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RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

FLOW EXPERIMENTS ON PACKED BEDS USING THE UNIVERSITY OF ADELAIDE WATER TUNNEL

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G. SAIVA

September 1967

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ABSTRACT

Experiments were carried out using the University of Adelaide Water Tunnel to determine pressure drop and flow distribution data for packed beds of spheres. Two randomly packed and two regularly packed beds were investigated. The preparation, assembly and testing of these sphere packings are described and the results analysed and discussed.

The friction factors for the two regular beds were found to be higher than for the two random beds. The agreement of the random bed data with that from similar studies is good. Flow profiles, except for the wall region, were essentially flat and independent of Reynolds number.

CONTENTS

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CONTENTS

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1. INTRODUCTION

In the A.A.E.C. Research Establishment's study of high temperature gas-cooled pebble bed reactors, knowledge was required of the dynamics of flow through both randomly and regularly packed beds of spheres. Literature surveys by Hart, Lawther and Szomanski (1965) and Price (1966) indicate that the available information about pressure drop and fluid flow distribution in packed beds is limited, particularly at the higher Reynolds numbers (Re > 10,000, based on sphere diameter and mean fluid velocity through an empty tube). Carefully controlled experiments are required to obtain useful data. In particular, the survey by Price of flow distribution in packed beds indicates that there are large inconsistencies in the published data.

To supplement pressure drop and flow distribution studies undertaken at Lucas Heights using the air-flow facilities, similar experiments were performed in the University of Adelaide Research Water Tunnel between 12th July and 5th August, 1966. The Adelaide tunnel was selected in preference to those at the Universities of Queensland and Sydney as higher Reynolds numbers could be achieved.

The experiments also provided valuable water tunnel operating experience in anticipation of the installation of a small unit at Lucas Heights.

2. CHOICE AND PREPARATION OF TEST BEDS

2.1 Choice of Test Bed Parameters

Of interest in the pebble bed reactor study are pressure drop and flow distribution data for beds having bed to pebble diameter ratios, $D/d \geqq 30$, bed lengths $L \geqq 30d$ and Reynolds numbers (based on pebble diameter d = 1 in) up to 5×10^4. Both randomly and regularly packed reactor core beds are under consideration. The randomly packed beds would be formed by continuous recirculation of the pebbles and the expected mean voidage for these beds would be 39 to 40 per cent. For the regularly packed cores, which would be non-circulating, voidage would probably be between 30 and 33 per cent.

To test models of these cores in a water tunnel at ambient water temperatures, an adequate mass flow is required at a head of about 300 ft of water. Since the available head in the Adelaide tunnel is only 32 ft (Section 3.1), it is clear that the abovementioned bed parameters and the maximum Reynolds number cannot be satisfied simultaneously. If meaningful Reynolds numbers (say, at least 5×10^3) are to be obtained it would not be possible to maintain geometrical similarity between the prototype and model beds. Successful use of models which are dissimilar to the prototype models requires a substantial understanding of the physical phenomena involved. Unfortunately such understanding is lacking and application of the data to other geometries is doubtful.

It is known that the pressure drop through packed beds depends on a number of bed, pebble and fluid parameters. For the present study it is sufficient to consider only the effect of those parameters which are affected by departure from geometrical similarity, that is, D/d, L/d, and mean bed voidage, ϵ.

The maximum diameter of the model bed was governed by the diameter of the tunnel working section (18 in.). Since this cannot be readily removed and replaced it was necessary to insert into it a section of smaller diameter containing the pebble packing. This matter is discussed more fully in Section 3.3. Since a working clearance was required around the test bed to facilitate the connection of static pressure tubing, the diameter of the test bed was selected as 12 in.; also this offered the additional advantage of being of the same bed diameter as that chosen for the pressure drop and flow distribution studies at Lucas Heights.

With the diameter fixed at 12 in., a bed length of at least 12 in. and pebble diameter of 0.4 in. were required for geometrical similarity to typical reactor core configurations. The maximum Reynolds number that could have been expected for such a bed was below 3,000. However, to obtain both higher Reynolds numbers (around 10,000) and data directly comparable with air rig data from Lucas Heights, the same bed length and pebble diameter were selected (9 in. and 0.5 in. giving D/d = 24 and L/d = 18). To obtain still higher Reynolds numbers a bed was prepared using 0.66 in. diameter pebbles, giving D/d = 18.2 and L/d = 13.7.

Rose and Rizk (1949) have provided a plot of relative flow resistances of beds having different D/d ratios. It shows that the wall effect becomes negligible for D/d > 50. The relative resistance at the maximum quoted Reynolds number of 3,000 is approximately 0.93 for D/d = 30 and 0.89 for D/d = 24. Although these relative resistances are only at best approximate, they indicate that a relatively small error (about 5 per cent) results from extrapolating data between D/d = 24 and D/d = 30.

The experimental evidence indicates that the pressure drop for beds of interest in the present study is directly proportional to the bed length, since for beds above a minimum length, the entrance and exit losses (end effects) become negligible compared with the pressure drop per unit length of bed. The survey of Hart et al. (1965) suggests that the end effects become negligible for L/d > 10.

A large number of correlations for the effect of voidage on pressure drop have been suggested (for example, see Rose 1951). Hart (private communication) has checked a large number of experimental data and suggests that the friction factor proposed by Blake (1922) in which

$$\bar{f} = f \frac{\epsilon^3}{1 - \epsilon} ,$$

where $$f = \frac{\Delta p d}{2 L \rho V^2} ,$$

correlates the experimental data better than most others, the accuracy being approximately ± 15 per cent for Reynolds numbers above 1,000.

