efficiency by a factor of about 5.

Three different gases, helium, carbon dioxide, and air, were used in the experiments to determine the effect of nozzle gas properties on entrainment efficiency. Figure 11 shows that decreasing the gas molecular weight reduces the solids entrainment efficiency.

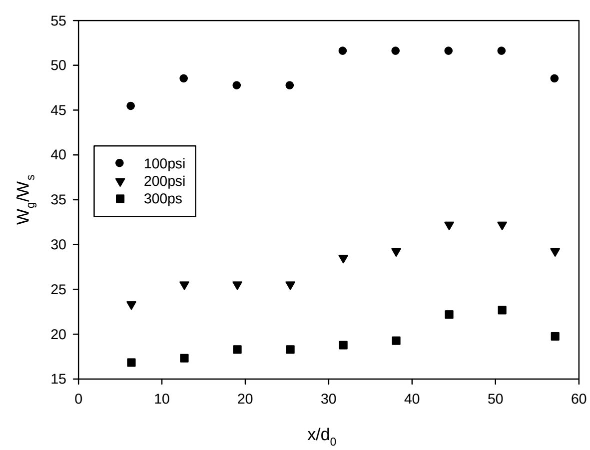

Figure 3 - Effect of nozzle air flowrate on the entrainment efficiency at varying distance from the nozzle (1.2mm nozzle, air)

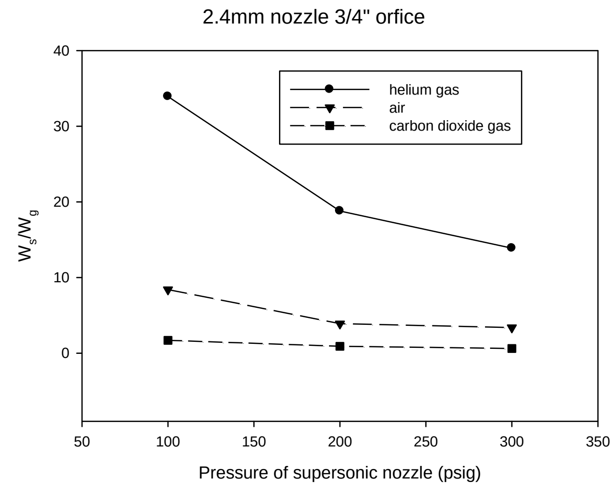

Figure 4 - Effect of nozzle gas density on the entrainment efficiency (2.4mm nozzle, 19mm orifice).

Conclusions

A novel technique has been developed to reliably measure the solids entrainment rate into jets issuing from supersonic convergent-divergent nozzles in fluidized beds

If the objective is to increase the entrainment efficiency, i.e. the ratio of the mass flowrate of entrained solids to the mass flowrate of nozzle gas, then it is better to operate with smaller nozzles, at lower nozzle gas flowrates and a low nozzle gas density.

Notation

A area of nozzle exit (m^2)
A^* area of nozzle throat (m^2)
d_0 diameter of nozzle exit (m^2)
G mass flux (kg/m^2s)
M Mach number
M_w Molar weight (kg/mol)
p_0 upstream pressure of nozzle (Pa)
p_1 pressure at throat (Pa)
p_2 pressure at nozzle exit (Pa)
p_3 ambient pressure (Pa)
R ideal gas universal constant
T_0 absolute temperature at nozzle throat (K)
T absolute temperature at nozzle exit(K)
U_0 gas velocity at nozzle exit (m/s)
U_m gas velocity on jet axis (m/s)
u^* gas velocity at nozzle throat (m/s)
W_s solid entrainment rate through nozzle (kg/s)
$W_{g.}$ flow-rate of gas injection (kg/s)
x distance to nozzle exit (m)

Greek letters

ρ gas density at nozzle exit

$\rho *$ gas density at nozzle throat

γ ratio of specific heat

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