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PENETRATION OF HIGH VELOCITY HORIZONTAL GAS JETS INTO A FLUIDIZED BED AT HIGH TEMPERATURE

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PENETRATION OF HIGH VELOCITY HORIZONTAL GAS JETS INTO A FLUIDIZED BED AT HIGH TEMPERATURE

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Abstract:

High velocity horizontal gas jets are applied to various industrial processes. In this work, a new thermal technique has been developed to measure the penetration length of horizontal gas jets. Experiments were conducted in a fluidized bed with a height of 1.23m and a rectangular cross section of 0.10m × 0.50m. The fluidized bed particles, which were either petroleum coke or sand, were heated by an in-bed electrical heater to temperatures between 300°C and 500°C. Cold gases, such as helium, nitrogen, carbon dioxide, were injected into the hot fluidized bed via a horizontal nozzle operating over a range of velocities. Based on the experimental results, a new empirical correlation was developed to predict the penetration length of jets issuing from the horizontal sonic nozzle at high temperature.

Keywords: Jet Penetration, Fluidized bed, Penetration Length, Supersonic Nozzle

Introduction

A number of industrial processes, such as fluid coking, use high velocity horizontal gas jets for particle attrition in high temperature fluidized beds. In the fluid coking process, the size of coke particles must be controlled because large particles cause poor fluidization and degrade the operation of the coke transport lines (Dunlop et al., 1958). This is achieved by injecting steam into the fluidized bed through high velocity nozzles. According to McMillan et al. (2007b), the high velocity gas jet issuing from these nozzles entrains bed particles and accelerates them to a high speed; due to their inertia, these particles slam on slow moving bed particles near the jet tip, causing breakage and thus, reducing the particle size. Minimizing steam consumption is essential to maximize reactor throughout and reduce wastewater volumes. Typically, convergent-divergent nozzles are more efficient than regular nozzles, i.e. they require less steam to achieve the same attrition rate (McMillan et al., 2007a). Knowing the penetration depth of the high velocity jets is important to maximize their attrition efficiency and avoid the erosion of fluidized bed internals, because most of particles attrition and collision occurs in the void area of the horizontal jets in fluidized beds.

However, the current knowledge of the hydrodynamics and fundamental phenomena of high velocity horizontal gas jets is mostly limited to ambient temperature conditions. Among the published correlations for penetration length, many are unreliable for jets issuing from convergent-divergent nozzles, particularly at high temperature. A high velocity jet injected horizontally in a fluidized bed can be assumed to behave as a submerged jet, similar to a turbulent jet spreading through a liquid medium at rest. Abramovich (1963) developed a submerged jet model. This model has been adapted to fluidized beds of fine particles (De Michele et al., 1976). Many studies confirmed that the model gives a good description of momentum, heat, and mass transfers (Behie et al., 1970, and 1975; Hong et al., 1997).

Table 1 provides examples of published correlations for jet penetration length. The jet penetration length increases with increasing gas density and gas velocity. However, all these correlations were developed from data obtained with nozzle operating at subsonic velocities.

Table 1 Correlations for horizontal jet penetration length

Correlation	Reference
$\frac{L_j}{d_0} = 7.8\left(\frac{\rho_f U_0}{\rho_P \sqrt{g d_P}}\right)$	Shakhova (1968)
$\frac{L_j}{d_0} + 4.5 = 5.25\left(\frac{\rho_0 U_0^{\ 2}}{(1-\varepsilon)\rho_P g d_P}\right)^{0.4}\left(\frac{\rho_f}{\rho_P}\right)^{0.2}\left(\frac{d_p}{d_0}\right)^{0.2}$	Merry (1971)
$0.044\frac{L_j}{d_0} + 1.48 = 0.5\log(0.67\rho_f U_0^{\ 2})$	Zenz (1968)
$\frac{L_j}{d_0} + 3.80 = 1.64\times10^6\left(\frac{\rho_0 U_0^{\ 2}}{(1-\varepsilon)\rho_P g d_P}\right)^{0.327}\left(\frac{\rho_f}{\rho_P}\right)^{1.974}\left(\frac{d_p}{d_0}\right)^{-0.040}$	Hong (1997)
$\frac{L_j}{d_0} = 5.52\left(\frac{\rho_0 U_0^{\ 2}}{(\rho_p - \rho_f) g d_0}\right)^{0.27}$	Benjelloun (1991)
$\frac{L_j}{d_0} = 2.8\left(\frac{\rho_0 U_0^{\ 2}}{(\rho_p - \rho_f) g d_0}\right)^{0.4}$	Yates (1991)