2.2 Preparation of Test Beds

Two random and two regular beds were tested in the Adelaide water tunnel. Glass marbles (0.49 in. and 0.66 in. diameter) were used in separate random beds and steel spheres (0.499 in. diameter) in both regular beds.

2.2.1 Random beds

Since the force exerted by the water on the pebble packing at the maximum flow was to be about 1,500 lb. it was thought that a loose packing might change its structure during the tests, especially as the tunnel working section was horizontal. The two random packings were therefore consolidated on a linear vibrator, and the total vibration time for each bed was about 9 hours. The final mean voidage was 36.4 per cent for the bed of 0.49 in. marbles and 36 per cent for the 0.66 in. marbles. The voidages were calculated from the known number of marbles in the bed and the mean marble volume determined by a water displacement method.

To investigate the axial voidage distribution a bed composed of the 0.66 in. diameter glass marbles was prepared in the manner described above. Known volumes of water (to which some detergent had been added to reduce surface tension) were then introduced into the bed and the increase in water level observed with a cathetometer. The results are shown in Figure 1. The voidage was larger near the bottom, the mean voidage being 36.7 per cent, while for the central region the voidage was only 35.5 per cent. Axial voidage distributions similar to this for vibrated packed beds have been observed by Debbas and Rumpf (1966) and Tingate (private communication).

2.2.2 Regular beds

Body-centred self-stacking array

This is a square-pitch regular packing, for which the voidage can be varied between 26 and 32 per cent. Once the bottom layer has been fixed the bed is self-stacking, and for the particular pitch used (horizontal separation 0.55 in. (1.1 d) and vertical separation 0.388 in. (0.778 d)) the infinite bed voidage was 31 per cent. The bed was packed in a vessel of octagonal cross section with alternate sides at 11.5 in. and 10.61 in. across flats, and the end view of the bed is shown diagrammatically in Figure 2. The overall mean voidage for this bed was 33 per cent.

Cylindrically ordered array

This bed was composed of concentric cylindrical shells of the 0.499 in. diameter steel spheres, the mean voidage being 32 per cent.

3. EXPERIMENTAL EQUIPMENT

3.1 Brief Description of the Adelaide Water Tunnel

A diagram of the University of Adelaide Research Water Tunnel is given in Figure 3, and the tunnel has been described in detail by Norrie (1964). It is of the closed circuit type, having a horizontal closed-jet working section, 18 in. diameter and 8 ft long. Two 125 h.p. electrically driven centrifugal pumps, connected in parallel, circulate water around the tunnel circuit. The tunnel performance curves (Figure 4) show that the maximum velocity in the working section is 20.5 ft/sec with one of the pumps in operation and 31 ft/sec with both pumps in operation. The maximum head developed by the pumps is about 32 ft of water and flow rate in the tunnel is controlled by motorised gate valves fitted downstream from the pumps. Upstream from the working section is a 16:1 ratio contraction section and a large stilling tank. The stilling tank is fitted with a series of weirs, which normally are inoperative, the level of water being just below the weir crests. The static pressure in the tunnel may be controlled by varying the air pressure in the stilling chamber air space.

Figure 5 shows the velocity profiles across the working section for a velocity of about 18 ft/sec at the first cover position, this being from the beginning of the working section. Except for a wall boundary region of approximately 1 inch, the velocity profile is uniform to within about 3 per cent for the horizontal traverse and 2 per cent for the vertical traverse.

A single 5 in. centrifugal pump is used for both charging and emptying the circuit. Water to fill the tunnel is taken from the common sump of the hydraulic laboratory and it is returned there when the tunnel is being emptied. There is no special provision for controlling the water temperature, but the lower part of the loop is immersed in this laboratory sump. The sump, because of its large capacity, is an effective heat sink and limits the rise in tunnel water temperature to a few degrees, even after several hours operation.

3.2 Modifications to the Adelaide Tunnel

The usual experiments performed in the Adelaide tunnel are marine propeller studies. For these the pressure loss in the tunnel working section is small and the tunnel is normally operated with the free surface in the stilling section open to the atmosphere, or sometimes with a cover over the stilling section and reduced pressure in the enclosed air space.

For the high pressure-drops associated with flow through the pebble packings there is a possibility of cavitation occurring downstream from the test bed. Hence arrangements were made to pressurize the tunnel. This work was done by the University and involved (a) the installation of two 4 in. valves in the weir-draining lines to enable the water level to be raised above the weirs, and (b) the installation of a 4 in. diameter header and overflow pipe above the stilling section to raise the free surface about 7 feet above the top of this section.

During experiments the arrangement of the header-overflow pipe was found to be unsatisfactory. The additional head provided was less than the maximum pump head and resulted in some water being forced out through the overflow pipe and a free surface being formed at the point of minimum pressure (immediately downstream from the test bed).

This problem was overcome by blocking off the header pipe and using the town water supply to provide additional pressure. This had to be manually controlled and kept to the maximum pressure that the tunnel circuit could withstand (about 20 ft).

