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EVALUATION OF THE JET PENETRATION DEPTH IN GAS-FLUIDIZED BEDS BY PRESSURE SIGNAL ANALYSIS

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Abstract—The interaction between a single jet and a bed of fluidized solids was investigated with the aim of evaluating a characteristic height of the jetting region corresponding to the distance from the nozzle at which the dispersion of jet momentum is practically complete. A new experimental technique, based on simultaneous measurements of the static pressure at the bed side wall and on the jet axis and on their elaboration, was used. Various experimental configurations, based on the combination of two fluidization columns (0.35 and 0.20 m, i.d.) and four jet nozzles (6, 10, 19 and 25 mm, i.d.), were employed. Glass ballotini of 800–1200 μm were used as bed material. The influence of the nozzle gas velocity, of the fluidization velocity, and of the nozzle and the column sizes on the characteristic height of the jet was investigated. This height increases as nozzle gas velocity and nozzle size increase. In contrast, the influence of the fluidization velocity appears more complex and, in particular, cannot be separated from that of the nozzle diameter. The effect of the column diameter was negligible. Experimental results were compared with predictions of jet penetration length from literature correlations since the characteristic height shows up evident similarities with the jet penetration length based on momentum dissipation. © 1997 Elsevier Science Ltd.

Key Words: fluidization, gas jets, pressure fluctuations, jet penetration depth

1. INTRODUCTION

Gas injection in fluidized bed through an upward facing orifice may result in a number of patterns ranging from the periodic formation of single bubbles at the orifice to the establishment of a permanent cavity above the orifice behaving like a jet. A complex interrelation between nozzle and column geometry, bed solids characteristics and operating conditions of the jet-fluidized bed system results in the establishment of one of several possible configurations (Rowe *et al.* 1979; Yang and Keairns 1979; Yates *et al.* 1984; Massimilla 1985; Tsukada and Horio 1990; Huang and Chyang 1991).

Irrespective of the type of configuration assumed, the momentum rate associated with gas injection produces fluid-dynamic disturbances downstream from the nozzle (Behie *et al.* 1970; Werther 1978; Knowlton and Hirsan 1980; Massimilla 1985; Musmarra *et al.* 1992; Musmarra *et al.* 1995; Kimura *et al.* 1995). The distance L_j, to which such disturbances extend, is known as jet penetration length (Knowlton and Hirsan 1980). The knowledge of the jet penetration length in fluidized beds is mainly relevant to two applications. One is the minimum distance from the nozzle at which bed internals, such as tube banks and buffles, can be safely located to prevent erosion by the gas–solid mixture. The other is the extension of the region downstream from the nozzle where high gas–solids relative velocities enhance mass and heat transfer rates increasing significantly the overall process rate when fast chemical reactions occur.

A large number of measurements of jet penetration length in fluidized beds have been performed by means of various techniques ranging from the simple direct visual observation to the sophisticated measurements by X- and γ-radiation densimeters (Zenz 1968; Basov *et al.* 1969; Behie *et al.* 1970; Behie *et al.* 1971; Markhevka *et al.* 1971; Merry 1975; Wen *et al.* 1977; Knowlton and Hirsan 1980; Hirsan *et al.* 1980; Wen *et al.* 1982; Yutani *et al.* 1983; Yates *et al.* 1986; Raghunathan *et al.* 1988; Tsukada and Horio 1990; Kimura *et al.* 1995). In spite of the extensive experimental work carried out, a generalized expression for L_j prediction, able to describe the variety of working conditions encountered in practice, is still lacking. Actually, various empirical and semi empirical correlations have been developed on the basis of experimental findings (Shakhova 1968; Basov *et al.* 1969; Vahkrushev 1972; Merry 1975; Wen *et al.* 1977; Yang and Keairns 1978; Yang and Keairns 1979; Hirsan *et al.* 1980; Wen *et al.* 1982; Yates *et al.* 1986; Blake *et al.* 1990; Tsukada and Horio 1990) but large discrepancies subsist between them as was remarked by Massimilla (1985). The reasons for the spread of results sometimes in conflict with each other may be ascribed to the markedly unsteady character of the phenomenon, to the subjectivity of some L_j measurements and to the ambiguity about what was measured as jet penetration length. For instance, according to Merry (1975), L_j is defined as the distance from the nozzle at which the jet plume degenerates into a gas bubble. Alternatively, definitions based on the momentum dissipation of the jet were proposed (Behie *et al.* 1971). They have been supported by experimental evidences (Yang and Keairns 1978; Knowlton and Hirsan 1980) showing that detached bubbles may still possess a significant portion of the jet momentum. An attempt to clarify the matter was made by Knowlton and Hirsan (1980) distinguishing among three different penetration lengths of the jet: the deepest penetration of jet bubbles into bed before losing their momentum, L_B, the penetration length of a series of interpenetrating cavities, L_{max}, and the penetration length of a cavity permanently attached to the nozzle, L_{min}.

In the context above, the distance at which bed internals can be safely located, being related to the complete dispersion of the jet momentum, conforms to the definition of L_j by Behie *et al.* (1971) that substantially coincide with L_B. On the contrary, the distance where the gas–solids relative velocity is high seems to be closer to the definitions of L_j by Merry (1975) or, equivalently, of L_{max} (Knowlton and Hirsan 1980). In this view, indeed, the distance L_{max} from the nozzle may be recognized as that at which the gas–solids relative velocity has become low at such a point that the transfer process rate slows down significantly but the overall gas–solids mixture may still possess enough momentum to represent a threat for obstacles located along its path.

Recently, the present authors developed a novel experimental technique for the determination of a characteristic height of the jetting region (Vaccaro *et al.* 1997) which is an improvement on a method previously devised by Vaccaro *et al.* (1989). The technique, based on the comparison of fluctuations of the static pressure simultaneously recorded at the bed wall and on the jet axis during normal jet-fluidized operation, yields a characteristic height corresponding to the distance at which the dispersion of jet momentum is practically complete, i.e. to L_B (Knowlton and Hirsan 1980). With respect to other techniques it is relatively simple to apply and does not require moving parts inside the bed. Therefore, it appears particularly appropriate for measurements of jet penetration length at high temperature and/or high pressure.

The purpose of the present paper is to apply this technique to study how geometrical and operating variables affect the jet penetration length. L_B measurements have been carried out varying nozzle gas velocity and nozzle size and the results have been compared with available literature correlations for L_j. In addition, the influence on L_B of variables which have been studied less, such as column size and fluidization velocity, has been investigated.

2. EXPERIMENTAL

2.1. Apparatus

A sketch of the experimental apparatus is given in figure 1. Two cylindrical fluidization columns made of perspex, with inner diameters (D_c) of 0.35 and 0.20 m, were used in the experiments. For both columns the distributor for the fluidizing gas was a perforated plate whose 0.6 mm holes are arranged in a 2 mm square pitch. An axially-upward discharging nozzle, flush with and centered on the distributor, was used to inject gas at high velocity. Four different nozzle diameters (d_n) (0.006, 0.010, 0.019 and 0.025 m) were tested. Column and nozzle combinations employed in the experiments gave rise to the six different geometrical configurations listed in table 1. Separate air feeds were provided for fluidizing gas and jet gas.