The objective of the study illustrated in this paper was the development of a correlation to predict the penetration of horizontal jets issuing from convergent-divergent nozzles at high temperature, operating under supersonic conditions.

Experimental Setup

Experiments were performed in a hot fluidized bed with a height of 1.23m and a rectangular cross section of 0.10m × 0.50m (Figure 1). The bed particles were heated with an in-bed electrical heater to temperatures between 300°C to 500 °C. Cold gases, such as helium, nitrogen, carbon dioxide, or mixtures of these gases, were injected into the hot fluidized bed via a horizontal nozzle at a distance of 0.127m above the gas distributor. Two different types of particles were used in the experiments, silica sand with a Sauter-mean diameter of 200 µm and petroleum coke with a Sauter-mean diameter of 120 µm. Tests were conducted with a range of nozzle flowrates dependent on the temperature and injection pressure. Three different sizes of convergent-divergent nozzles were used to test the effects of nozzle size on the penetration length of supersonic gas jets.

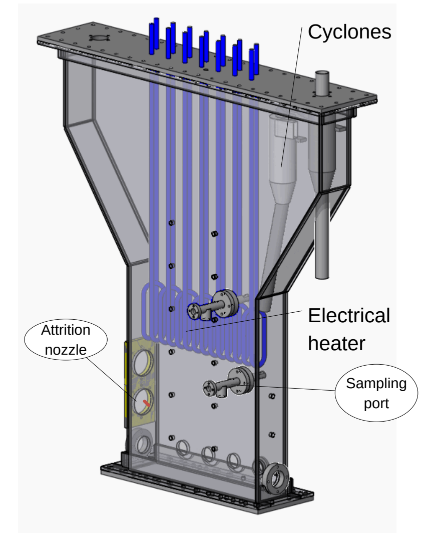

Figure 1 Hot fluidized bed

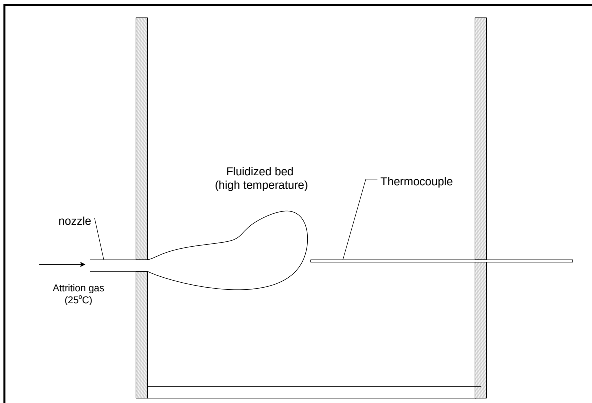

Figure 2 Diagram of the thermal method to measure penetration length in fluidized beds at high temperature

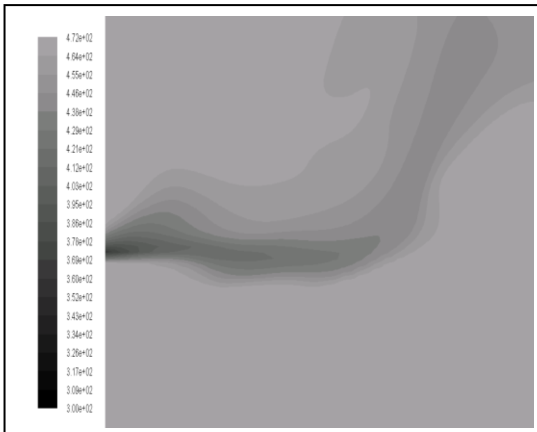

Figure 3 Temperature profile of jet cavity with a supersonic nozzle in fluidized beds

A novel thermal method was developed to measure the penetration length of the high velocity horizontal gas jets. It used the observation that, because cold gas was used to form the jet, the jet cavity was always at a temperature below that of the hot fluidized bed, and that the bed temperature was nearly uniform. The thermal method used a fast thermocouple, which was inserted along the axis of the jet from the opposite wall (Figure 2), a series of temperature signals were recorded while moving the thermocouple progressively towards the jet. The end of the jet cavity could be detected from the sharp increase in temperature at the boundary of the jet cavity, due to the hot bed solids (Figure 3).

