R & D NOTES

This manuscript is dedicated to the memory of C. Y. Wen

Transient Forces on Tubes within an Array in a Fluidized Bed

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Heat transfer tubes immersed in gas fluidized beds encounter time-varying forces of an irregular nature due to the action of gas bubbles and/or turbulence within the bed. These transient forces lead to tube vibrations which may enhance transfer rates somewhat, but which can also lead to tube failure when combined with the erosive environment inside the bed. In previous studies forces have been analyzed either for an instrumented tube in a fixed array (Kennedy et al., 1981; Turner and Irving, 1982) or for a single tube in isolation (Hosny and Grace, 1984; Grace and Hosny, 1985). It is evident that the forces may be influenced by nearby tubes since tubes are known to affect bubble splitting and coalescence and the local hydrodynamic regime of operation (Harrison and Grace, 1971; Newby and Keairns, 1978; Staub and Canada, 1978). In this note, we show how forces on a tube are influenced by the presence of upstream and downstream neighboring tubes.

EXPERIMENTAL SET-UP

The experimental apparatus and calibration procedure have been described in detail by Hosny (1982). In brief, a steel tube of outer diameter 32 mm and inner diameter 19 mm was supported at each end by a strain-

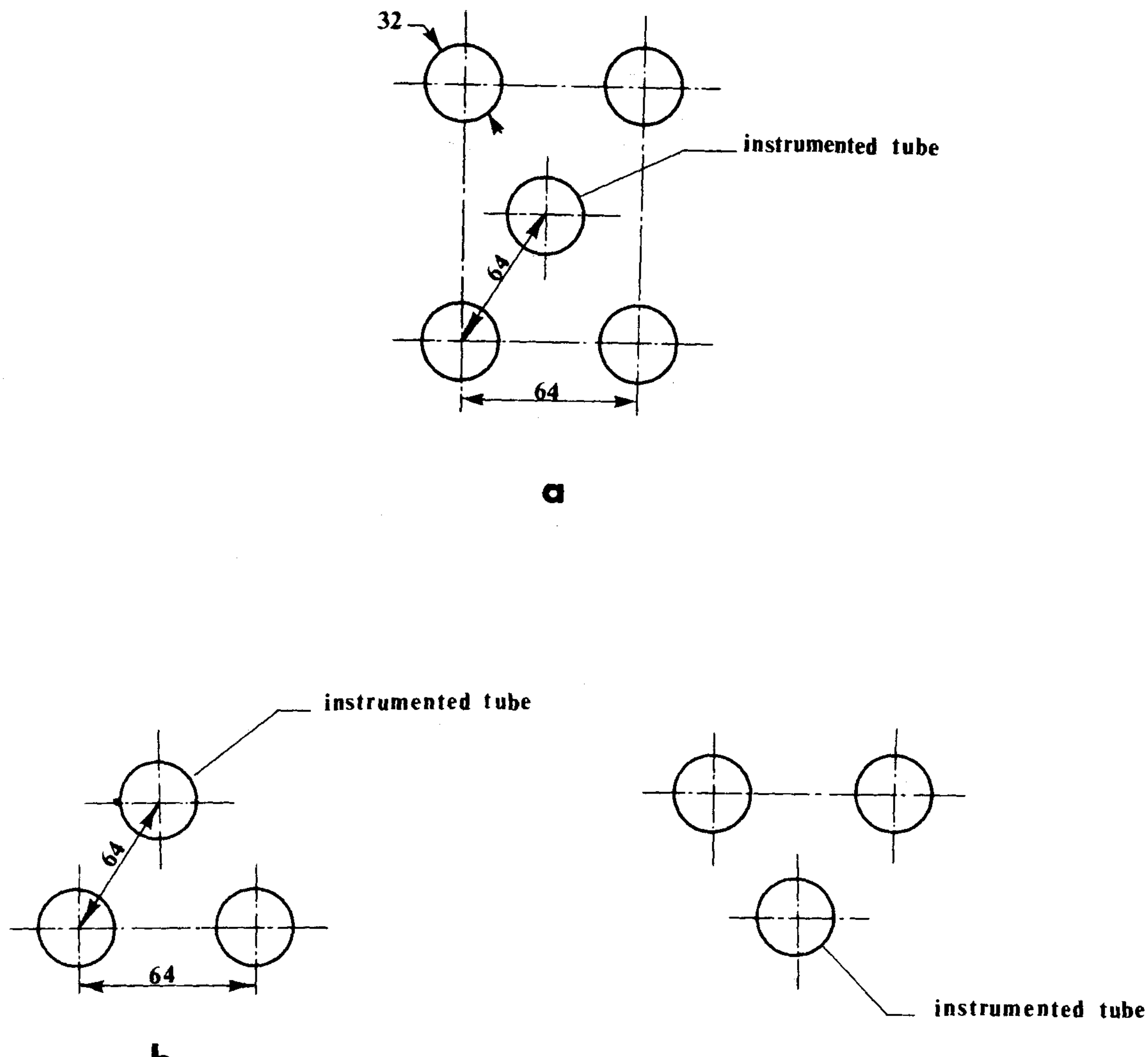

Figure 1. Arrays used to investigate the influence of neighboring tubes: (a) five-tube array, instrumented tube at center; (b) three-tube array, instrumented tube downstream; and (c) three-tube array, instrumented tube upstream. Dimensions are in mm.

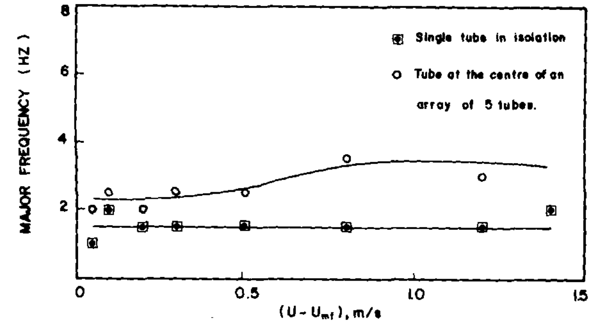

Figure 2. Comparison of major power spectral frequency for isolated tube with that for the same tube at the center of a five-tube array.