Measurements of static pressure were carried out at the wall using a pressure tapping located on the column wall 0.06 m above the gas distributor. At the same height measurements of

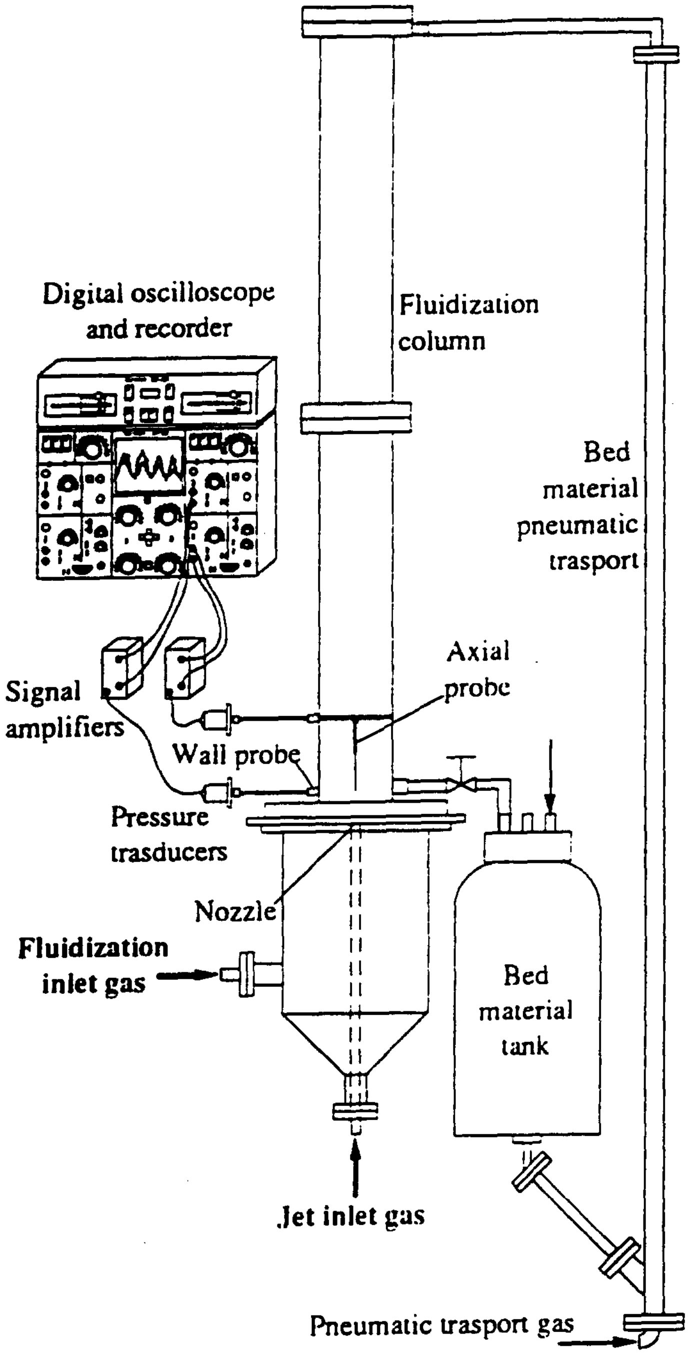

Figure 1. Experimental apparatus.

static pressure were also carried out on the column axis using an axial probe made of 1.0 mm, o.d. tube with a closed conical tip. Four 0.3 mm pressure tapping are drilled on the lateral surface of the axial probe 5 mm from the tip, corresponding to a distance of 0.06 m from the gas distributor.

Table 1. Geometrical configurations used in the experiments

	$d_n = 0.006$ m	$d_n = 0.010$ m	$d_n = 0.019$ m	$d_n = 0.025$ m
$D_c = 0.20$ m	A	B	C	D
$D_c = 0.35$ m		E		F

Glass ballotini of 800–1200 μm with density (ρ_p) of 2600 kg/m^3 were used as bed material. For this material the measured minimum fluidization velocity (U_{mf}) is 0.55 m/s and the bed voidage at minimum fluidization (ϵ_{mf}) is 0.445. Bed height (H_b) was varied between 0.1 and 0.8 m. The nozzle gas velocity (u_j) was varied over the range 35–95 m/s while the fluidization velocity was varied from 1.1 to 2.3 times that of minimum fluidization. All the experiments were performed at ambient temperature and pressure.

The data acquisition system includes Schaevitz P502 strain-gauge pressure transducers, signal amplifiers and a Nicolet 4094 digital oscilloscope and recorder. Simultaneous pressure–time records were taken on the axis and at the wall of the column. Both records consist of about 8000 point values at equally spaced intervals of 0.02 s. The corresponding run time is about 160 s.

2.2. *Technique*

The experimental technique, discussed in detail elsewhere (Vaccaro *et al.* 1997), is based on the comparison between the signals of static pressure simultaneously recorded at the wall and on the jet axis during normal jet-fluidized bed operation. This comparison is implicitly obtained through the evaluation of a parameter Y_d, defined as:

$$Y_d = \frac{1}{P_{wav}} \sqrt{\frac{\sum_N (P_j(t) - P_w(t))^2}{N}} \qquad [1]$$

where $P_j(t)$ and $P_w(t)$ are the pressures simultaneously recorded, respectively, on the jet axis and the bed side wall at time t. N is the number of data points and P_{wav} is the average of the $P_w(t)$ values. Y_d may be considered as the standard deviation of the axis pressure profile with respect to the wall profile. Indeed, it is a measure of the difference between the axis pressure profile and the corresponding wall profile. In particular, when axis and wall profiles approach each other, Y_d approaches zero, while it progressively increases as the differences between axis and wall pressure profiles increase. Typical trends of Y_d as a function of H_b for four different experimental configurations are shown in figure 2 from which it is evident that as H_b increases, Y_d decreases and asymptotically approximates zero. Results presented in figure 2 support the evaluation of a characteristic height, H_j, of the jetting region. It is the bed height at which disturbances attributable to the jet flow become negligible compared with bed disturbances; pressure fluctuation intensities are then virtually equal everywhere in the bed. Such a height may be defined as that for which Y_d is practically zero, e.g. $\simeq 0.1$ as exemplified in figure 2.

It is worth noting that the choice of the limiting value of Y_d is somewhat arbitrary. Actually, it must be well above zero that represents the asymptotic value as H_b increases. The limiting value of 0.1 for Y_d was chosen in previous work (Vaccaro *et al.* 1997) where the present technique was developed. In that paper the height H_j was first determined on the basis of the comparison between the Power Density Spectra (PDS) of the signals as the bed height at which the areas below the spectra of the axis and wall pressure signals were practically coincident. In the same paper it was also realized that the same results, in terms of H_j, could be obtained by direct comparison of the pressure records through the evaluation of the parameter Y_d. The critical value of Y_d was chosen by matching the characteristic heights obtained by the first and the second procedure. A sensitivity analysis of H_j with respect to variations of the limiting value for Y_d around 0.1 ($0.095 < Y_d < 0.105$), performed on the whole set of data, yielded an average error on H_j of 6%, even though in a few cases (as in the case shown in figure 2(a)) it reached much larger values, i.e. 16%.