Even with this additional pressure, at all but very low flow conditions the pressure downstream from the test assembly was still below atmospheric. The tunnel had a number of small leaks between the working section and the pumps through which air could enter the tunnel circuit. This air kept accumulating in the stagnant region downstream from the test assembly fixing flange (see Figure 6). At maximum flow conditions the top of the flow separator soon became exposed to this air pocket. Removal of this air was difficult but the problem was partly solved by admitting extra water to this region via a suction hose from an external water tank. Although a small air pocket still occurred, the flow separator was submerged at all times.

3.3 Design of Test Equipment

As already mentioned in Section 2.1 , the working section of the Adelaide tunnel could not be removed readily and hence the pebble packing had to be contained in a smaller (12 in. diameter) test section inside the tunnel working section.

Access to the working section was through eight 10 in. diameter inspection doors, four at each of the No. 1 and No. 2 cover positions. All equipment that could not enter the tunnel through these inspection doors had to be lowered into the tunnel through an opening in the stilling section and then moved through the contraction into the working section. Hence the test equipment had to be designed so that (a) it could be lowered into the stilling section through an opening 17.5 in. wide at its narrowest part and then moved along the tunnel contraction into the working section, and (b) the operations of fixing the test section in position, sealing the annulus between the two sections and attaching the static pressure lines could be performed either through the inspection doors or from inside the tunnel.

After careful planning of each operation involved, the design shown schematically in Figure 6 was adopted. This consisted of four major parts: a spun aluminium contraction section, an inlet section, the test section containing the pebble packing, and an annular flow separator to channel the flow for flow distribution studies. The last three sections formed a sub-assembly which was put together before being lowered into the tunnel. The packing was held in place by 4-mesh (18 S.W.G.) grids clamped at each end of the test section. Pressure sealing was provided by two O-rings and two steel rings at the test section upstream flange.

The flow separator consisted of a 5 in. diameter central tube, surrounded by six concentric annuli decreasing in width from 15/16 in. to 1/4 in. in the radial direction. Radial vanes divided each annulus into four cells for flow distribution measurements. A separator length of 9 in. was selected to give uni-directional flow free from small scale fluctuations at the exit. Since the flow survey was limited to one diameter only, it was thought that such a length would lead to more meaningful results than would be possible with a shorter length.

For pressure-drop measurements static pressure tappings were provided at four stations. At each station there were four tappings spaced 90° apart on the horizontal and vertical centre lines. The first station was $1\frac{3}{4}$ in. upstream from the bed, the second and third stations were inside the bed for intermediate pressure

drop measurements 3 in. and 7 in. from the upstream end, and the fourth station was in the flow separator 2 in. downstream from the bed. The individual tappings of the first station were permanently connected together in a piezometric ring.

4. INSTALLATION AND REMOVAL OF TEST EQUIPMENT

For each of the four beds tested, the following procedure was adopted:

1. The sub-assembly of the inlet, test, and flow separator sections was lowered into the stilling section through the 17.5 in. wide opening.
2. In the stilling section a pair of rollers was fitted to the flow separator section to facilitate movement of the sub-assembly through the tunnel and to minimize damage to the internal surface of the tunnel.
3. The sub-assembly was moved manually up the incline of the contraction and into the 18 in. diameter working section, where it was manoeuvred until it was opposite the inspection doors at the No. 1 cover position. This enabled 13 static pressure lines to be attached.
4. The subassembly was moved to its final position and secured by four 3/4 in. diameter screws at the front flange and centralized at the flow separator end.
5. The O-rings and steel sealing rings were installed and secured from inside the tunnel.
6. The contraction section was placed in position and secured from inside the tunnel.
7. Pressure lines were connected to a special pressure transfer plate, which was inserted in one of the inspection doors at the No. 2 cover position, so that the lines could be taken out from the tunnel and connected to the manometer manifolds.
8. Upstream (No. 1 cover position) and downstream (No. 2 cover position) pitot tubes were installed.
9. All remaining inspection door covers were placed in position and secured.
10. The stilling tank cover was placed in position and secured.
11. The tunnel was filled with water.

To remove the test assembly the above procedure was reversed. The complete cycle, including experimentation, took about 15 hours.

5. MEASUREMENTS OF FLOW AND PRESSURE DROP

5.1 Total Flow

For the type of experiments usually performed in the Adelaide tunnel, only the velocity in the central region of the working section is of interest. This velocity is measured by a fixed pitot static tube located on the centre-line upstream from the test object. If the total flow is required, as it was for these experiments, then it must be calculated from the horizontal and vertical velocity traverses. Since the minimum velocities commonly used in the tunnel are of the order of 15 ft/sec, standard U-tube manometers give a high degree of accuracy (for example, 18 ft/sec corresponds to 5.2 ft of water gauge).

However, for the packed bed pressure-drop experiments the maximum velocity in the 18 in. diameter section was about 1 ft/sec which corresponds to only 0.186 in. of water gauge. Since for pitot static tubes $V = (2gh)^{0.5}$, the differential head decreases rapidly as V decreases. At 0.4 ft/sec, the differential head is only 0.030 in. of water. There are no difficulties in measuring such differential pressures if the flowing medium is air, since several micro-manometers are available that can measure accurately pressure differentials down to 0.001 in. of water. If the flowing medium is water the problem becomes more difficult, since there are very few suitable manometer liquids that are immiscible with water, do not stick to the sides of the glass, form a sharp clear meniscus at the surface of separation, and have a specific gravity close to unity. Only two such fluids were readily available: kerosene (s.g. about 0.78) for use in an inverted U-tube manometer, and carbon tetrachloride (s.g. about 1.60) for use in a conventional U-tube manometer. The University made available a suitable U-tube stand, with a telescopic sight and vernier attachment that allowed readings to 0.001 in. The absolute pressure (up to 30 ft of water above atmosphere) was too high to consider the use of some of the more delicate micro-manometers.

