AAEC/TM354

AAEC/TM354

AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

A METHOD FOR MEASURING THE FLUID FLOW DISTRIBUTION AT EXIT FROM A RIGHT CYLINDRICAL, RANDOMLY PACKED BED

by

J. PRICE
J.R. STEVENS

October 1966

AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

A METHOD FOR MEASURING THE FLUID FLOW DISTRIBUTION AT EXIT FROM A RIGHT CYLINDRICAL, RANDOMLY PACKED BED

by

J. PRICE
J.R. STEVENS

ABSTRACT

A method for measuring the fluid flow distribution at exit from a right cylindrical, randomly packed bed of spheres has been investigated using a flow separator to prevent redistribution of the flow between the exit face of the bed and the plane of measurement. Three designs of separator were tested, for each of which steady fluid velocities were measured with a pitot static tube in the exit plane of the separator, and unsteady velocities with a hot wire anemometer. A separator with contracting flow passages was developed which facilitated measurement and reduced turbulence intensities without causing any significant flow redistribution within the bed.

Measurements are presented for a loosely packed bed of glass spheres which show that the velocity profile is reasonably uniform over the bed except for a region within a half sphere diameter of the vessel wall. This differs substantially from the profiles measured by most previous investigators.

CONTENTS

Page

1. INTRODUCTION 1
2. EXPERIMENTAL EQUIPMENT 1
3. SCOPE OF TESTS AND PROCEDURE 2
4. EXPERIMENTAL RESULTS 3
    - 4.1 Test Series I 3
    - 4.2 Test Series II 4
    - 4.3 Test Series III 6
5. DISCUSSION 7
6. COMPARISON OF MEASURED PROFILE WITH EXISTING DATA 8
7. CONCLUSIONS 9
8. REFERENCES 9

Appendix 1. Notation

Figure 1. Experimental Arrangement Used for Measuring the Flow Distribution Through a Packed Bed.

Figure 2. Three Dimensional Plot Showing the Variation of Mean Velocity Within Compartments of the Original Honeycomb.

Figure 3. Mean Velocity Profile and Turbulence Data for a Packed Bed Using the Original Honeycomb - Test Series I.

Figure 4. Three Dimensional Plot Showing the Variation of Mean Velocity Within Compartments of the Modified Honeycomb (Contraction Ratio 3.1) - Test Series II.

Figure 5. Mean Velocity Profile and Turbulence Intensities for a Packed Bed Using the Modified Honeycomb (Contraction Ratio 3.1) - Test Series II.

Figure 6. Mean Velocity Profile and Turbulence Intensities for a Packed Bed Using the Modified Honeycomb (Contraction Ratio 2.1) - Test Series III.

Figure 7. Comparison of Measured Velocity Profiles for the Packed Bed from Test Series I, II and III.

Figure 8. Comparison of Measured Velocity Profile for a Packed Bed with Existing Published Data.

1. INTRODUCTION

Measurement of the flow distribution through packed beds presents a number of problems; consideration must be given to the choice of experimental technique, otherwise substantial errors may result (Price 1966).

Of the methods used previously, that employing a flow separator, or honeycomb, between the exit face of the bed and the point of measurement (Collins 1958) appears promising. The packing structure of the bed remains undisturbed by the instrumentation and the flow distribution at the exit face of the bed is preserved until the plane of measurement is reached. The resulting superficial velocity profile is derived from measurements of local volume flow and is based upon empty tube areas.

The principal design requirement of the honeycomb is that it should provide adequate flow separation without causing any significant redistribution of the flow within the bed. In addition, to facilitate measurement, the flow leaving the honeycomb should not have steady radial or circumferential components, should be as uniform as possible within each honeycomb compartment, and the fluctuating velocities should not be large enough to affect the measurements of steady velocity. The experimental work reported herein was undertaken to investigate these factors.

The notation used in this report is given in Appendix 1.

2. EXPERIMENTAL EQUIPMENT

The apparatus used is shown schematically in Figure 1. Air was delivered to the test section from a compressor, at a pressure slightly above atmospheric and a temperature of 60°C, via an orifice plate and a 90° bend. The latter was fitted with turning vanes and a 60 mesh screen at outlet to ensure a uniform velocity profile at entry to the test bed. The right cylindrical test section was 12 inches in diameter by 9 inches long. Except for preliminary trials it was filled with $\frac{1}{2}$ inch diameter glass spheres, loaded by hand-pouring a full beaker at a time. This gave a loosely packed bed with an overall voidage fraction of 0.40. The spheres were contained at the top and bottom of the bed by a 5 mesh wire screen. Support for the bottom screen was provided by two thin struts across perpendicular diameters. The honeycomb was placed immediately on top of the bed and located firmly in position against the wire mesh. Above the honeycomb was mounted a rotatable tube of the same diameter as the test section. This tube contained the probe holder and a mechanism permitting both axial and radial probe traverses; circumferential traverses were effected by rotating the tube.

The steady air velocities were measured by means of a 0.150 inch pitot static tube and micromanometer; impact pressures could be measured to an accuracy of 0.001 inches of water. The pitot static tube was made to N.P.L standards and checked against an orifice plate. Where necessary a correction was made to allow for variation of static pressure between the total head and static tappings. The use of a D.I.S.A. constant temperature hot wire anemometer to measure the steady air velocities was also considered, but even with probes designed to give a substantially higher sensitivity to steady velocities than the D.I.S.A. probes, this method was less satisfactory than that using the pitot static tube. The anemometer was used for measurement of the fluctuating velocities and a Bruel Kjoer wave analyser was used to investigate their frequency range.

3. SCOPE OF TESTS AND PROCEDURE

After preliminary trials with both loosely packed and vibrated beds, a programme comprising three series of tests was carried out in which measurements of the steady velocity profile and root mean square (r.m.s) fluctuating velocities were obtained on the loosely packed test bed using three different designs of honeycomb. The honeycomb and wire mesh prevented levitation of the bed during the tests. The mean superficial exit velocity was approximately 12 ft/sec and the corresponding Reynolds number 2500.

The experimental procedure was the same in each test series; local air velocities were measured with the nose of the pitot static tube positioned approximately 1/16 inch from the exit face of the honeycomb. A number of readings were taken along the centre line of each compartment; the total number depended upon the honeycomb design but was large enough to provide reasonable definition of the velocity profile. The r.m.s. velocities were measured by hot wire anemometer with the probe positioned as for the pitot static tube. Radial and circumferential r.m.s velocities were obtained by rotating the probe about its own axis.

Before any test run a soaking period of approximately three hours was allowed before any readings were taken. During a test, steady conditions were ensured by checking the orifice readings continuously and by monitoring a control pitot static tube mounted upstream of the test bed. Frequent check readings were made at the exit face of the honeycomb with both the pitot static tube and the hot wire anemometer.