Results and discussion

Figure 4 shows the results of measurements obtained using with the thermal method at various bed operating temperatures. The results demonstrate that the bed temperature has a minimal influence on the jet penetration length. On the other hand, it was observed that the jet penetration length increased with increasing nozzle exit diameter, as illustrated in Figure 5.

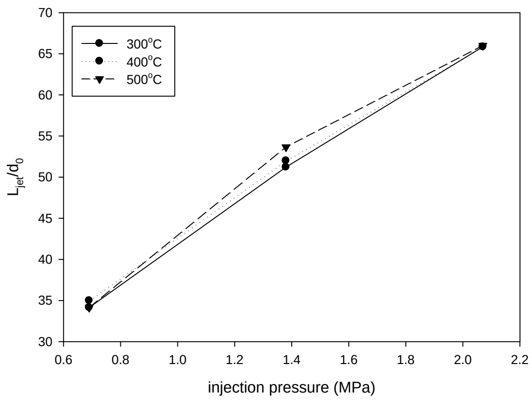

Figure 4 Comparison the experimental results with various temperatures (sand, d_t= 2.4mm, air)

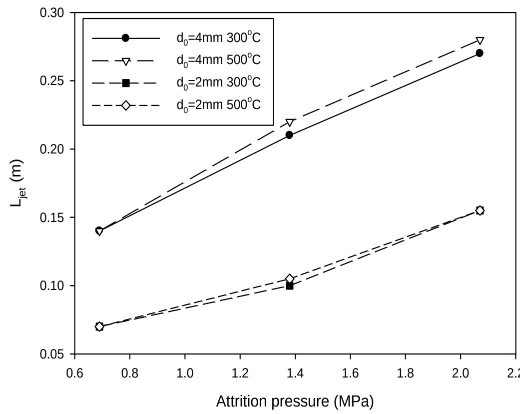

Figure 5 Comparison the experimental results with various nozzle size (Sand, air)

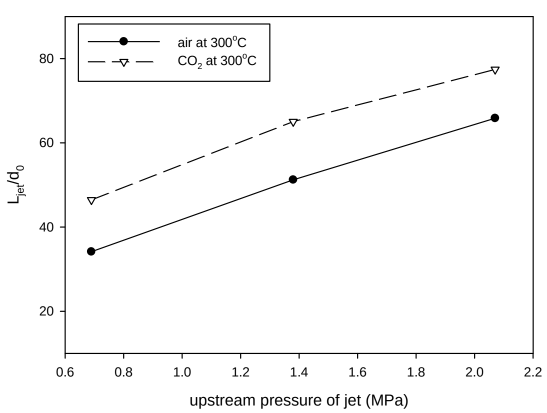

Figure 6 Influence of the attrition gas properties on the penetration length

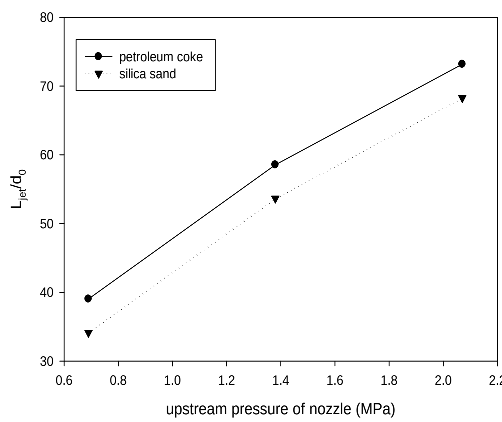

Figure 7 Influence of particle size and density on penetration length

The influence of the particle density on the penetration length was studied using two different types of particles, i.e. petroleum coke and silica sand. It was observed that the jet penetrated further in a bed of coke (ρ_p=1450 kg/m^3) than in a bed of silica sand (ρ_p=2650 kg/m^3), as shown in Figure 6. Similar results were reported by Dawe et al. (2008) and Musmarra (2000). Figure 7 illustrates that the jet penetration length increased as the gas density increased, in agreement with other literature data (Dawe et al., 2008 and Vaccaro, 1997).