The values of H_j in figure 2 were obtained from Y_d values evaluated by pressure measurements taken at 0.06 m above the distributor. However, in previous work (Vaccaro *et al.* 1997) the authors showed that if the evaluation of Y_d were performed with axis and wall pressure signals measured at a different distance from the distributor, the value of H_j would be the same.

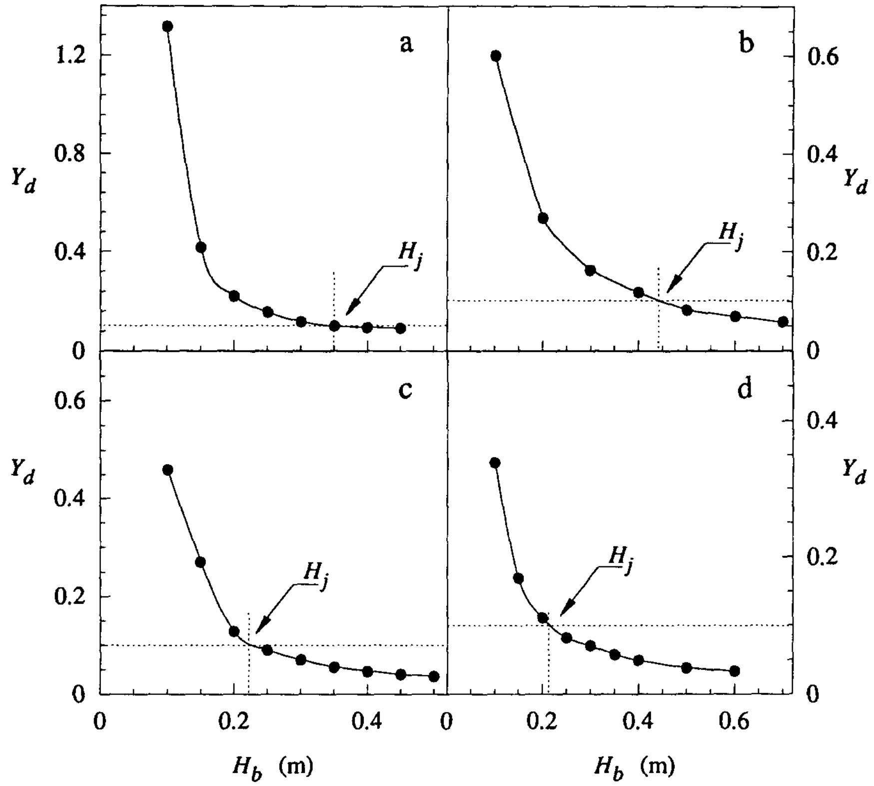

Figure 2. Typical trends of Y_d as a function of H_b and determination of the characteristic height H_j.

Figure	a	b	c	d
Configuration	D	F	B	E
u_j, m/s	35	35	35	35
U/U_{mf}	2.27	1.55	1.18	2.00

3. RESULTS

3.1. *Qualitative*

Typical pressure–time profiles recorded in the 0.2 m, i.d. column equipped with the 0.025 m, i.d. nozzle (configuration D in table 1) are reported in figure 3. In particular, figure 3(a)–(c) show profiles obtained at the same bed height ($H_b = 0.50$ m), at two fluidization velocities for a given u_j (figure 3(a) and (b)), and at two nozzle gas velocities for a given U/U_{mf} (figure 3(b) and (c)). In the same way, figure 3(d)–(f) and figure 3(g)–(i) report profiles recorded at $H_b = 0.25$ and 0.15 m, respectively. With $H_b = 0.50$ m the wall pressure profile (dashed line) closely follows that on the jet axis (continuous line) when U/U_{mf} is above 2 (figure 3(b)). On the contrary, the profiles exhibit considerable differences in frequency and amplitude when U/U_{mf} approaches 1 (figure 3(a)). Alternatively, even when $U/U_{mf} = 2.27$, differences between wall and axis profiles emerge with u_j increasing from 35 m/s (figure 3(b)) to 95 m/s (figure 3(c)). Decreasing H_b enhances differences between the two signals in both cases where at $H_b = 0.50$ m the signals were nearly coincident (figure 3(e) and (h)) or already intersecting (figure 3(d), (f), (g) and (i)). Similar results were previously observed in 2D columns (Filla *et al.* 1986) and 3D (Vaccaro *et al.* 1989).

The influence of the nozzle diameter on the wall and axis pressure profiles can be appreciated from figure 4. For given u_j, U/U_{mf} and H_b, an increase in the nozzle diameter from 0.006 to 0.025 m results in a progressive change from nearly coincident profiles to profiles which intersect each other.

The effect of the column diameter on the characteristics of wall and axis pressure profiles can be seen from figure 5. For a given operating condition, an increase in the column diameter from

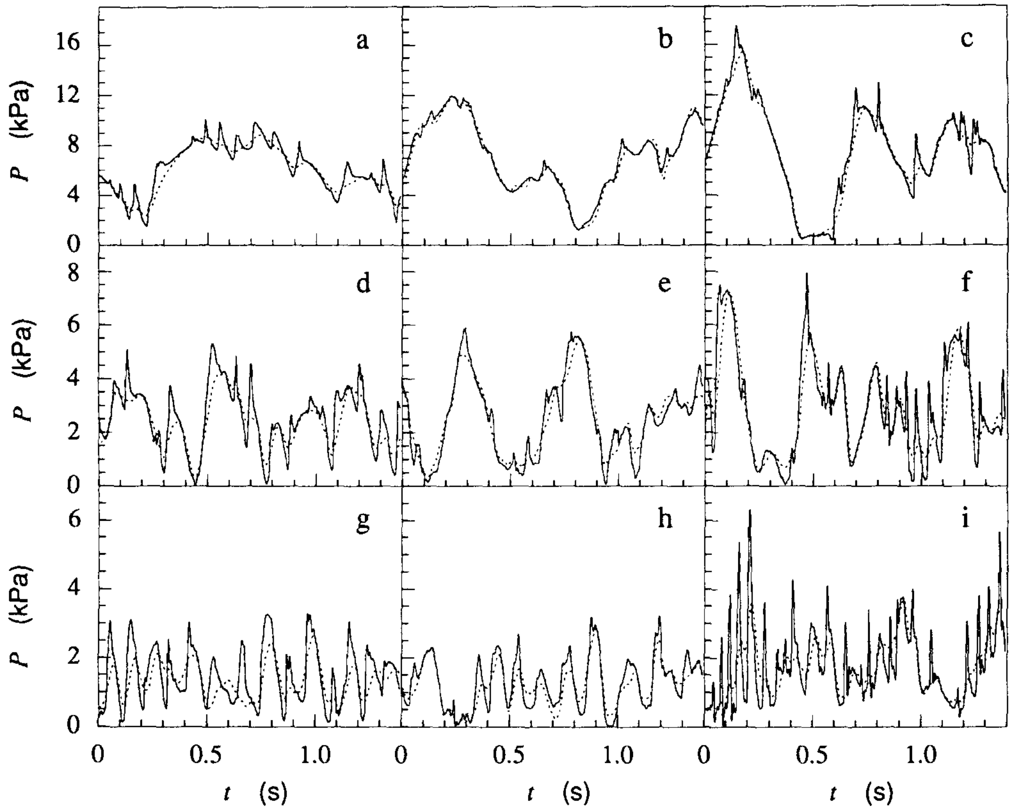

Figure 3. Wall (·····) and axis (——) pressure-time profiles recorded in the geometrical configuration D at different values of u_j, U/U_{mf} and H_b.