4. EXPERIMENTAL RESULTS

4.1 Test Series I

The first design of honeycomb consisted of a series of concentric cylinders, 4 inches long by 0.018 inches thick, which were intersected by twenty-four equally spaced radial vanes (Figure 1). Some of the vanes near the centre of the honeycomb were removed to ease assembly. The cylinders were spaced $\frac{1}{2}$ inch apart except for the four nearest the walls of the test section which were spaced 1/4 inch apart. The problem of flow redistribution within the bed did not arise with this design as the friction loss through the honeycomb was negligible compared with that over a single row of balls, and the location of the pitot static tube did not cause blockage of the individual compartments.

Initial tests with the hot wire anemometer showed that the honeycomb was long enough to ensure axial flow at its exit. Measurements of the local air velocities were then made with the pitot static tube, one thousand readings being taken in all. The number of measurements taken in each compartment varied, depending mainly upon its size; generally five were taken in the compartments near the walls, reducing progressively to two as the centre of the bed was approached.

The results showed that the mean velocities in each compartment varied markedly, both radially and circumferentially; these variations are illustrated in Figure 2. Within compartments, variations as high as 4:1 occurred. This irregularity of profile has been noted by previous workers. It arises from the disposition of the balls on the exit face of the bed.

The mean velocity profile, obtained by averaging over 360° the velocities at each radius, is shown in Figure 3 plotted in normalised form as $U/\bar{V}$. Allowance was made for the blockage area of the honeycomb. The value of $\bar{V}$ used was that derived from orifice plate measurements. The profile shown was derived from two identical tests, one made in this test series and the other at completion of the test programme. The maximum deviation of either curve from that shown was 5 per cent.

A comparison of the overall flow rate obtained by integrating the measured velocity profile, with that derived from the orifice plate, showed that the former was about 14 per cent. high; limited data from the preliminary trials indicated discrepancies of 12 per cent. to 16 per cent. for other beds. This could have arisen from insufficient definition of the flow fields within the individual compartments or as a result of errors induced in the pitot static measurements by fluctuating velocities.

To resolve this, turbulence measurements were made with the hot wire anemometer. Axial turbulence intensities $\frac{\sqrt{\overline{u'^2}}}{U}$ x 100, calculated using linear theory, were found to vary substantially between compartments and to a lesser extent within compartments. Their range extended from 10 per cent. to 80 per cent.; no systematic trend with position was observed. Radial and circumferential intensities $\frac{\sqrt{\overline{w'^2}}}{U}$ x 100 and $\frac{\sqrt{\overline{v'^2}}}{U}$ x 100 were generally lower than the axial intensities. These results are plotted in Figure 3 together with a curve showing the variation of r.m.s. voltage with frequency, as measured on the Bruel and Kjoer wave analyser on the 20 db setting. Axial turbulence intensities were found to be virtually independent of flow rate and to increase significantly as the probe was traversed into the honeycomb towards the bed face.

The effect of these fluctuating velocities upon the measurements made with the pitot static tube was calculated using the method proposed by Goldstein (1936), assuming isotropy. This showed that the velocities determined from the pitot static measurements were, on average, about 4 per cent. too high. Attention was thus focused on improving the definition of the flow field within the honeycomb compartments.

4.2 Test Series II

A reduction in turbulence intensity and a damping of the velocity variations within compartments could have been achieved by increasing the length of the honeycomb but only at the expense of increased friction loss and boundary layer build-up at the walls of each compartment. Instead the method chosen was to accelerate the air in its passage through the honeycomb by gradually decreasing the cross-sectional area for flow. This not only allowed the introduction of well rounded flow passages at exit from the honeycomb but produced more uniform flow fields within each compartment. It also reduced turbulence intensities, increased the sensitivity of measurement for a given overall flow rate, and decreased the number of readings required by a factor of three. It was necessary to ensure that the change in static pressure associated with the acceleration through the honeycomb did not cause any significant redistribution of the flow within the bed.

The honeycomb for test series II was based on the design used in test series I with the number of radial vanes reduced from twenty four to eight. This decreased the number of flow compartments, within each of which the cross-sectional area for flow was reduced by contracting the flow passages in the circumferential direction, using formers around which a quick setting cement was cast. The resulting flow passages provided a smooth transition from inlet to outlet of the honeycomb (Figure 1). Measurement of the exit flow areas was made from inked impressions. The initial design utilised a contraction area ratio of approximately 3.1 between inlet and outlet, over the whole cross-section of the honeycomb.

The results showed all the expected improvements. In particular the velocities within the individual compartments were all uniform to within close proximity of the walls, and turbulence intensities were reduced to below 10 per cent. At this level their effect upon the pitot static readings was negligible. The upper limit of the frequency range of the r.m.s. velocities increased from 800 c/s to approximately 2kc/s. The circumferential variations of the mean velocities within each compartment were substantially reduced because the catchment area of each compartment at inlet to the honeycomb was three times greater than that of the original design. Figure 4 shows the results from the second test in this series.

The normalised profile, averaged over 360°, is shown in Figure 5. The mean velocity in each annulus is represented by a point, for ease of presentation. Comparison of this profile with that obtained using the original honeycomb design (Figure 3) shows that significant flow redistribution occurred in the outer layers of the bed. The high velocities which arose within one half ball diameter from the outer wall produced a larger change of static pressure, due to acceleration through the honeycomb, than was produced over the remainder of the bed and fluid was diverted from this region. Assuming a maximum velocity in the outermost ring of 1.7 times that over the rest of the bed, the pressure change due to acceleration through this outer ring would be approximately the same as the loss over a single row of balls and a factor of 3 higher than that over the rest of the bed.

Decreasing this pressure change due to acceleration, in the outer ring only, to the same value as that over the rest of the bed should eliminate this redistribution. This is illustrated in Figure 5 which shows the velocity profile obtained when the contraction area ratio in the outer ring was reduced to 1.8. This value was deliberately chosen to produce a slight over-correction of fluid redistribution, again assuming a maximum velocity in the outer ring of 1.7 times the mean.

The high values of $U/\bar{V}$ that occurred near the centre of the bed were diminished. This is attributed primarily to the improved definition of the flow fields within the individual compartments and the reduced turbulence intensities (Figure 5). Flow redistribution may have contributed.

Integration of the measured velocity profiles resulted in an overall flow rate that was approximately 9 per cent. higher than the value derived from the orifice plate. This represents a significant improvement over the original design. Investigation of the flow fields within compartments with the hot wire anemometer showed that this discrepancy arose from the effects of friction at the walls of each compartment which reduced the velocities within a distance of approximately 1/32 inch from the walls. Turbulence intensities were found to increase significantly in these regions.

4.3 Test Series III

The contraction area ratio between inlet and outlet of the honeycomb was reduced to approximately 2.1, all other aspects remaining unchanged. Calculation showed that for this case the average pressure change, due to acceleration through the honeycomb was an order of magnitude less than the loss over a single row of balls. Thus problems of flow redistribution within the bed were considerably eased.