Table 2 lists all experimental conditions for the measurements of the jet penetration length by the thermal measurement method. In addition, the experimental data have been compared to the predictions derived from existing empirical correlations in the literatures.

Table 2 Experimental conditions used for tests with typical divergent-convergent nozzles in a fluidized bed at high temperature

Attrition gas	Bed particles	Diameter of nozzle throat (mm)	Diameter of nozzle exit (mm)	Bed temperature (°C)	Pressure Upstream of nozzle (MPa)
helium	Coke	2.4	4	300, 500	0.7-2.0
helium	Coke	1.2	2	500	0.7-2.0
helium	sand	2.4	4	300, 500	0.7-2.0
Nitrogen	Coke	2.4	4	300, 400, 500	0.7-2.0
Nitrogen	Coke	1.2	2	300, 500	0.7-2.0
Nitrogen	Coke	2.4	5.2	210	0.7-2.0
Air	Sand	1.2	2	400, 500	0.7-2.0
Air	Sand	2.4	4	300, 400, 500	0.7-2.0
Air	Sand	2.4	4.85	300,400,500	0.7-2.0
Air	Sand	2.4	5.2	200,300,500	0.7-2.0
CO_2	coke	2.4	4	300,400,500	0.7-2.0
CO_2	Sand	2.4	4	300, 400, 500	0.7-2.0

The study shows that the empirical correlations listed in Table 1 are unable to predict the experimental data at high temperature, as shown by Figure 8. All these correlations were developed using data collected with low velocity, subsonic straight nozzles. Correlations from both Merry and Yates overestimated the jet penetration length, whereas Hong's correlation shows predicted values that are smaller than experimental results. Only the predictions from the Benjelloun's correlation are in relatively good agreement with the measurements. The majority of the correlations use dimensionless terms such as the Froude and Galileo numbers, shown in equations 1 and 2, respectively. The Froude number has been used in the empirical correlations of Merry, Benjelloun (1991), and Ariyapadi (2003).

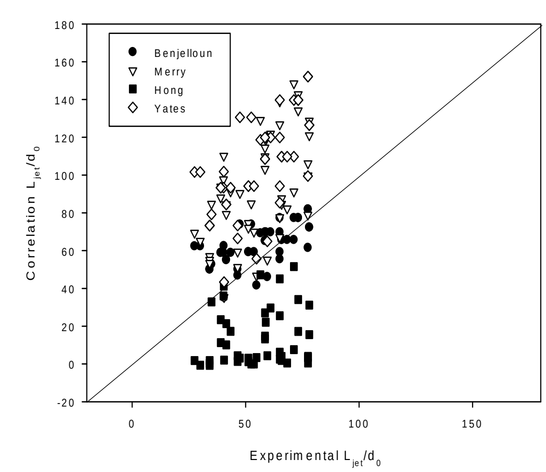

Figure 8 Comparison the experimental results with predicted data by empirical coefficients

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$$Fr = \frac{\rho_0 U_0^{\ 2}}{(\rho_p - \rho_f) g d_0} \qquad 1$$

$$Ga = \frac{\rho_0 (\rho_p - \rho_f) g d_p^{\ 3}}{\mu^2} \qquad 2$$

The Froude number integrates the effects of particle size, jet diameter and jet gas velocity, and represents the ratio of the inertial force of gas at the nozzle and the gravity force of particles. Benjelloun (1991) suggested that the relationship between the gas momentum at the orifice and gravity forces acting on the jet can be written as a function of the Froude number, from which the penetration length can be obtained. Using the experimental data obtained in this study, a new empirical correlation is proposed based on the same basic concept as the one proposed by Benjelloun and adapting his correlation to supersonic nozzles discharging into hot fluidized beds. Assuming that the ratio of jet penetration length and nozzle diameter is proportional to the Froude number, a generic form of the relationship can be represented as:

$$\frac{L_{jet}}{d_o} = \alpha \left(\frac{\rho_0 U_0^{\ 2}}{(\rho_p - \rho_f) g d_0} \right)^{\beta} \qquad 3$$