Figure	a	b	c	d	e	f	g	h	i
u_j, m/s	35	35	75	35	35	75	35	35	75
U/U_{mf}	1.1	2.3	2.3	1.1	2.3	2.3	1.1	2.3	2.3
H_b, m	0.50	0.50	0.50	0.25	0.25	0.25	0.15	0.15	0.15
Y_d	0.091	0.072	0.078	0.248	0.157	0.308	0.491	0.419	0.685

0.20 to 0.35 m does not significantly change the relative characteristics of the wall and axis profiles either when d_n is 0.01 m and when it is 0.025 m. However, for both values of d_n the amplitudes of the axis and wall signals decrease as D_c increases.

The set of Y_d values, calculated from pressure profiles in figures 3–5 and reported in the captions of such figures, reflect the qualitative observations above. Indeed, Y_d progressively decreases as H_b increases and is lower than 0.1 only when H_b is 0.5 m (figure 3). Furthermore, Y_d values increase as the nozzle diameter increases (figures 4 and 5), while they are substantially constant as D_c changes (figure 5).

The overall results show that wall pressure profiles approach axis profiles only at high H_b. This result means that disturbances associated with the introduction of gas flow through the jet affect conditions at the wall only if the bed is sufficiently high that the jet does not penetrate the bed. Specifically, in the case of relatively shallow beds (figure 3 (g)–(i)) differences in frequency and in amplitude of wall and axis signals are associated with a more or less pronounced bed penetration by the gas discharged at the nozzle. In this case the jet momentum is not completely transferred to the dense phase but it is dispersed in the solid spout above the bed free surface. With increasing bed height, the wall signal progressively approaches the axis signal and less frequent bed penetrations occur. Above a certain H_b wall and axis signals become substantially equal and solids spouts above the free surface disappear showing that periodic pinching of the jet and bubble generation exert their full effects on the bed and hence at the wall.

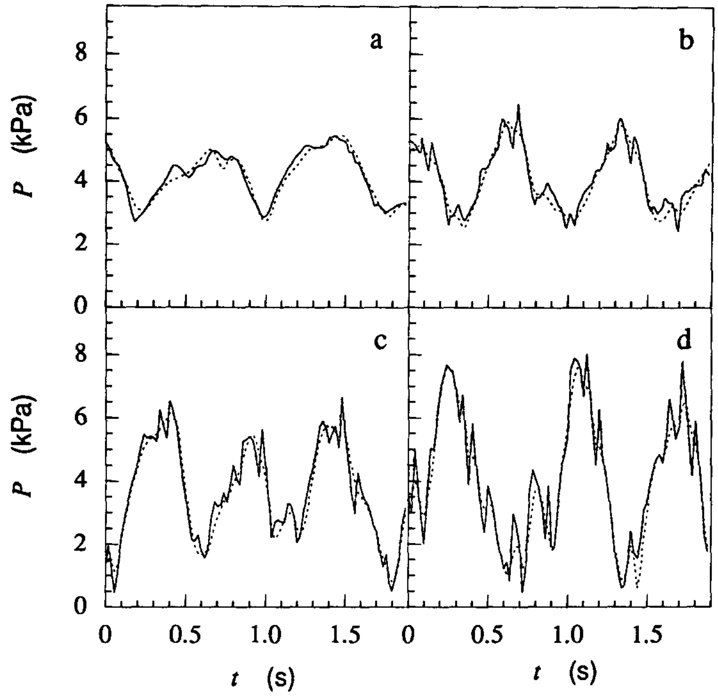

Figure 4. Wall (. . .) and axis (—) pressure-time profiles recorded at the same operating conditions at four different nozzle sizes. $D_c = 0.2$ m; $u_j = 35$ m/s; $U/U_{mf} = 1.35$; $H_b = 0.35$ m.

Figure	a	b	c	d
d_n, m	0.006	0.010	0.019	0.025
Y_d	0.056	0.073	0.116	0.144

3.2. *Quantitative*

Extensive evaluations of H_j, performed using the procedure shown in figure 2, have been carried out. In particular, H_j was evaluated for the six geometrical configurations reported in table 1 by changing both nozzle gas and fluidization velocities.

Experimental results of H_j, obtained at $U/U_{mf} = 1.35$ in the geometrical configurations A, B, C and D in table 1, are reported in figure 6 as a function of nozzle gas velocity u_j. For all nozzle diameters H_j increases with a decreasing slope as u_j increases. Furthermore, the larger the nozzle diameter the higher H_j.

The effect of the fluidization velocity on H_j, for a given u_j, is shown in figure 7 where data, obtained for the geometrical configurations A, B, C and D in table 1, are reported. Data pertaining to the larger nozzle (configuration D) show that H_j decreases monotonically from 0.5 to 0.3 m when U/U_{mf} changes from 1 to 2.6. On the contrary, data pertaining to the smaller nozzle (configuration A) show that H_j slightly increases in the same range of U/U_{mf}. Data relative to the other two nozzles lie between the boundaries above.

The influence of the column diameter on the characteristic height H_j is shown in figure 8 which shows data for H_j vs u_j obtained in the column configurations B, D, E and F in table 1, i.e. with the two column diameters and with 0.010 and 0.025 m nozzle diameters. For both values of d_n a change in column diameter does not significantly affect the values of H_j, whatever the value of u_j. This result is in conformity with the slight differences in the relative characteristics of the wall and axis profiles (figure 5) as D_c changes. Furthermore, results in figure 8 suggest that the decrease of signals amplitude as D_c increases, evident from figure 5, do no affect the value of H_j. The slight influence of D_c is also confirmed by H_j data reported in figure 9 as a function of U/U_{mf}, for various geometrical configurations. It is worth noting that Blake *et al.* (1990), correlating experimental data of jet penetration length, found that L_j/d_n is a very weak function of D_c.

