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LETTER TO THE EDITOR

AUTHORS' REPLY TO RAMAYYA & KOLAR'S LETTER† REGARDING THE PAPER "PROPAGATION CHARACTERISTICS OF PRESSURE DISTURBANCES ORIGINATED BY GAS JETS IN FLUIDIZED BEDS"‡

In the preceding letter to the editor Ramayya & Kolar (1993), focusing on the pressure disturbances induced by a rising bubble in a fluidized bed, find a surprising agreement between their "pseudo-wave velocities" calculated on the basis of Davidson's theoretical model (Davidson & Harrison 1963) and the wave propagation velocities measured by Musmarra *et al.* (1992) with reference to pressure disturbances originated by gas jets in fluidized beds.

The pressure field modification of the whole bed due to the rise of a bubble was first modelled by Davidson & Harrison (1963), assuming that the bed particulate phase around the bubble behaves like an incompressible inviscid fluid having the same bulk density as the bed at incipient fluidization. Detailed measurements of pressure variations induced by bubble rise by Zhang *et al.* (1982) showed good agreement with that model, giving experimental confirmation of the rapid decay of the excess pressure around the bubble with the distance from the bubble boundary.

Discrete gas injection in an otherwise fluidized bed of light and fine solids results in a bubble chain (Massimilla 1985), whose rise to the bed surface can produce modifications of pressure profiles according to Davidson & Harrison's (1963) model. However, further phenomena associated with gas injection, such as the formation, coalescence and splitting of bubbles, also give rise to pressure fluctuations, whose amplitude decay with the distance from the point of gas injection is comparatively small (Filla *et al.* 1986; Vaccaro *et al.* 1989; Musmarra *et al.* 1992). In view of this, if the pressure diagrams of figure 1 in Ramayya & Kolar (1993) had been referred to the appropriate scales, as in figure 1 below, the reason for excluding the mechanism suggested by Ramayya & Kolar would have become apparent, since the centreline and wall probes did measure pressures of the same order of magnitude (Musmarra *et al.* 1992, figure 4) rather than 2 orders of magnitude apart. Further experiments reported by Musmarra *et al.* (1992) showed that step compression of the bed free surface in a bubble-free fluidized bed induces pressure disturbances which propagate along the bed with velocity and attenuation characteristics similar to those generated by gas jet injection.

Ramayya & Kolar (1993) cross-correlate the theoretical pressure time profiles of figure 1, and do not realize that the only result independent of their choices and assumptions is that the pressure propagation velocity is infinite in this case. This is the necessary consequence of the underlying assumption of fluid incompressibility, and the correct result of the cross-correlation above. Their finding a range of finite values is probably due to the application of the cross-correlation to varying portions of the pressure cycle of figure 1 instead of extending the operation to the whole cycle. The incorrect nature of such a procedure can be appreciated simply by inspection of figure 1 with reference to the sign rather than to the values of the time delay, since the portion of the pressure maximum is detected by the wall probe in advance with respect to the centreline probe, while that of the pressure minimum is delayed.

To conclude, two specific questions remain to be answered:

(i) There is experimental evidence that the pressure disturbance propagation velocity is finite and of the order of 10 m/s (Filla *et al.* 1986; Roy *et al.* 1990; Musmarra *et al.* 1992), as confirmed also by fluid dynamic models (Wallis 1969; Fanucci *et al.* 1981) which predict that the dynamic