Equation 3 can be rearranged to:

$$L_{jet} = \frac{\alpha}{g^{\beta}} \frac{1}{(\rho_p - \rho_f)^{\beta}} \left(\rho_0 U_0^{\ 2} \right)^{\beta} d_0^{\ (1-\beta)} \qquad 4$$

The value of α and β vary according to the particle type and the bed temperature.

Table 3 Values of empirical constants of Equation 4 derived from experimental data

Bed Temperature (^{o}C)	Particles	α	β
200~500	Sand	0.15	0.664
200~500	coke	0.38	0.540

The new empirical correlation shows a much better agreement with the experimental data, compared to existing correlations, as illustrated in Figures 9 and 10. The relationships among the horizontal jets, bed solids characteristics and operating conditions are complex. The effects of nozzle gas mass flow-rate, nozzle size, and operation temperature on the penetration length are well predicted by the new empirical correlation for supersonic horizontal nozzles proposed in this work.

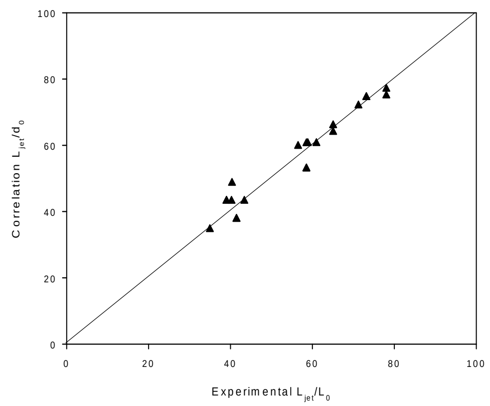

Figure 9 Comparison of new empirical correlation with experimental data (Petroleum coke, high temperature)

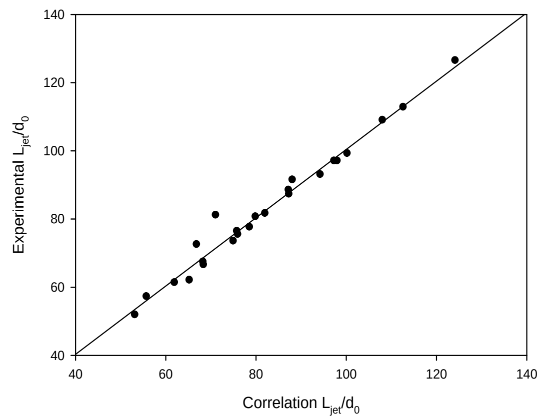

Figure 10 Comparison of new empirical correlation with experimental data (Silica sand, high temperature)

Conclusion

A novel technique has been developed to measure the penetration length of high velocity horizontal jets in fluidized beds at high temperatures. Based on the experimental data obtained, a new and improved empirical correlation has been proposed, derived with a variety of nozzle sizes, gas properties, and operating temperatures.

Notation

b	radius of jet region(m)
d_0	nozzle exit diameter (m)
d_p	particle diameter (m)
d_t	nozzle thoat diameter (m)
g	gravity constant (m/s^2)
h	inclined nozzle position (m) (Hong correlation)
h_0	bed depth (m) (Hong correlation)
L_j	Jet penetration depth (m)
U_0	gas velocity at nozzle (m/s)
u	velocity at jet axis (m/s)
u_m	velocity at radius (m/s)

Greek letters

α	correlation constant
β	correlation constant
ε	Bed voidage (-)
ξ	Specific heat ratio of the gas (-)
ρ_0	Gas density at the nozzle exit (kg/m^3)
ρ_f	Gas density in the bed (kg/m^3)
ρ_p	Particles density in the bed (kg/m^3)

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