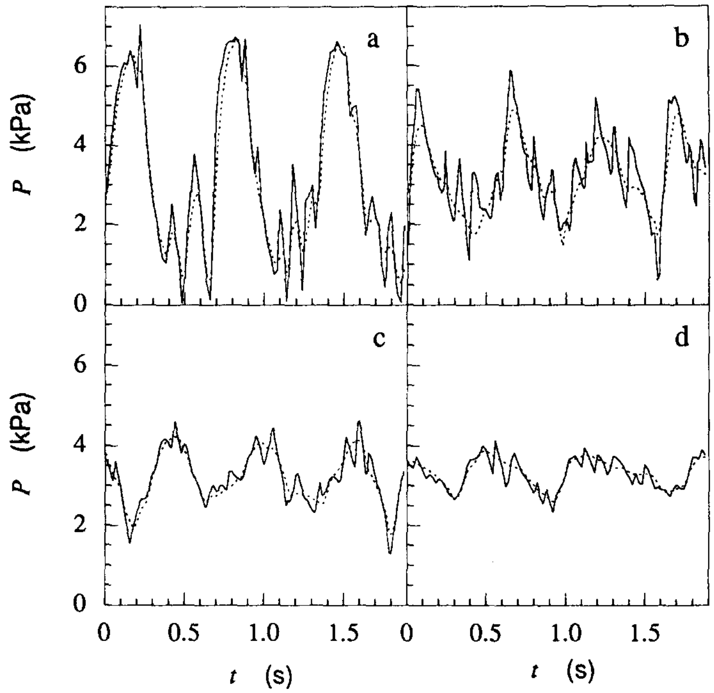

Figure 5. Wall (. . .) and axis (—) pressure-time profiles recorded at the same operating conditions in four different geometrical configurations. u_j35 m/s; $U/U_{mf} = 1.35$; $H_b = 0.30$ m.

Figure	a	b	c	d
Configuration	D	F	B	E
Y_d	0.173	0.164	0.059	0.057

4. DISCUSSION

The characteristic height H_j defined above (figure 2) represents the bed height at which pressure fluctuations, specifically caused by jet phenomena, become practically negligible with respect to those at the bed side wall. Since pressure fluctuation intensities reflect momentum associated with gas and solids in the dense phase and in the jet, H_j corresponds to the distance at which the dispersion of jet momentum is practically complete. This definition conforms to that of jet penetration depth L_B proposed by Knowlton and Hirsan (1980). This is, indeed, defined as the greatest depth of penetration of jet bubbles into the bed before they lose their momentum. The parallel between H_j and L_j may present a limit in that L_j has been obtained by gas injection in deep beds while H_j is determined as limiting value for beds of progressively increasing heights. However, the limit above is only apparent in that all the experimental data of L_j have been obtained under the implicit assumption that the bed height or the depth of bed above L_j could not influence significantly L_j. Furthermore, when specific investigations on this point were made, it was found that the bed height did not influence the jet penetration length (Basov *et al.* 1969).

Comparisons of H_j with the relevant literature correlations for L_j (Basov *et al.* 1969; Merry 1975; Yang and Keairns 1978; Yang and Keairns 1979; Hirsan *et al.* 1980; Wen *et al.* 1982; Yates *et al.* 1986, Blake *et al.* 1990) have been performed. The comparison is limited to these correlations in that they are all dimensionless in form and are often quoted in the literature. The correlations by Shakhova (1968), Vahkrushev (1972) and Tsukada and Horio (1990) have been excluded because of the difficulty in determining parameters involved in them. Blake *et al.* (1990) proposed separate correlations for single jet and multiple jets penetration lengths both of which are considered here for comparison; in the following they will be indicated as SJ–Blake *et al.* (1990) equation and MJ–Blake *et al.* (1990) equation, respectively. Hirsan *et al.* (1980) proposed two

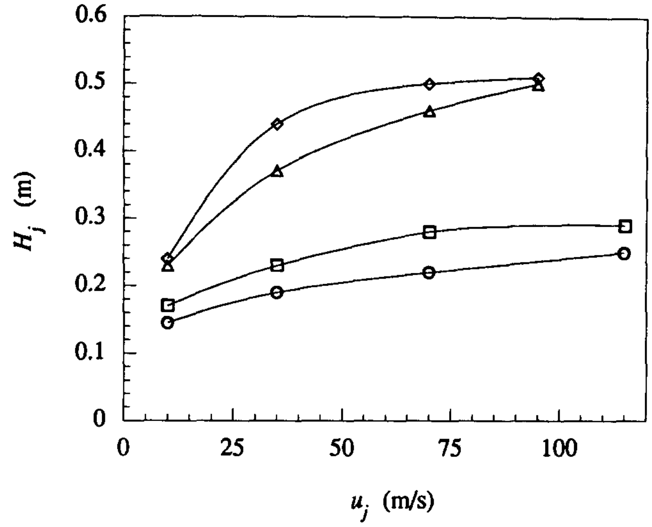

Figure 6. Characteristic height H_j as a function of nozzle gas velocity at four different nozzle sizes. $U/U_{mf} = 1.35$.

	○	□	△	◇
Configuration	A	B	C	D

different correlations: one for L_{max} and another for L_B. Here we consider only the latter since its definition conforms better to the meaning of H_j.

A two phase Froude number (Fr), has been suggested as the relevant dimensionless group for the jet-fluidized bed system (Yang and Keairns 1978; Yang and Keairns 1979; Hirsan *et al.* 1980; Yang 1981; Filla and Massimilla 1984). It is generally included, even though with slight differences from case to case, in the jet penetration length correlations. Therefore, the correlation of H_j data against such a parameter would be appropriate, but this has been omitted in this work since the use of a single bed material makes the influence of Fr equivalent to that of u_j.

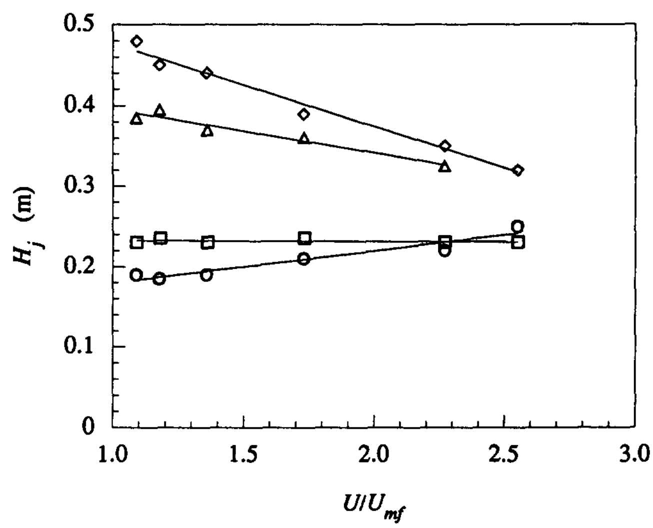

Figure 7. Characteristic height H_j as a function of the relative fluidization velocity at four different nozzle sizes. $u_j = 35$ m/s.

	○	□	△	◇
Configuration	A	B	C	D

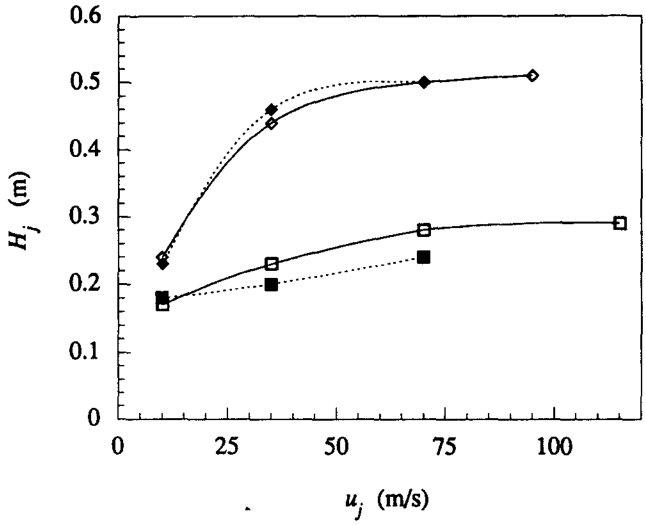

Figure 8. Characteristic height H_j as a function of nozzle gas velocity in four different experimental configurations. $U/U_{mf} = 1.35$.