Kerosene was tried first in an inverted U-tube arrangement, but was found unsatisfactory. Although this system gave a magnification factor of about 5, it was found that there was a tendency for the kerosene to stick to the sides of the gauge glass and hence give large zero errors (up to 0.05 in. and higher). The sticking was mostly caused by the continual contamination of the U-tubes and the kerosene-water interface by the tunnel water.

The carbon tetrachloride system was found to have a faster response to pressure changes and smaller zero errors (maximum of about 0.005 in). Although the magnification factor was down to 1.66, this system was considered superior to the kerosene system and was used in all the experiments.

Since every reading could be in error by at least 0.005 in. the minimum tunnel velocity was arbitrarily limited to 0.5 ft/sec, corresponding to a manometer deflection of 0.050 in. The velocity error could then be up to 5 per cent, and the friction factor error up to 10 per cent. In addition (see Figure 4) the tunnel velocity fluctuations (caused by motor speed fluctuations) could be of the order of ± 1.5 per cent. The combined error at the minimum velocity could be 6.5 per cent for the velocity and 13 per cent for the friction factor. At a tunnel velocity of 1 ft/sec, the corresponding errors are 4 and 8 per cent.

To relate the centre line velocity to the mean tunnel velocity it was necessary to determine the velocity profiles at the experimental velocities. Because of the relatively high errors associated with the measurement of these low velocities, it was decided to utilise the available velocity profiles obtained at higher velocities in conjunction with the results of a study (Ross 1956) of turbulent flow in the entrance region of a pipe. From the available traverses at 18 ft/sec it was calculated that the mean velocity was 0.987 of the centre line velocity and that the corresponding displacement thickness of the boundary layer was 0.072 in. According to Ross, if the boundary layer had been turbulent from the start, the effective point of zero thickness at a tunnel velocity of 18 ft/sec would be 3.45 ft upstream from the point of velocity measurement. If it is further assumed that the start of the turbulent boundary layer remained unaltered for the lower velocities then the theory allows calculation of the corresponding boundary layer displacement thickness for any given tunnel velocity. Thus for a velocity of 1 ft/sec, the displacement thickness was calculated to be 0.204 in. and the corresponding mean velocity 0.96 of the centre line velocity. This velocity ratio was assumed to remain constant over the range of experimental velocities.

5.2 Flow Distribution

Measurement of the flow distribution downstream from the bed was limited to a single traverse along the horizontal diameter. The velocity was measured by an impact tube $\frac{1}{8}$ in. downstream from the flow separator. The static pressure was measured in the same horizontal plane, but 8 in. downstream and at the wall of the 18 in. diameter tunnel working section. An ordinary U-tube manometer using carbon tetrachloride as the measuring fluid gave sufficient accuracy, since (from Section

5.1) the average velocity at the exit from the 12 in. diameter section was 2.25 times higher than in the 18 in. diameter section, and this gave manometer deflections 5 times as large. A suitable traversing mechanism was made available by the University and measurements were made at midpoints of the concentric annuli of the flow separator.

5.3 Pressure Drop

Since the pressure drops were quite high (between 1.5 and 32 in. mercury) ordinary mercury-water U-tube manometers were used for the differential pressure-drop measurements.

For the overall pressure-drop measurements the four static pressure tappings at each of Nos. 1 and 4 stations were connected together and only the mean differential pressure recorded.

For the intermediate pressure drop measurements provision was made to measure the individual pressure drops between the corresponding tappings, as well as the mean pressure drop between Nos. 2 and 3 stations. This was made possible by connecting the tappings of each station to separate manifolds and fitting each pressure line with a valve.

The manometers were subject to relatively small mercury column oscillations and could be read to within 0.1 inHg, which far exceeded the accuracy of tunnel velocity measurements.

6. EXPERIMENTAL RESULTS

6.1 Pressure Drop

The experimental results are shown in Figures 7 and 8 as plots of the friction factor against the Reynolds number. In all cases both the intermediate and overall friction factors are given and it will be observed that, with the exception of the concentric shell bed, the intermediate friction factors are significantly higher than the overall factors. The intermediate friction factors were calculated from the mean piezometric differential pressures between Nos. 2 and 3 stations. There were large differences between the individual readings, shown in Figure 9 where the readings are plotted for the 0.6 in. diameter marble random bed, but the piezometric mean was always in good agreement with the arithmetic mean.

At first the fact that the overall friction factor was lower than the intermediate was rather disturbing. If anything, because of the end effects, the opposite trend was expected. For this reason the axial voidage distribution was determined for an identically prepared bed of 0.66 in. diameter marbles (see Section 2.2.1) assuming that for this bed the voidage distribution followed the same trend as for the bed tested in the water tunnel. The results were then replotted in Figure 10 against Blake's friction factor allowing for a lower voidage in the central region of the bed, where it was assumed to be 35 per cent. The measured mean overall voidage was 36 per cent and the voidage distribution on a similar bed was measured as 35.5 and 36.7 per cent respectively. Allowance for the lower voidage in the central region leads to good agreement between the two factors.