This is confirmed by consideration of Figure 6 which shows that the velocity profile obtained with a contraction area ratio of 2.1 over the whole cross-section of the honeycomb was hardly affected when the area ratio, in the outer ring only, was reduced to 1.85 and 1.7 respectively. Generally the differences were within the limits of experimental accuracy but in the vicinity of the wall the trend was systematic, indicating that slight redistribution occurred. Based upon the assumption made previously, an area ratio of 1.7 in the outer ring would produce a pressure change in this outer ring, due to acceleration through the honeycomb, which would still be marginally higher than that over the rest of the bed; thus slight flow redistribution may still have been present.

The high values of $U/\bar{V}$ found near the centre of the bed with the original honeycomb design again diminished. This confirms that they arose mainly from the poorly defined flows within compartments and high turbulence intensities, as the velocities in this region would not be sufficient to cause redistribution. Undue significance is not placed upon the variations still evident because the area monitored by each ring of the honeycomb decreased as the centre of the bed was approached and ball disposition became increasingly important.

The velocities within compartments were reasonably uniform across the width of each annulus of the honeycomb to within close proximity of the walls and in the circumferential direction the variations were generally less than 1.5:1. The turbulence intensities shown in Figure 6 are insignificantly higher and produce less than a 1 per cent. effect upon the pitot static measurements. The overall flow rate obtained by integration of the velocity profile was approximately 12 per cent. higher than that derived from the orifice plate.

5. DISCUSSION

During each test, frequent check readings were taken of the steady and r.m.s. velocities, which showed excellent repeatability. Variations of the mean circumferential velocities between tests were generally less than ± 5 per cent. They were attributed to slight differences in the position of the pitot static tube, positional errors in the location of the honeycomb and slight disturbances to the top layer of balls as the honeycomb was tightened into position on the bed.

There is no absolute reference against which the velocity profiles measured in these tests may be assessed. Their validity has to be inferred from inter-comparison. Figure 7 shows profiles from the three test series. The honeycomb used to produce the curve shown for test series II provided a slight over-compensation for flow redistribution in the outer layers of the bed, whilst that used for the test series III curve provided slight under-compensation. In the region near the walls these curves agree, within the limits of experimental accuracy; hence it may be concluded that the design developed in test series III, (contraction ratio 2.1; outer ring 1.7) does not induce any significant flow redistribution in the outer layers of the bed. Figure 6 shows that velocities of about 1.7 times the mean velocity have little effect when the contraction ratio of 2.1 is constant over the whole section; hence problems of flow redistribution over the remainder of the bed do not arise with this design.

Figure 7 shows that the results of test series I agree well with those shown for test series II and III except near the centre of the bed. This is attributed to the reduced number of readings taken in this region in test series I, which implies that adequate definition of the velocity profile could be achieved with the original honeycomb design, if the number of measurements in the central region were increased.

The honeycomb developed in test series III is suitable for measuring the velocity profile for the loosely packed bed used in these tests. Its use with other beds or at different Reynolds Numbers has yet to be demonstrated. There is considerable evidence to show that the normalised velocity profile is virtually independent of flow rate (for example, Schwartz and Smith 1953, Collins 1958, Cairns and Prausnitz 1959, and Bundy 1966). Also, the preliminary trials indicated that the velocity profiles for beds packed by different methods, using wooden instead of glass balls, were not very different from those reported here. The maximum velocities were confined to the outermost ring of compartments and the velocities in the central region were reasonably uniform. There are therefore strong grounds for believing that the honeycomb developed in test series III will be suitable in its present form though the contraction ratios can be modified if necessary.

6. COMPARISON OF MEASURED PROFILE WITH EXISTING DATA

The velocity profile resulting from test series III (contraction ratio 2.1; outer ring only 1.7) is shown in Figure 8. The discrepancy in overall flow rate has been removed by normalising to a value of $\overline{V}$ derived from the integrated profile rather than the orifice plate. This assumes a correction factor for frictional effects at the wall of each compartment which is constant with radius. The measured profile is compared with the results of other observers in Figure 8, assuming that the velocity profiles are independent of Reynolds Number over a range extending from approximately 100 (Morales et al. 1951, Schwartz and Smith 1953) to more than 6000 (Bundy 1966, Cairns and Prausnitz 1959).

Measurements made with hot wire anemometers located in the open tube at exit from the bed face have been reported by Morales et al. (1951), Schwartz and Smith (1953), Dorweiler and Fahien (1959), and Bundy (1966). The profiles differ substantially from that measured in these experiments and also from one another. The validity of their method of measurement may be questioned, since at best it involves a compromise in which an attempt is made to minimise the errors arising from momentum transfer in the open tube and those associated with the measurement of steady axial velocities in a non-uniform, non-axial, highly turbulent flow field.

Collins (1958), utilised a honeycomb at the exit face of a bed and obtained velocity profiles by inserting a hot wire probe into the compartments of the honeycomb. The resulting velocity profiles were rather similar to those of Schwartz and Smith. His method is suspect, however, as he confined his measurements to only two perpendicular diameters and Figure 2 indicates that this could lead to substantial error. High turbulence intensities and blockage of

the honeycomb compartments, by insertion of the probe, may also have influenced his results.

Cairns and Prausnitz (1959) obtained limited data on average velocities inside a bed of overall voidage fraction equal to 0.38. They measured the time taken for a wavefront of reduced conductivity to travel between two fixed points in the bed; results were only obtained for radii less than r/R = 0.75. Their measurements showed, essentially, a uniform velocity profile within this radius which is in good agreement with the results of this investigation.

7. CONCLUSIONS

A method for measuring the superficial velocity profile through a right cylindrical, loosely packed bed has been developed. Preliminary investigations have shown that it will be suitable for use with beds produced by a variety of packing methods.

The measured velocity profile differs substantially from those of previous investigators whose measurements were made at the exit face of the bed. Good agreement is found with the limited data of Cairns and Prausnitz (1959), who measured mean velocities inside the bed.

8. REFERENCES

Bundy, R.D. (1966). - Oak Ridge Nat. Lab. (U.S.A.), TM 1075.

Cairns, E.J., and Prausnitz, J.M. (1959). - Ind. and Eng. Chem. 51 : 1441.

Collins, M. (1958). - B.Ch.E Thesis, Univ. of Delaware (U.S.A.).

Dorweiler, V.P., and Fahien, R.W. (1959). - A.I.Ch.E. Journal 5:139.

Goldstein, S. (1936). - Proc. Roy. Soc. 155:570.

Morales, M., Spinn, C.W., and Smith, J.M. (1951). - Ind. and Eng. Chem. 43:225.

Price, J. (1966). - A review of fluid flow distribution through randomly packed beds. AAEC/TM332.

Schwartz, C.E., and Smith, J.M. (1953). - Ind. and Eng. Chem. 45:1209.