gauge force-transducer assembly mounted on the outside of a 215 mm × 200 mm × 1.52 m tall column. Annular rubber rings, one at each end, prevented particles and gas from escaping around the ends of the test cylinder. For some of the experiments, two or four noninstrumented tubes of identical size and material were fixed parallel to the test cylinder to show the influence of neighbouring tubes. Equilateral triangular configurations were employed, Figure 1. The tube center-to-center spacing adopted, twice the outer diameter of each of the tubes, is within the range typically used for heat transfer tube bundles in fluidized beds. The axis of the test cylinder was always 300 mm above the gas distributor. All of the experiments were carried out with a static bed height of 0.45 m using sand particles of density 2,600 kg/m^3, U_{mf} = 0.15 m/s, voidage at minimum fluidization 0.41, and mean particle diameter 430 μm.

Forces on the test cylinder were measured by recording the strain caused by deflection of the load beam with strain gages, one at each end of the instrumented tube. The maximum deflection was less than 0.25 mm. Each strain gage had a capacity of 98N and an overload capacity of 200%. The natural frequency of the test cylinder-gage assembly was two orders of magnitude higher than the range of frequencies due to bubbling in the bed. The entire assembly could be rotated through 90° to permit both vertical forces and horizontal forces (normal to the tube axis) to be measured separately. The strain gages were connected electrically to form balanced Wheatstone bridges. The electrical signals were amplified, filtered to remove frequencies higher than 50 Hz and recorded on magnetic tape for subsequent analogue-to-digital conversion and analysis. Each average force or frequency spectrum for a given tube configuration and superficial gas velocity was derived from 9,000 or more individual digital data points.

EXPERIMENTAL RESULTS

For the entire range of superficial air velocities studied (0.2 to 1.6 m/s) the bed operated within the bubbling regimen. As in previous work (Hosny and Grace, 1984), tubes were found to be subject to irregular pulses, primarily upwards or downwards, but with some horizontal components in addition. The frequency content of the measured forces always fell within the 0–20 Hz range.