	□	◇	■	◆
Configuration	B	D	E	F

In figures 10 and 11 values H_j from figure 6, made dimensionless with respect to the nozzle diameter, are compared with predictions of equations for dimensionless jet penetration length as a function of u_j at four different nozzle sizes. For the sake of clarity some of the predictions of literature correlations for L_j/d_n have been reported in figure 10 and some in figure 11. Only the predictions of Basov *et al.* (1969) and Yang and Keairns (1979) equations are reported in both figures together with experimental values of H_j/d_n. The comparison between predictions and experimental findings shows that there is a fair agreement between measured H_j/d_n and the predictions of Basov *et al.* (1969) and of Yang and Keairns (1979) equations. The Basov *et al.* (1969) equation better describes H_j results obtained with the smaller nozzles, while the Yang and

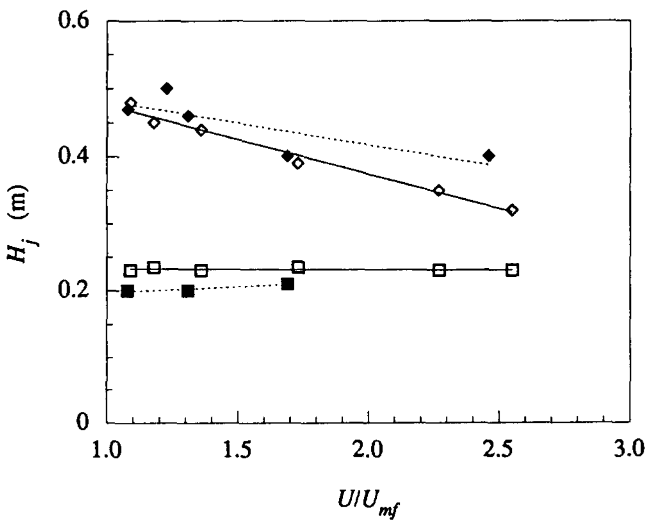

Figure 9. Characteristic height H_j as a function of the relative fluidization velocity in four different experimental configurations. $u_j = 35$ m/s.

	□	◇	■	◆
Configuration	B	D	E	F

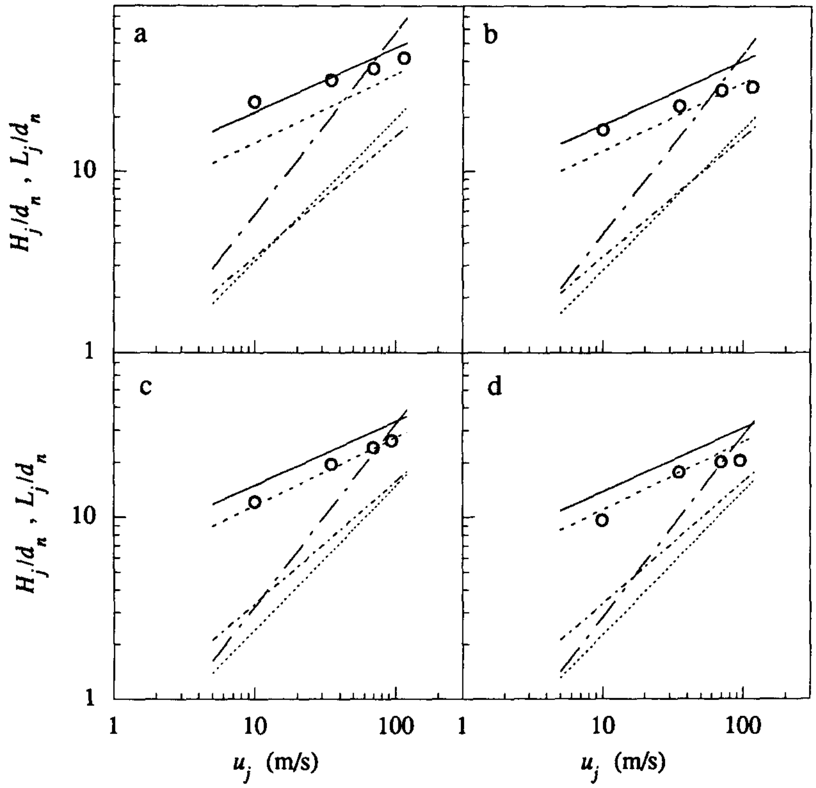

Figure 10. Dimensionless characteristic heights from the experiments (symbol) and predictions of correlations for dimensionless jet penetration lengths (lines) as a function of u_j at four different nozzle sizes. $U/U_{mf} = 1.35$.

Basov *et al.* (1969)	——
Yang and Keairns (1979)	-----
Hirsan *et al.* (1980)	-·-·-
Yates *et al.* (1986)	...
Yang and Keairns (1978)	-·---

Figure	Configuration
a	A
b	B
c	C
d	D

Keairns (1979) equation seems more appropriate for predicting results pertaining to the larger nozzles. The other equations strongly underpredict H_j/d_n. In particular, in some cases the discrepancies regard the trend of H_j/d_n with u_j, as shown in figure 10, while in the other cases the trend appears correct but the curves are markedly shifted downwards with respect to the experimental points (figure 11).

The values of H_j/d_n, obtained at different u_j and at $U/U_{mf} = 1.35$, are reported in figure 12 as a function of d_n together with the L_j/d_n predictions. The comparison is limited to those correlations for which L_j/d_n is a function of d_n (Basov *et al.* 1969; Merry 1975; Yang and Keairns 1978; Yang and Keairns 1979; Wen *et al.* 1982; Yates *et al.* 1986; Blake *et al.* 1990). Once again the Basov *et al.* (1969) and Yang and Keairns (1979) equations show a fair agreement with the experimental findings (figure 12) even though the slope of the lines does not conform closely to the experimental trend. The lines obtained from Wen *et al.* (1982) and Yang and Keairns (1978) equations show a slope in agreement with that found experimentally; however, the line of Wen *et al.* (1982) is lower by more than 30 nozzle diameters, while that of Yang and Keairns (1978) strongly underestimates H_j/d_n at a low nozzle gas velocity (figure 12(a)) but shows a very good agreement at high u_j (figure 12(c)). This peculiar behaviour reflects the fact that the Yang and Keairns (1978) correlation correctly predicts the H_j/d_n trend with d_n but it is not able to describe the trend with u_j (figure 10). Actually, data in figure 12(c) correspond to the points in figure 10 intersected by the line of the Yang and Keairns (1978) equation. Merry's (1975) equation, in contrast with the H_j/d_n trend, predicts that, L_j/d_n increases as d_n increases. The others equations (Yates *et al.* 1986; SJ–Blake *et al.* 1990; MJ–Blake *et al.* 1990) show a trend with respect to d_n similar to those shown by the Basov