APPENDIX 1 - NOTATION

d	diameter of spheres inside the bed
D	diameter of the bed
R	radius of the bed
Reynolds Number	$\frac{\rho \bar{V} d}{\mu}$
U	superficial fluid velocity at radius r
$\sqrt{\overline{u'^2}}$	r.m.s. axial velocity
$\bar{V}$	mean superficial velocity at exit from the bed, based on empty tube area
$\sqrt{\overline{v'^2}}$	r.m.s. radial velocity
$\sqrt{\overline{w'^2}}$	r.m.s. circumferential velocity
ρ	fluid density
μ	fluid viscosity

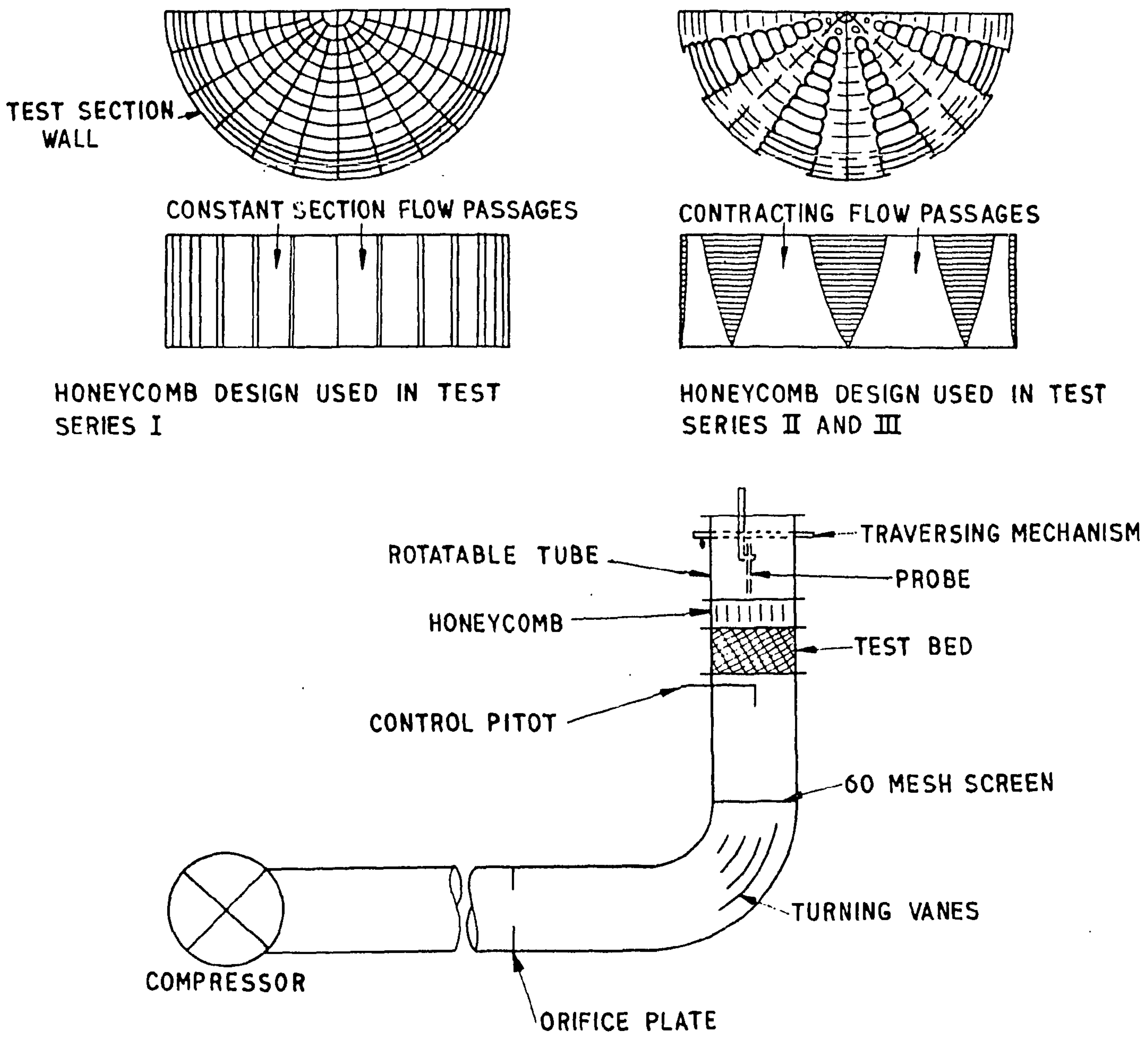


FIGURE 1. EXPERIMENTAL ARRANGEMENT USED FOR MEASURING THE FLOW DISTRIBUTION THROUGH A PACKED BED

P993

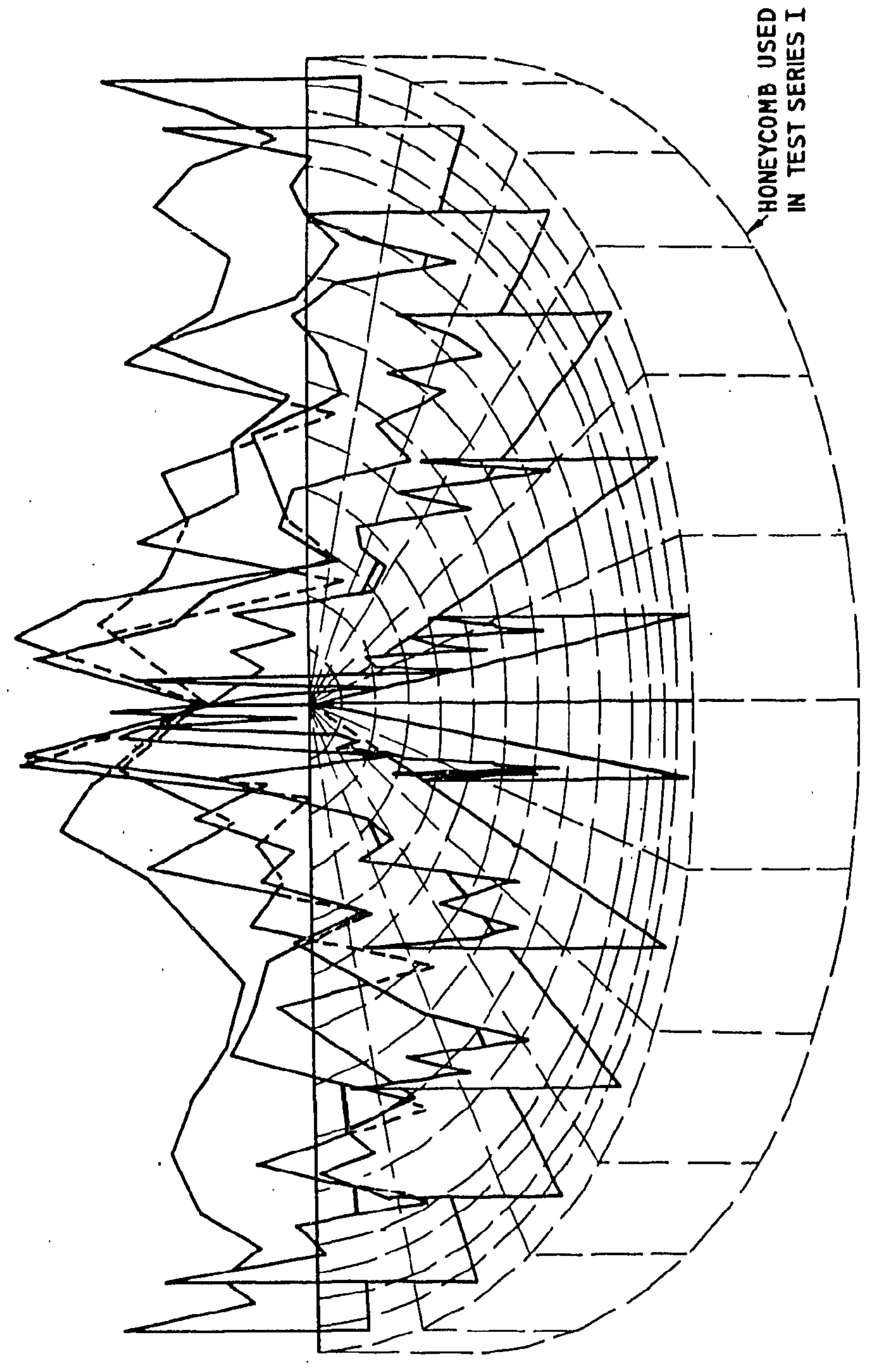
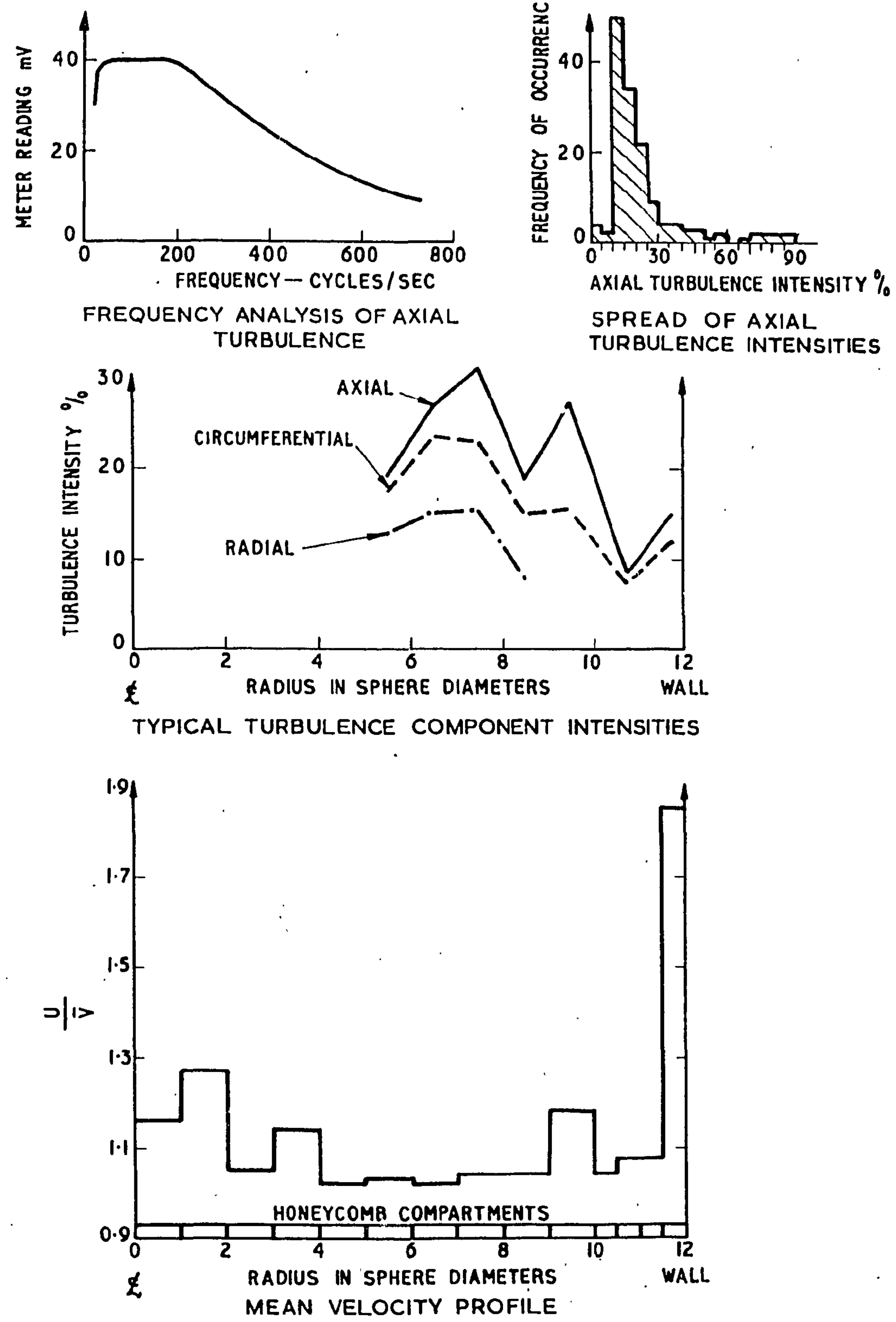