There seems little doubt that static pressure readings are strongly affected by the location of the tapping with respect to the surrounding pebbles and in random beds this may be overcome by providing a number of tappings at each station. The relatively good agreement between the intermediate and overall friction factors shown in Figure 10 does not necessarily indicate that 4 tappings are sufficient and the minimum number would have to be determined in carefully controlled experiments. To obtain true readings for regular beds the spacing between stations must be equal to whole multiples of packing pitch, otherwise both higher and lower pressure differentials may be indicated. Since this condition did not occur with either of the two regular packings it probably was the chief reason for any differences between the intermediate and overall friction factors.

A combined plot of the overall friction factor is shown in Figure 11 and these results have been replotted in Figure 12 using Blake's friction factor. Although the pressure drop (friction factor) is higher for the regular packings, their inherent resistance, allowing for decreased voidage, is lower than the resistance of the random packings. As expected the 0.66 in. diameter marble random packing, because of its lower D/d ratio, gives lower friction factors than the 0.49 in. diameter marble packing. The difference is larger than could be expected from the D/d correlations by Rose and Rizk (1949), which indicate a difference of about 3 per cent. A few selected results for an otherwise identical 0.49 in. diameter marble random packing, except for slightly higher voidage (37.3 per cent) have been plotted in Figure 12, from the data on air flow through packed beds obtained by Price (1967). The general agreement between the two sets of data is very good. No data were available for regular beds of comparable size, hence no comparisons can be made.

Since the experimental results cover a small Reynolds number range and may be subject to errors in excess of ± 8 per cent, no particular significance can be attached to slope and curvature of the best fit lines through the experimental points.

6.2 Flow Distribution Downstream From Test Beds

A survey by Price (1966) of earlier literature on flow distribution downstream from packed beds showed that the published flow distributions were inconsistent and conflicting. The basic reason for this was thought to be the difference in methods of measuring velocity adopted by the various experimenters. More recent experimental work by Price (1967), using a 4 in. long flow separator both to straighten and to channel the flow, showed that the mean velocity profile is essentially flat right across the packing to about half a pebble diameter from the wall, where there is a sudden significant increase in the velocity. At the wall itself the velocity, of course, drops again to zero. Price showed that along any radius there may be large departures from the mean distribution and that almost a complete survey of the whole bed is required to arrive at the true mean flow distribution.

Figure 13 shows some of the flow distribution results that were obtained in the Adelaide water tunnel for the concentric shell bed and the two random beds, as well as the results obtained by Price for a similar random bed of 0.49 in. dia. glass marbles. The non-dimensional velocity distribution v/V is shown as a function of the normalised radius, r/R. Only the results for the maximum flow are shown for each bed, since almost identical distributions were obtained for all other flows.

Considering that in the water tunnel investigation the velocities were determined only along the horizontal diameter, and hence are averages of two observations only, the results show fair agreement with those of Price.

The results in Figure 13 indicate a higher mean flow than the true mean and this discrepancy may arise because (a) the velocities were measured in the middle of each annulus and hence, because of the 9 in. long cells, were probably higher than the mean cell velocities, (b) velocity traverse was restricted to one diameter only, and (c) the static pressure was measured in the wake of the pitot tube.

7. CONCLUSIONS

The pressure-drop experiments indicated that the friction factors for the two regular beds, that is, the body-centred array and the cylindrically ordered array were higher than for the two random beds. However, when allowance was made for the lower voidage of the regular beds, the resulting specific resistances of these beds were lower than those of the random beds. Although the experimental results on the four beds could be subject to errors of at least ± 8 per cent the agreement with other similar random bed studies is good. No other experimental data were available for comparison with the results obtained for the two regular beds.

Intermediate pressure-drop measurements proved rather unreliable and further work is required to determine the minimum number and location of static pressure tappings for such measurements.

The flow distribution experiments, though not conclusive, indicate that except for the wall region the mean liquid flow profile is essentially flat and that it is independent of Reynolds number over the limited range tested.

8. ACKNOWLEDGEMENTS

The author wishes to acknowledge the cooperation of the Department of Mechanical Engineering, University of Adelaide, in planning and carrying out the experimental work described in this report. Mr. D. H. Norrie's counsel during the planning stage was very helpful, as also was Dr. J. Mannam's and Mr. M. Hale's assistance during the experiments. Special thanks are due to Professor H. H. Davis for making available the experimental facilities. Velocity profiles shown in Figure 5 were supplied by the University.

Mr. H. N. Harvey participated in the design of the experimental equipment, prepared the two random beds, and was of great help to the author in the preparation of the tunnel and in the experimental work. Mr. D. Metter's help over the final three days is also gratefully acknowledged.

Mr. F. Rocke prepared the cylindrically ordered array. Helpful discussions were held with Dr. K. R. Lawther, Mr. J. Price and Mr. J. A. Hart. The body-centred array was prepared under Dr. K. R. Lawther's supervision. The experimental work was initiated and arranged by Mr. G. W. K. Ford and Mr. E. Szomanski.