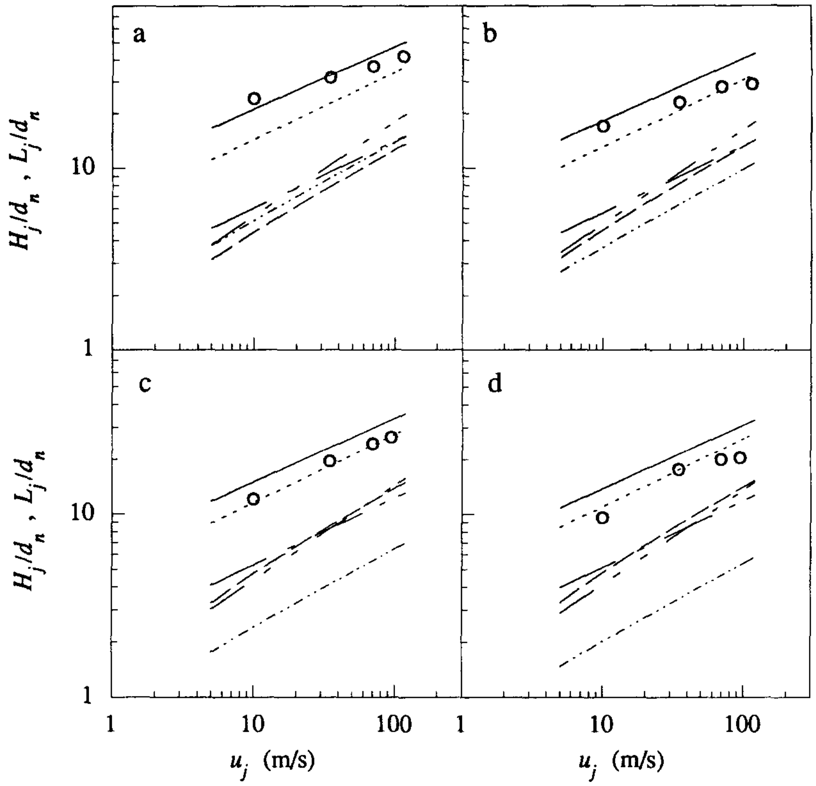

Figure 11. Dimensionless characteristic heights from the experiments (symbol) and predictions of correlations for dimensionless jet penetration lengths (lines) as a function of u_j at four different nozzle sizes. $U/U_{mf} = 1.35$.

Basov *et al.* (1969)	——
Yang and Keairns (1979)	-----
Merry (1975)	–––––
Wen *et al.* (1982)	–··–··–··–
SJ-Blake *et al.* (1990)	––·––·––
MJ-Blake *et al.* (1990)	—·—

Figure	Configuration
a	A
b	B
c	C
d	D

et al. (1969) and Yang and Keairns (1979) equations, but, whatever u_j, they strongly underpredict the experimental values.

The influence of fluidization velocity on L_j has been, generally, disregarded in the studies on jet penetration length except in the case of Yates *et al.* (1986). Operating with beds of coke and alumina, they found a decreasing trend of L_j with U/U_{mf} even though they did not incorporate such findings in the correlation they proposed. The only attempt to take into account the influence of U/U_{mf} in a jet penetration length correlation was made by Hirsan *et al.* (1980) through the ratio U/U_{cf}, where U_{cf} is the velocity required for complete fluidization which is more adequate than U_{mf} to define the degree of fluidization of the bed when solids containing a wide size range are employed. As suggested by Hirsan *et al.* (1980) U_{cf} is considerably higher than U_{mf} for solids of wide size range. However, the ratio U/U_{cf}, for a sufficiently narrow sized solids, as in the case of the present work, reduces to U/U_{mf} and, hence, in the correlation of Hirsan *et al.* (1980) U_{mf} has been used in place of U_{cf}. The comparison in figure 13 between experimental H_j/d_n and predicted L_j/d_n (Hirsan *et al.* 1980) appears poor. Indeed, on the one hand the predictions underestimate the experimental results whatever the value of d_n and, on the other hand, the trend with U/U_{mf}, shown by the correlation, conforms to that obtained with the larger nozzles but is the opposite to that obtained with the smaller nozzles. Such discrepancies are attributable to the fact that U/U_{mf} in Hirsan *et al.* (1980) correlation is raised to the power -0.24 and, therefore, it is not able to predict the different slopes shown by experimental results in figure 13. Furthermore, in the Hirsan *et al.* (1980) correlation L_j/d_n does not depend on d_n while the experimental value of H_j/d_n does, as shown in figure 13.

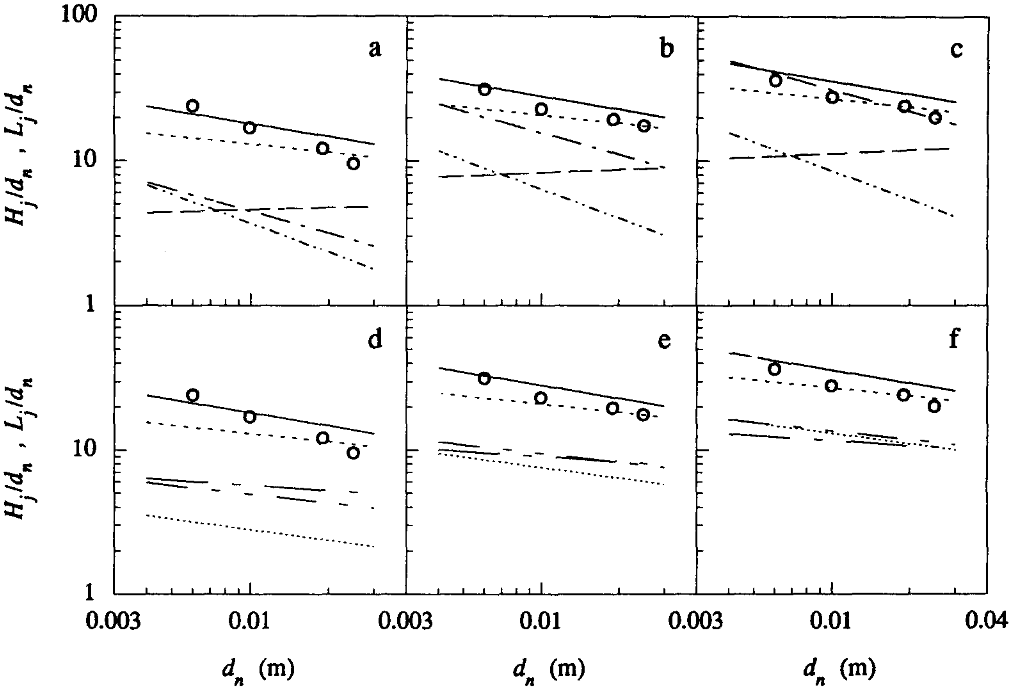

Figure 12. Dimensionless characteristic heights from the experiments (symbol) and predictions of correlations for dimensionless jet penetration lengths (lines) as a function of d_n at three different nozzle gas velocities. $U/U_{mf} = 1.35$.