FIGURE 2. THREE DIMENSIONAL PLOT SHOWING THE VARIATION OF MEAN VELOCITY WITHIN COMPARTMENTS OF THE ORIGINAL HONEYCOMB

P993



FREQUENCY ANALYSIS OF AXIAL TURBULENCE

SPREAD OF AXIAL TURBULENCE INTENSITIES

TYPICAL TURBULENCE COMPONENT INTENSITIES

MEAN VELOCITY PROFILE

FIGURE 3. MEAN VELOCITY PROFILE AND TURBULENCE DATA FOR A PACKED BED USING THE ORIGINAL HONEYCOMB — TEST SERIES I

P993

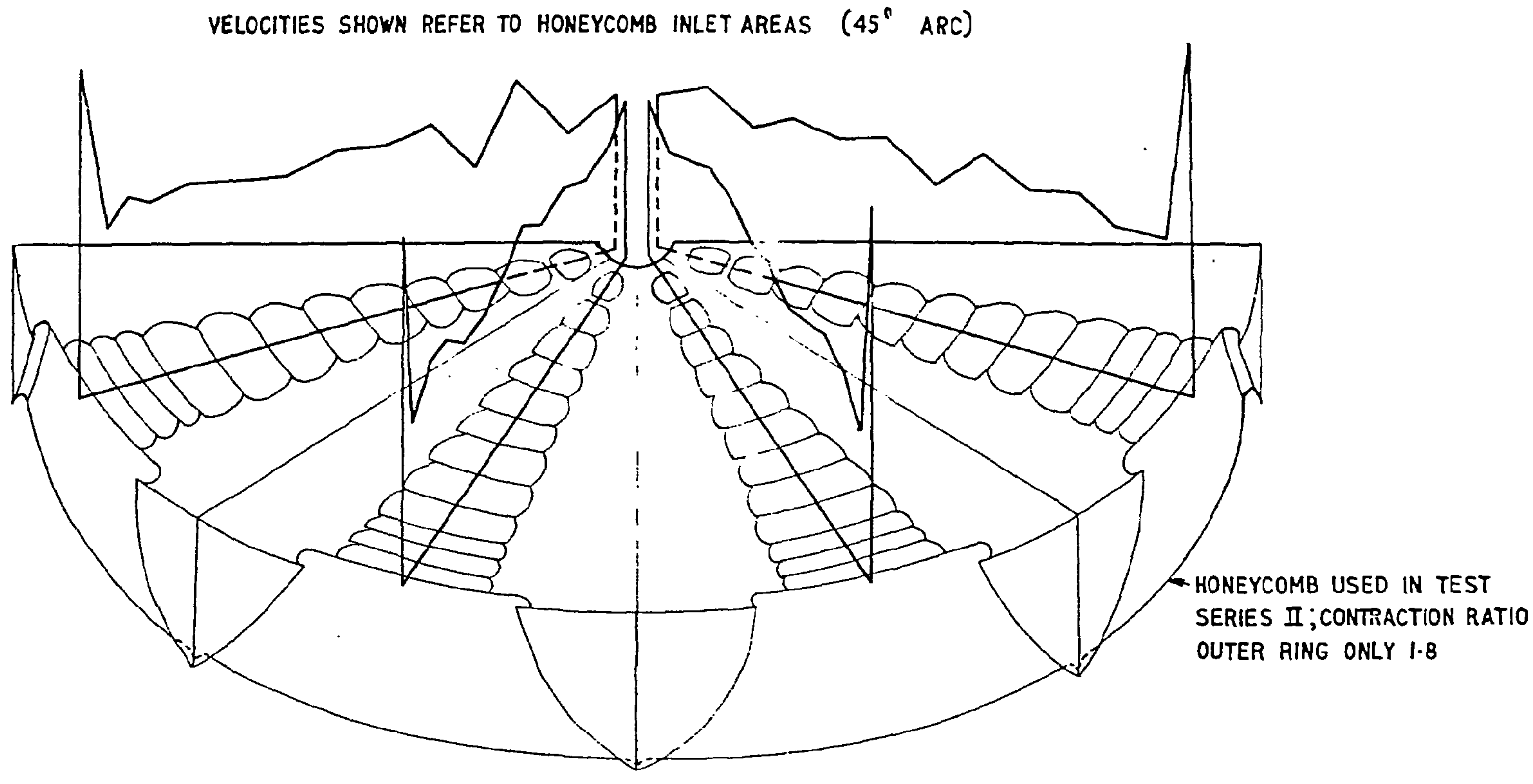


FIGURE 4. THREE DIMENSIONAL PLOT SHOWING THE VARIATION OF MEAN VELOCITY WITHIN COMPARTMENTS OF THE MODIFIED HONEYCOMB (CONTRACTION RATIO 3.1) – TEST SERIES II