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APPENDIX 1

NOTATION

D	diameter of cylindrical packed bed
L	packing length
R	radius of cylindrical bed
Re	pebble Reynolds number (dV/ν)
V	superficial velocity based on total cross-section of packing
d	diameter of pebble
f	packing friction factor $\Delta pd/(2L\rho V^2)$
$\bar{f}$	Blake's friction factor $f\epsilon^3/(1 - \epsilon)$
Δp	pressure drop across length L of packing
r	radius
v	local velocity
ϵ	voidage
ρ	fluid density
ν	kinematic viscosity

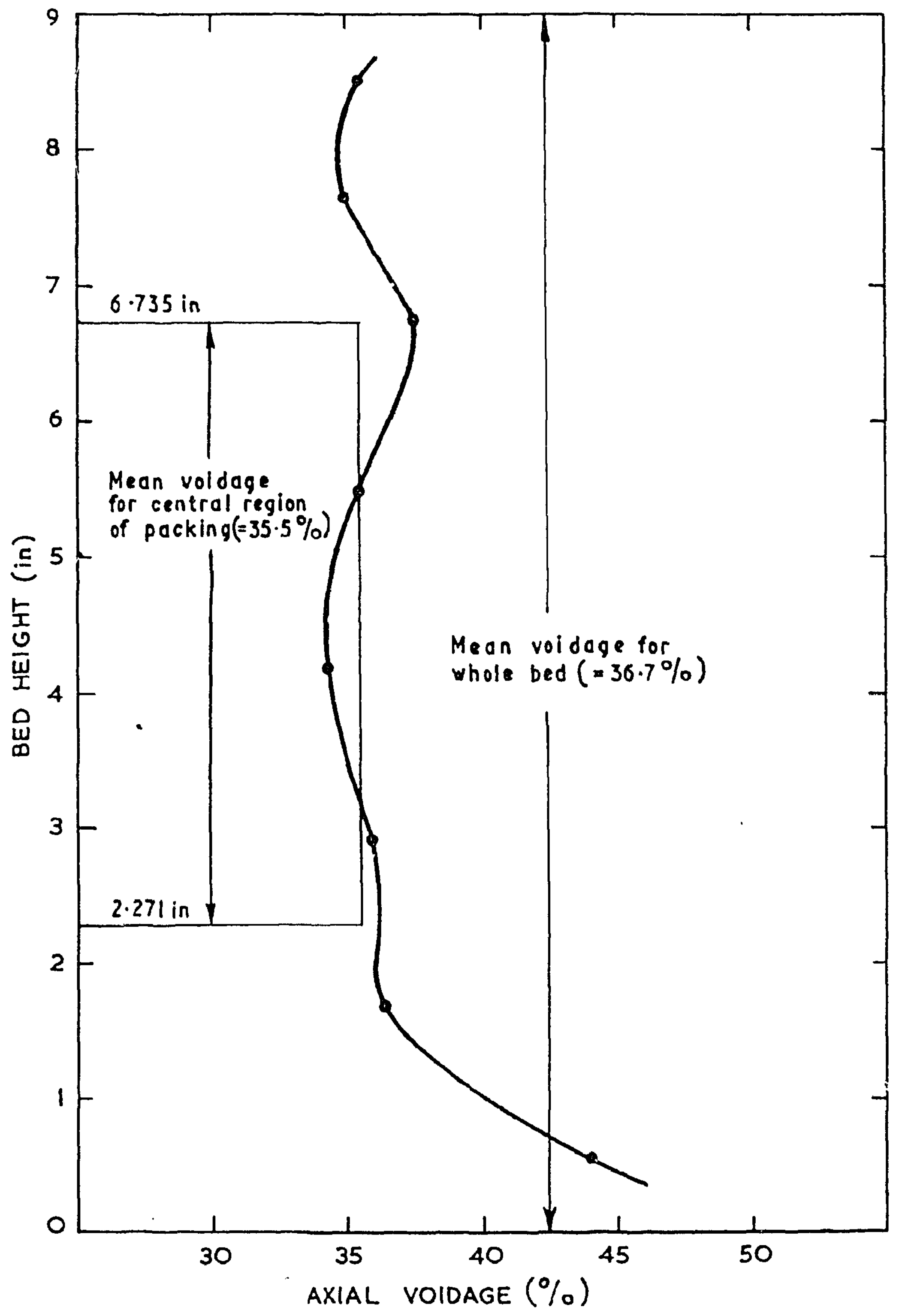

FIGURE 1. AXIAL VOIDAGE DISTRIBUTION FOR RANDOM PACKING
(MARBLE DIAMETER 0.66 in.)