Basov *et al.* (1969)	——
Yang and Keairns (1979)	-----
Merry (1975)	—— ——
Wen *et al.* (1982)	—··—··—
Yang and Keairns (1978)	—·—·—
Yates *et al.* (1986)	·····
SJ–Blake *et al.* (1990)	——·—·——
MJ–Blake *et al.* (1990)	— ▬ —

Figure	u_j, m/s
a, d	10
b, e	35
c, f	70

Figures 10–12 suggest that the Basov *et al.* (1969) and Yang and Keairns (1979) equations correctly predict experimental results while the other equations strongly underestimate the same data. Although this situation is quite common in dealing with jet penetration length in fluidized beds (Massimilla 1985), it deserves further considerations in order to understand better the meaning of the agreements and of the discrepancies in figures 10 and 12.

The first consideration is that among the correlations for L_j/d_n employed for the comparison with H_j/d_n there are some which are specifically derived for the penetration length of jets in multiple jet configurations (Basov *et al.* 1969; Yang and Keairns 1979; Wen *et al.* 1982; MJ–Blake *et al.* 1990) and others formulated for the prediction of single jet penetration lengths (Merry 1975; Yang and Keairns 1978; Hirsan *et al.* 1980; Yates *et al.* 1986; SJ–Blake *et al.* 1990). It is remarkable that correlations of the first group such as those by Basov *et al.* (1969) and Yang and Keairns (1979), but not those of the second group, describe well the experimental results of the present work, which were obtained operating with a single nozzle. This result is only apparently contradictory. Indeed, Yang and Keairns distinguished between equations for a single jet (Yang and Keairns 1978; Yang 1981) and the equation for multiple jets (Yang and Keairns 1979) which is based on the data obtained with multiple jets by Basov *et al.* (1969), Behie *et al.* (1971) and Wen *et al.* (1977). They also showed that such an equation correlated single jet penetration length data by Zenz (1968), Behie *et al.* (1971), Vahkrushev (1972), Markhevka *et al.* (1971) and Wen *et al.* (1977) with the same accuracy. This implicitly suggests that the differences between single jet data and multiple jet data were no greater than between those in each set.

Similar conclusions can be drawn with respect to the equations for jet penetration length derived by Blake *et al.* (1990) (figures 11 and 12(d)–(f)). Indeed, single and multiple jet equations show

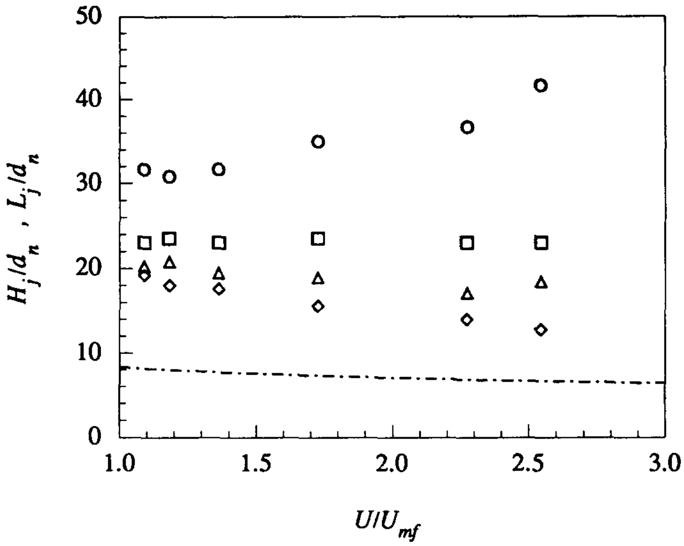

Figure 13. Dimensionless characteristic heights from the experiments (symbol) and prediction of Hirsan *et al.* (1980) correlation for the dimensionless jet penetration length (-.-.-) as a function of U/U_{mf} at four different nozzle sizes. $u_j = 35$ m/s; $D_c = 0.020$ m.

	○	□	△	◇
d_n, m	0.006	0.010	0.019	0.025

only small differences even though the authors derived the equation for multiple jets by correlating data of Basov *et al.* (1969), Behie *et al.* (1971), Tanaka (1980), Deole (1980) and Wen *et al.* (1977) and that for a single jet by correlating data of Markhevka *et al.* (1971), Yang and Keairns (1978), Knowlton and Hirsan (1980), Sit and Grace (1981), Ku (1982) and Yang *et al.* (1984).

The agreements and the discrepancies observed in figures 10–12 may be interpreted by considering the origin of the experimental data on which the various correlations are based. This can be accomplished by analyzing the kind of penetration length that a given experimental technique can yield. On the basis of such analysis, made recently by Vaccaro *et al.* 1997, it is possible to classify the various techniques into two main groups: the first group includes those suitable for L_{max} measurements and the second those appropriate for L_B evaluations. All the optical techniques, the capacitance probe technique and the radiation densimeter technique employed by Yates *et al.* (1986) pertain to the first group. The second group comprises the Pitot tube techniques, the radiation densimeter technique used by Basov *et al.* (1969) and the technique employed in this paper (i.e. the simultaneous measurement of axial and wall static pressure). The Basov *et al.* (1969) correlation was based on their own data, obtained by the radiation densimeter technique, and Yang and Keairns (1979) correlation was derived mainly on the basis of Basov *et al.* (1969) data and of data obtained by Pitot tube techniques. On the contrary, the equations of Merry (1975), Yang and Keairns (1978), Wen *et al.* (1982), Yates *et al.* (1986) and SJ–Blake *et al.* (1990) were derived on the basis of measurements performed by means of techniques pertaining to the first group above. In this way, the agreements and the discrepancies in figures 10–12 can be explained. Separate considerations are necessary in the cases of MJ–Blake *et al.* (1990) and Hirsan *et al.* (1980) equations. Indeed, the first adds an element of confusion since it was derived on the basis of experimental data most of which were the same as those employed by Yang and Keairns (1979) but it is evident from figures 10-12 that the predictions of the two equations show large differences. Predictions of the Hirsan *et al.* (1980) equation should be consistent with values of L_B as explicitly suggested by such authors. However, the direct visual observation technique, used by Hirsan *et al.* (1980), appears to be suitable for L_{max} measurements (Vaccaro *et al.* 1997). In any case there is disagreement between the present experimental data and the prediction of such an equation.

Results presented in figures 7 and 9 show that there may be a more or less significant influence of U/U_{mf} on H_j/d_n. This influence cannot be isolated from the effect indirectly exerted by the nozzle diameter on H_j/d_n. In any case, the lack of control of the fluidization velocity in the experimental investigations could be a further reason for the large discrepancies between the correlations and for the dispersion of the experimental results from literature.

5. CONCLUSIONS

The technique used yields a characteristic height that is comparable with the jet penetration length based on the concept of jet momentum dissipation. This is important since the technique is relatively simple to apply and allows the objective determination of the jet penetration length.

The effects of nozzle gas velocity and nozzle size on the characteristic height is well predicted by some of the correlations for jet penetration length. The effect of the column diameter was negligible for the column sizes investigated. The fluidization velocity influences the jetting region characteristic height especially when it is close to U_{mf} although the available correlations for L_j do not contain this parameter nor do they take it into due account.

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