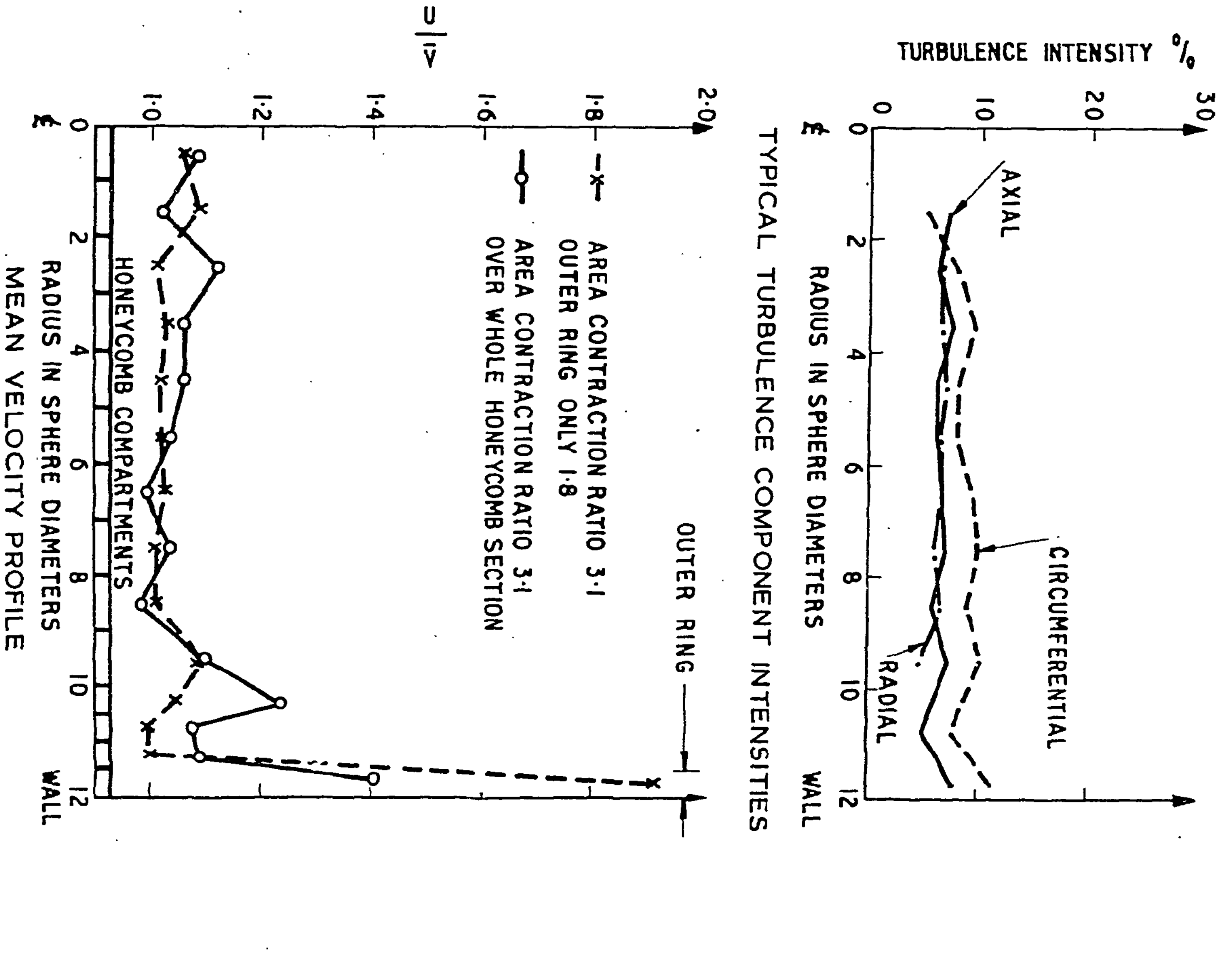
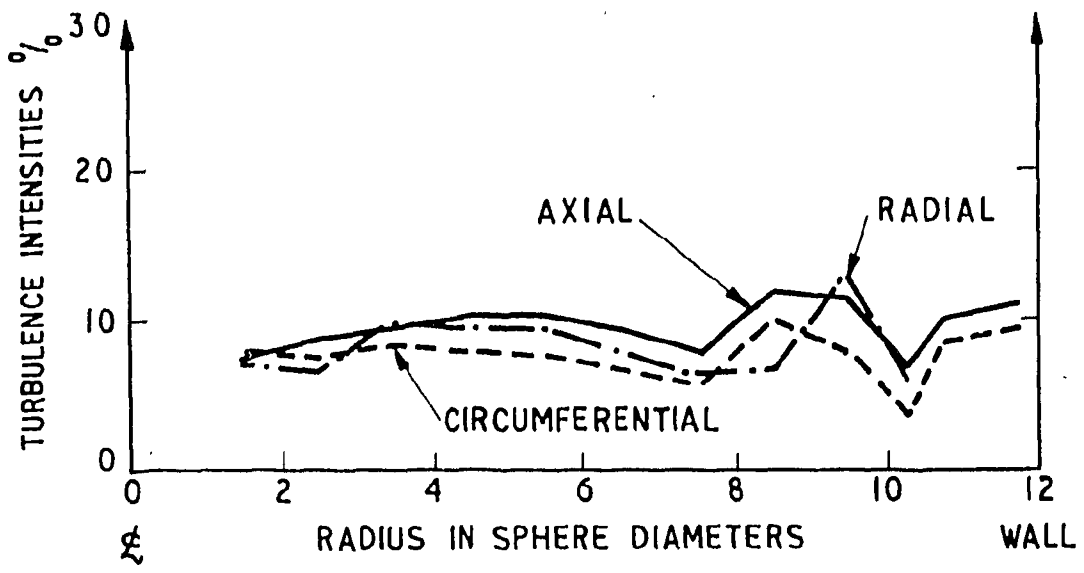
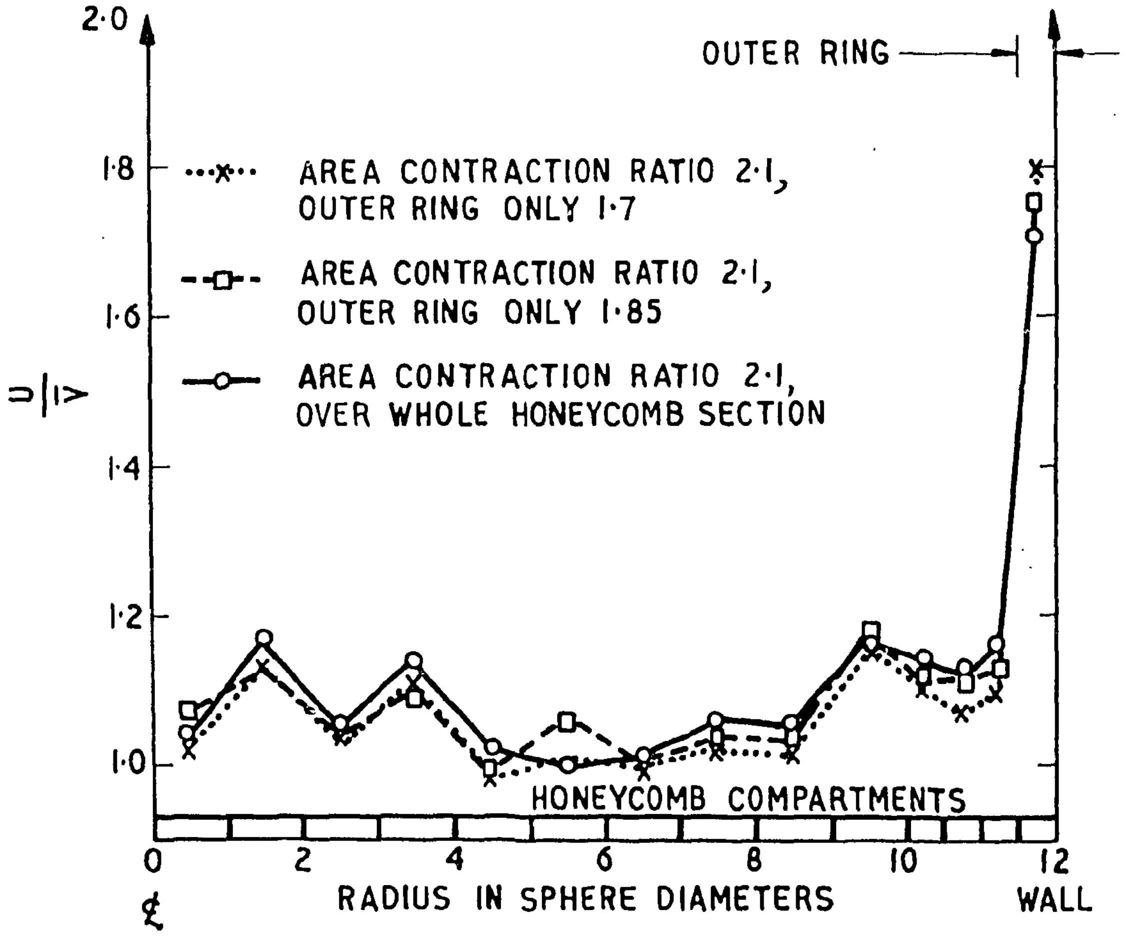


FIGURE 5. MEAN VELOCITY PROFILE AND TURBULENCE INTENSITIES FOR A PACKED BED USING THE MODIFIED HONEYCOMB (CONTRACTION RATIO 3.1) – TEST SERIES II



TYPICAL TURBULENCE COMPONENT INTENSITIES



MEAN VELOCITY PROFILE

FIGURE 6. MEAN VELOCITY PROFILE AND TURBULENCE INTENSITIES FOR A PACKED BED USING THE MODIFIED HONEYCOMB (CONTRACTION RATIO 2.1) – TEST SERIES III