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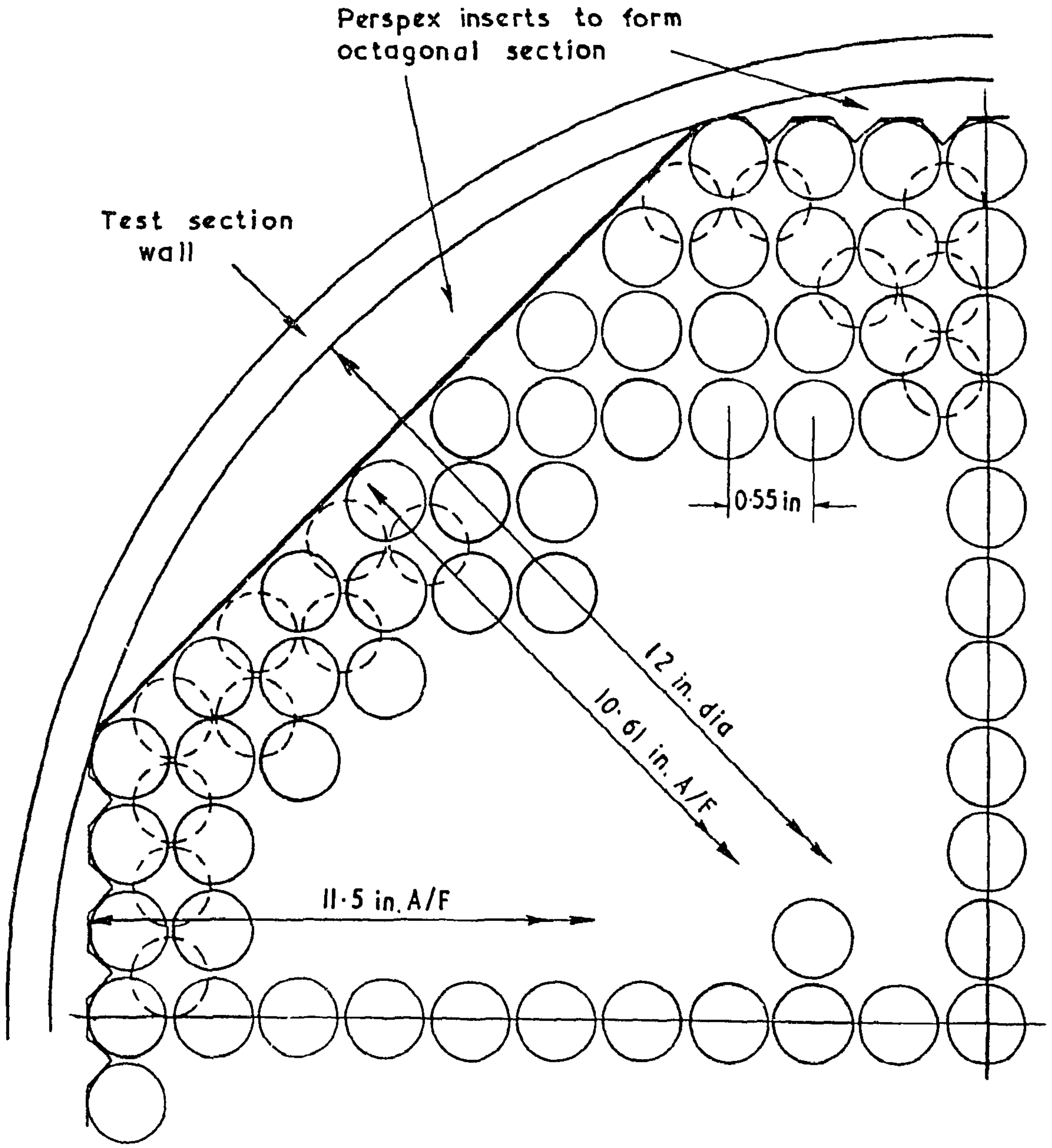

FIGURE 2. END VIEW OF BODY-CENTRED-ARRAY BED

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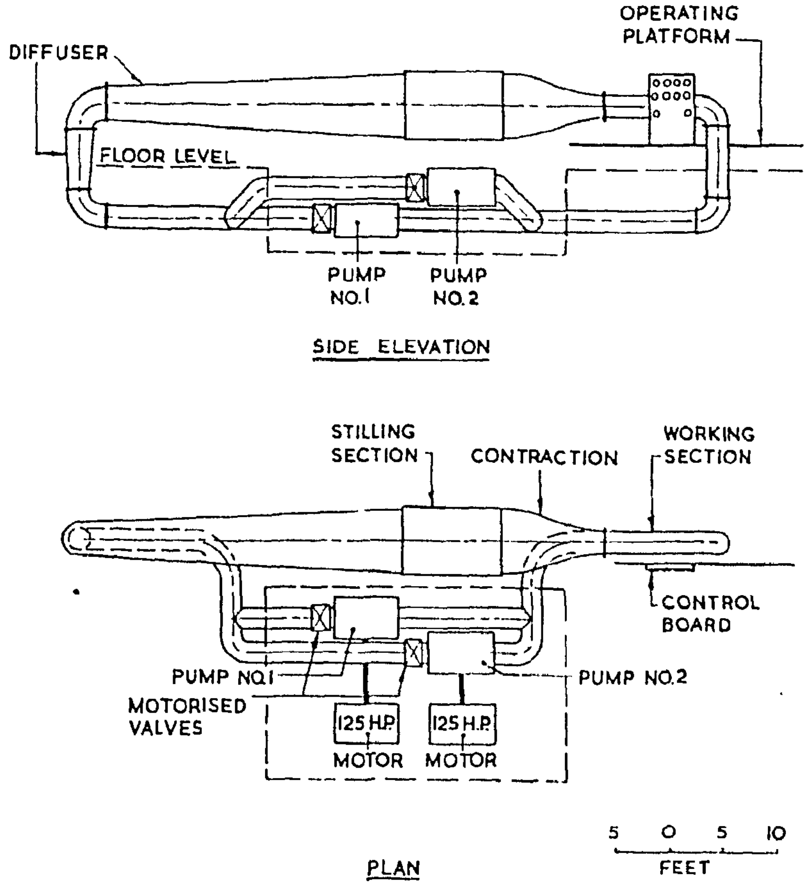