The peak frequency from the power spectral estimates for the vertical component of force is shown as a function of gas velocity in Figure 2 for the tube at the centre of a five-tube array (Figure 1a) and for the same tube in isolation. For the tube in isolation the peak frequency remained remarkably constant at 1.5 Hz. The frequency was always somewhat higher for the tube at the centre of the array, especially at large values of $(U\text{-}U_{mf})$. This indicates that bubbles are split by the neighbouring tubes, resulting in a greater frequency of bubble-induced pulses.

Vertical RMS forces are compared in Figure 3 for each of the configurations in Figure 1 together with the corresponding results for a single isolated tube. Comparing the curve for the single tube with the bottom curve, we see that the addition of two upstream tubes results in a significant reduction in the RMS vertical force, especially at high $(U\text{-}U_{mf})$. This reduction presumably arises from deceleration, deflection and/or splitting of bubbles approaching from below. Comparison of the two topmost curves reveals that two downstream tubes tend to increase the RMS force somewhat, the extent of this increase never exceeding 10%. This small increase probably occurs because the downstream pair of tubes both hinders recoalescence of divided bubbles and splits or attenuates solid streams or pressure waves descending from above. The RMS vertical force for the tube at the centre of the five-tube array lies below that for the single tube and between the curves for the two three-tube arrays. Evidently, the ability of the upstream tubes to retard, split and/or deflect bubbles impinging on the test cylinder from predominantes over the tendency of the two downstream tubes to reduce downward forces.

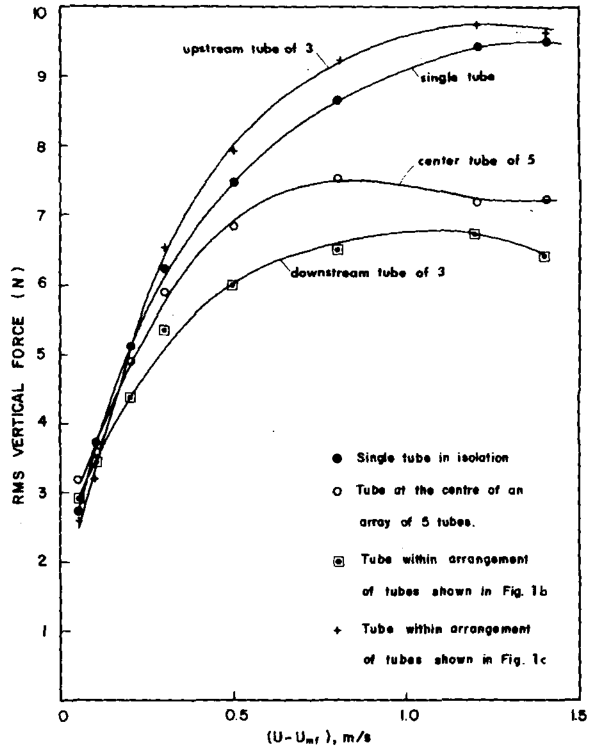

Figure 3. RMS vertical forces for different tube configurations: single tube, tube at center of 5 tube array (Fig. 1a); downstream tube in three-tube array (Fig. 1b); and upstream tube in three-tube array (Fig. 1c).

Figure 4 shows that RMS horizontal forces, like the vertical forces, are smaller for a tube in an array than for the same tube in isolation. Again this must result from bubble splitting by neighbouring tubes. Comparing the magnitude of the RMS forces in Figures 3 and 4, we see that the vertical forces are always substantially larger than the corresponding horizontal components, in agreement with previous work (Kennedy et al., 1981; Hosny and Grace, 1984). As expected, the mean horizontal force is zero for all cases in Figure 4, regardless of whether or not the test cylinder is in isolation or in a symmetric array.