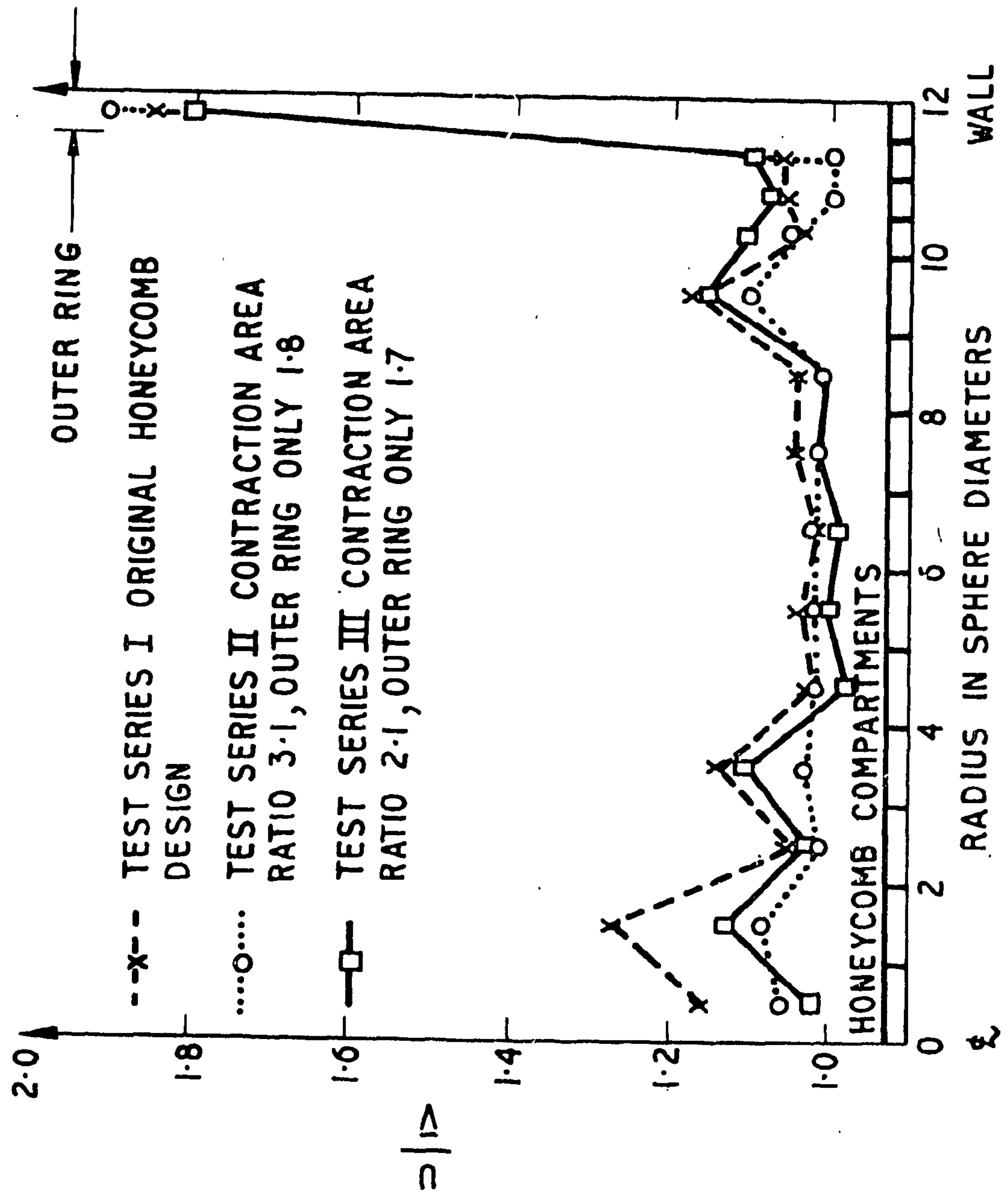


FIGURE 7. COMPARISON OF MEASURED VELOCITY PROFILES FOR THE PACKED BED FROM TEST SERIES I, II AND III

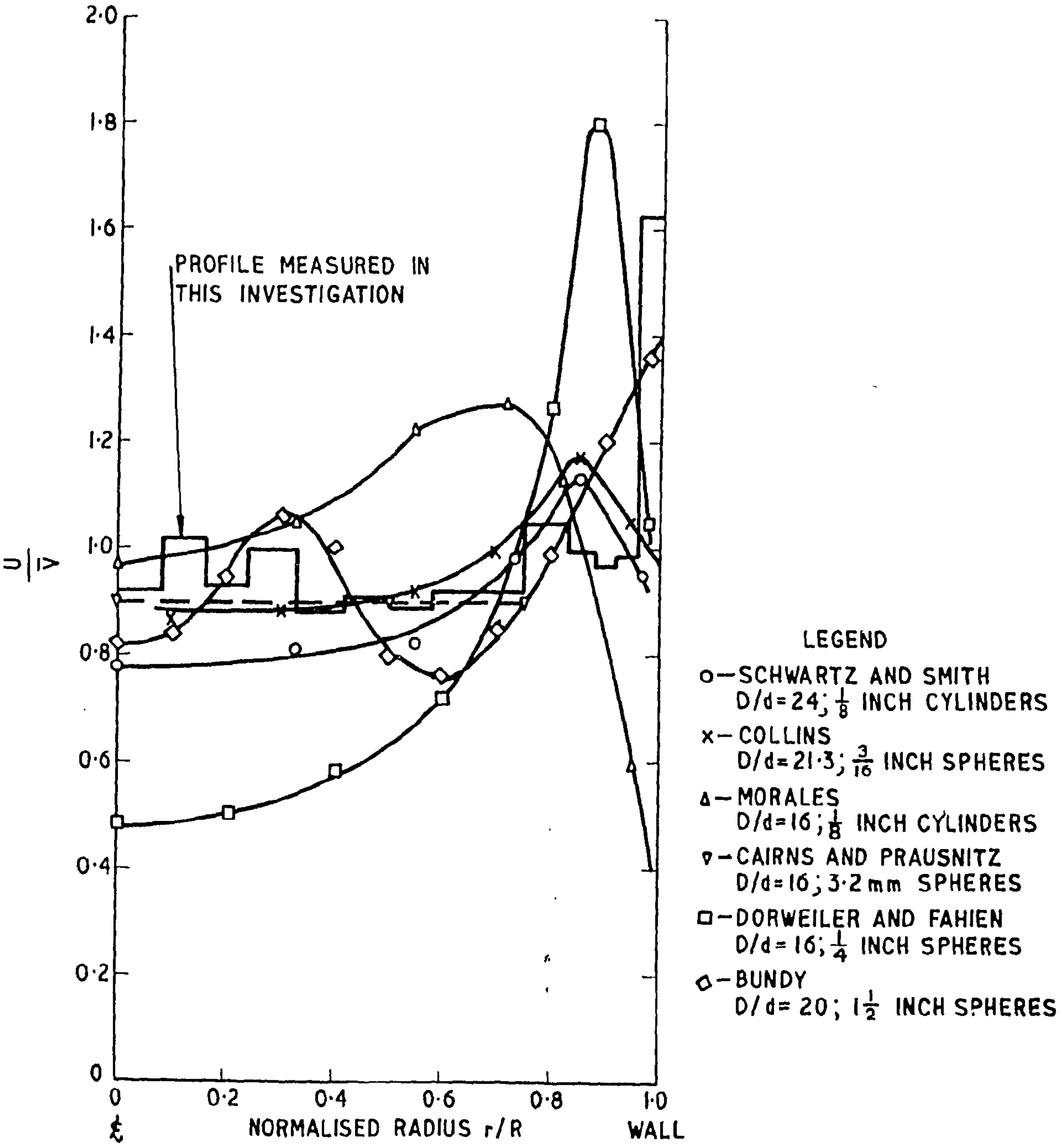


FIGURE 8. COMPARISON OF MEASURED VELOCITY PROFILE FOR A PACKED BED WITH EXISTING PUBLISHED DATA