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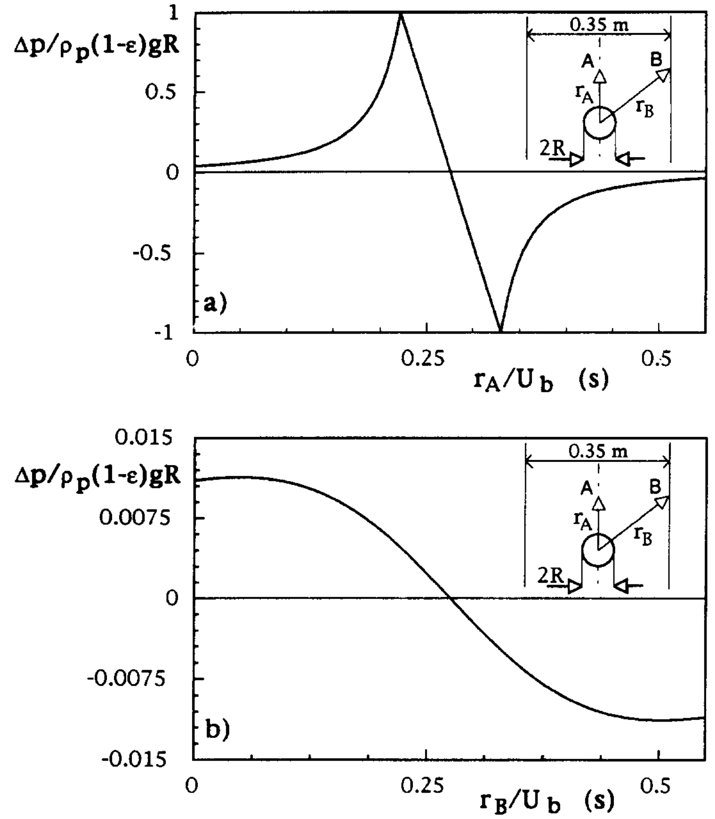

Figure 1. Dimensionless excess pressure due to a rising bubble in a bubble-free fluidized bed according to Davidson & Harrison's (1963) model. (a) At a point A on the axis. (b) At a point B at the same height as A 0.175 m away from the axis (bed solids density $\rho_p = 2600\ \mathrm{kg/m^3}$; bed voidage $\varepsilon = 0.4$; bubble radius $R = 0.03$ m; bubble rise velocity $U_b = 0.545$ m/s; gravity acceleration $g = 9.81\ \mathrm{m/s^2}$).

wave propagation velocity in a gas–solid mixture is much lower than that pertaining to the single mixture components, and, in particular, 2 orders of magnitude lower than in a suspension behaving as a liquid.

(ii) Two-point cross-correlation of pressure–time records admittedly gives only a component of the propagation velocity (Musmarra *et al.* 1992, table 2), whose value does become independent of the number of instantaneous values recorded if a sufficiently large number of pressure cycles N is taken into account [e.g. $N > 100$ in the case reported in Filla *et al.* (1986)].

REFERENCES

DAVIDSON, J. F. & HARRISON, D. 1963 *Fluidised Particles*. Cambridge Univ. Press, Cambs.

FANUCCI, J. B., NESS, N. & YEN, R. H. 1981 Structure of shock waves in gas particulate fluidized beds. *Phys. Fluids* **24**, 1944–1954.

FILLA, M., MASSIMILLA, L., MUSMARRA, D. & VACCARO, S. 1986 Pressure fluctuations associated with gas injection in fluidized beds. In *Fluidization V* (Edited by OSTERGAARD, K. & SORENSON, A.), pp. 71–78. Engineering Foundation, New York.

MASSIMILLA, L. 1985 Gas jets in fluidized beds. In *Fluidization* 2nd edn (Edited by DAVIDSON, J. F., CLIFT, R. & HARRISON, D.), pp. 133–172. Academic Press, London.

MUSMARRA, D., VACCARO, S., FILLA, M. & MASSIMILLA, L. 1992 Propagation characteristics of pressure disturbances originated by gas jets in fluidized beds. *Int. J. Multiphase Flow* **18**, 965–976.

RAMAYYA, A. Y. & KOLAR, A. K. 1993 Letter to the Editor. Comments on "Propagation characteristics of pressure disturbances originated by gas jets in fluidized beds". *Int. J. Multiphase Flow* **19**, 913–915.

ROY, R., DAVIDSON, J. F. & TUPONOGOV, V. G. 1990 The velocity of sound in fluidised beds. *Chem. Engng Sci.* **45**, 3233–3245.

VACCARO, S., MUSMARRA, D., FILLA, M. & MASSIMILLA, L. 1989 Diagnostics of gas injection in fluidized beds by pressure signal analysis. In *Fluidization VI* (Edited by GRACE, J. R., SHEMILT, L. W. & BERGOUGNOU, M. A.), pp. 245–252. Engineering Foundation, New York.

WALLIS, G. B. 1969 *One-dimensional Two-phase Flow*. McGraw-Hill, London.

ZHANG, M. C., WALSH, P. M. & BEÉR, J. M. 1982 Determination of bubble size distributions from pressure fluctuations in a fluidized bed combustors. Presented at the *7th Int. Conf. on Fluidized Bed Combustion*, DOE, Philadelphia, PA.

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