DISCUSSION

The experimental results presented in Figure 3 suggest that tests on a single tube give a good indication (within 10%) of the maxi-

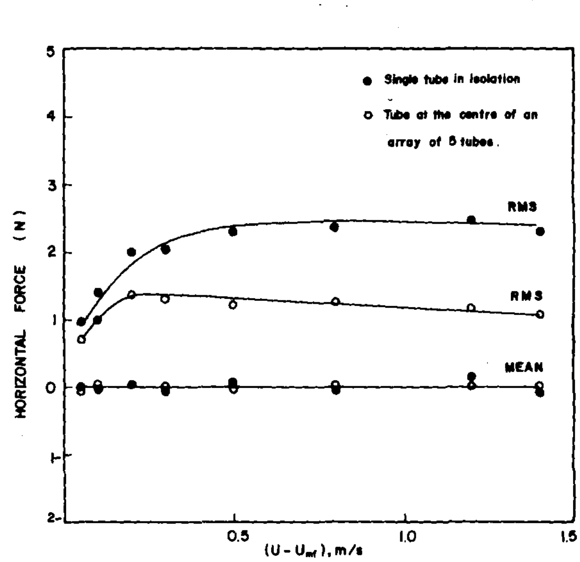

Figure 4. RMS and mean horizontal forces for isolated tube and the same tube at the center of a five-tube array.

mum RMS forces on tubes within a bundle. The upstream (lowermost) tubes in a bundle will experience the largest RMS forces of all the tubes providing that bubbles have grown to be large relative to the tubes before encountering the tube bank. Conversely, a tube in the top row will encounter the smallest dynamic forces; tubes in the interior rows tend to experience intermediate forces. These trends are in agreement with the findings of Kennedy et al. (1981) for tube banks beginning well above the grid. For a tube bank beginning near the distributor Kennedy et al. showed that the most severe loading occurs in the interior of the array, presumably because bubbles had not grown to be of comparable size to the intertube spacing before entering the bundle. Hence forces on the bottom row of a bundle can be decreased significantly by locating the bottom row as close as possible to the grid, but not so low that it is subject to severe erosion or causes severe attrition due to direct impingement of jets from the distributor.

Although not varied in the present study, intertube spacing and the geometrical arrangement of the tubes are also expected to play important roles. Increased spacing between tubes will allow bubbles to grow larger and decrease the shielding provided by neighboring tubes, hence increasing the intensity of forces on tubes in rows other than the bottom row. The experimental results of Turner and Irving (1982) are consistent with this trend. Some reduction in dynamic forces on tubes beyond the lowest row may be achieved by decreasing the gap between adjacent tubes. However, it is important to keep a distance of at least 20–30 particle diameters between tubes to allow solids to circulate freely through the tube bank (Grace, 1982), and tubes which are too close together will also show a decrease in their heat transfer coefficients (Lese and Kermode, 1972; Botterill, 1975; Saxena et al., 1978). If tubes are in a square-pitch array, instead of a triangular pitch, an even greater shielding effect is expected leading to a further decrease in the forces on the interior and highest tubes. Again, however, the decrease in the dynamic forces may be achieved at the expense of lower heat transfer coefficients.

Another factor not investigated in the present work is the effect of radial position of a tube. While gulf-streaming and radial gradients can be significant for fluidized beds without immersed tubes (Grace, 1982), there is a tendency for the introduction of tubes to cause greater radial uniformity (Botterill, 1975; Newby and Keairns, 1978). Hence we expect our results to be applicable, at least in a qualitative sense, to tubes at different radial positions in much larger beds, although there may be quantitative differences and some variation between tubes located near the outer wall and those in the core of the bed.

The time-varying forces measured for tubes immersed in fluidized beds differ markedly in character from those for cylinders in crossflow in single-phase fluids. In the latter case (Bevins, 1977), the largest transient forces tend to occur on downstream tubes due to vortex shedding and other motions induced by upstream tubes, whereas, as shown in this study, upstream tubes encounter the largest transient forces in fluidized systems. In addition, forces for tubes in crossflow of single-phase fluids often show a much greater periodic component as compared with the more random pulses on tubes in fluidized beds. It is important that equipment designers understand the nature of these differences when considering the support of tube bundles in fluidized beds.

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NOTATION

U = superficial air velocity

U_{mf} = superficial air velocity at minimum fluidization

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