FIGURE 3. GENERAL ARRANGEMENT OF ADELAIDE WATER TUNNEL

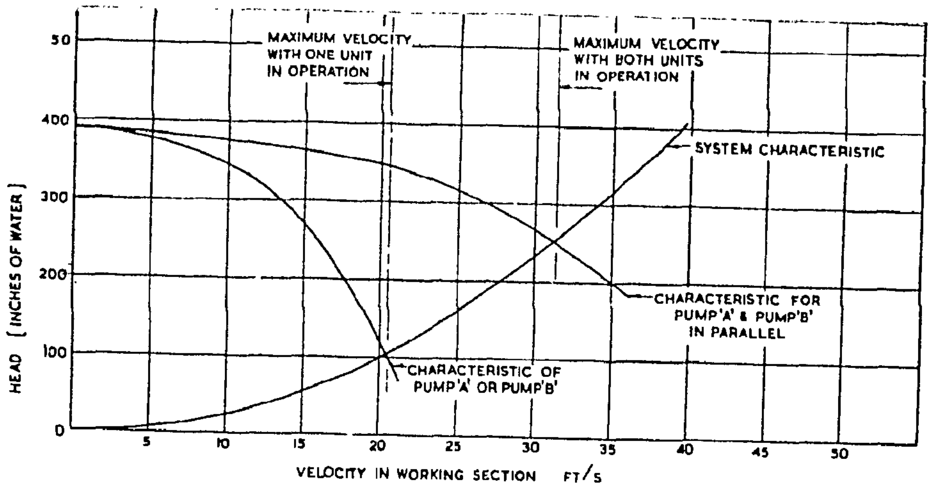

FIGURE 4. PERFORMANCE CURVES OF ADELAIDE WATER TUNNEL

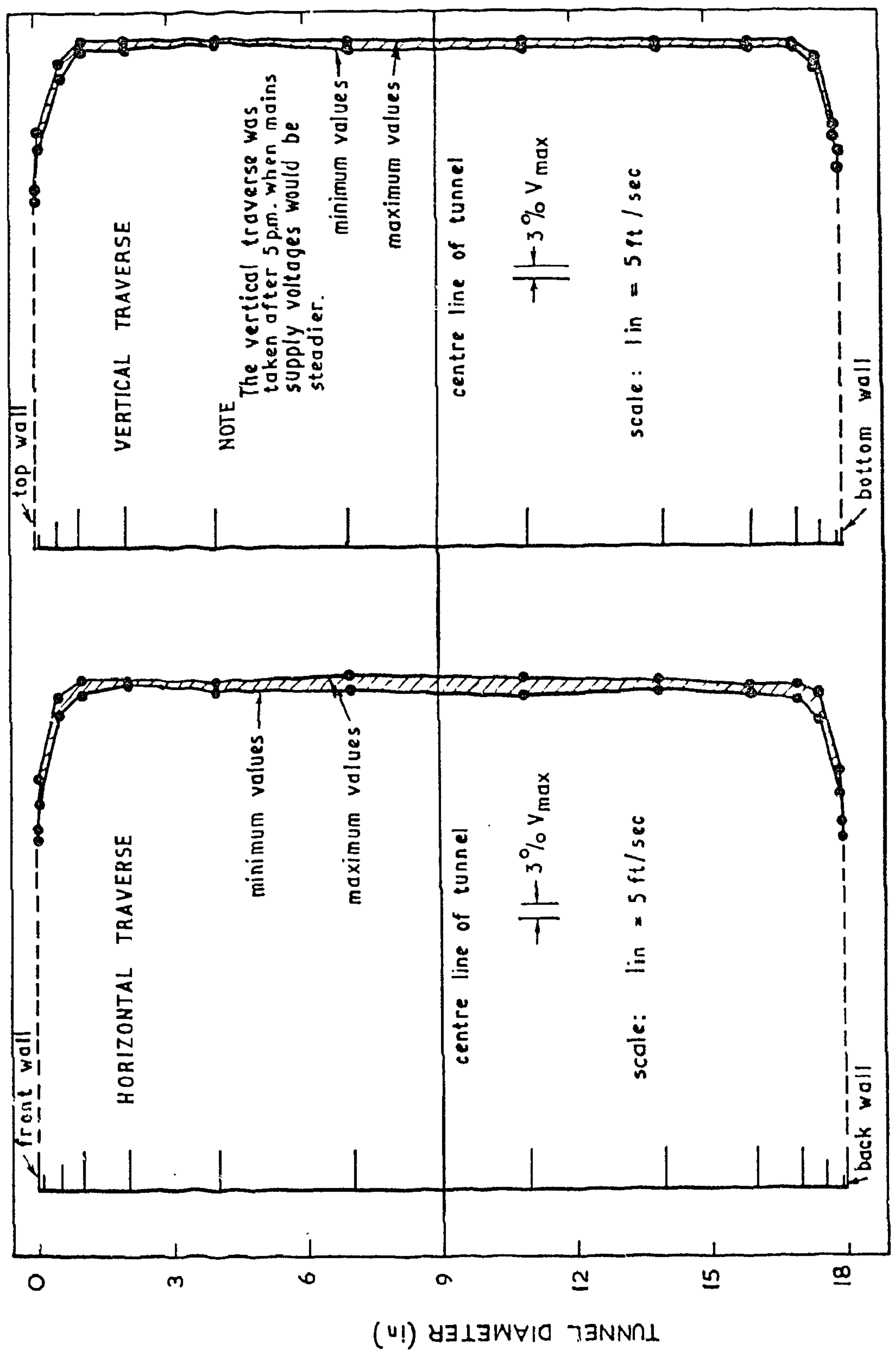

FIGURE 5. FLOW PROFILES AT NO. 1 COVER POSITION

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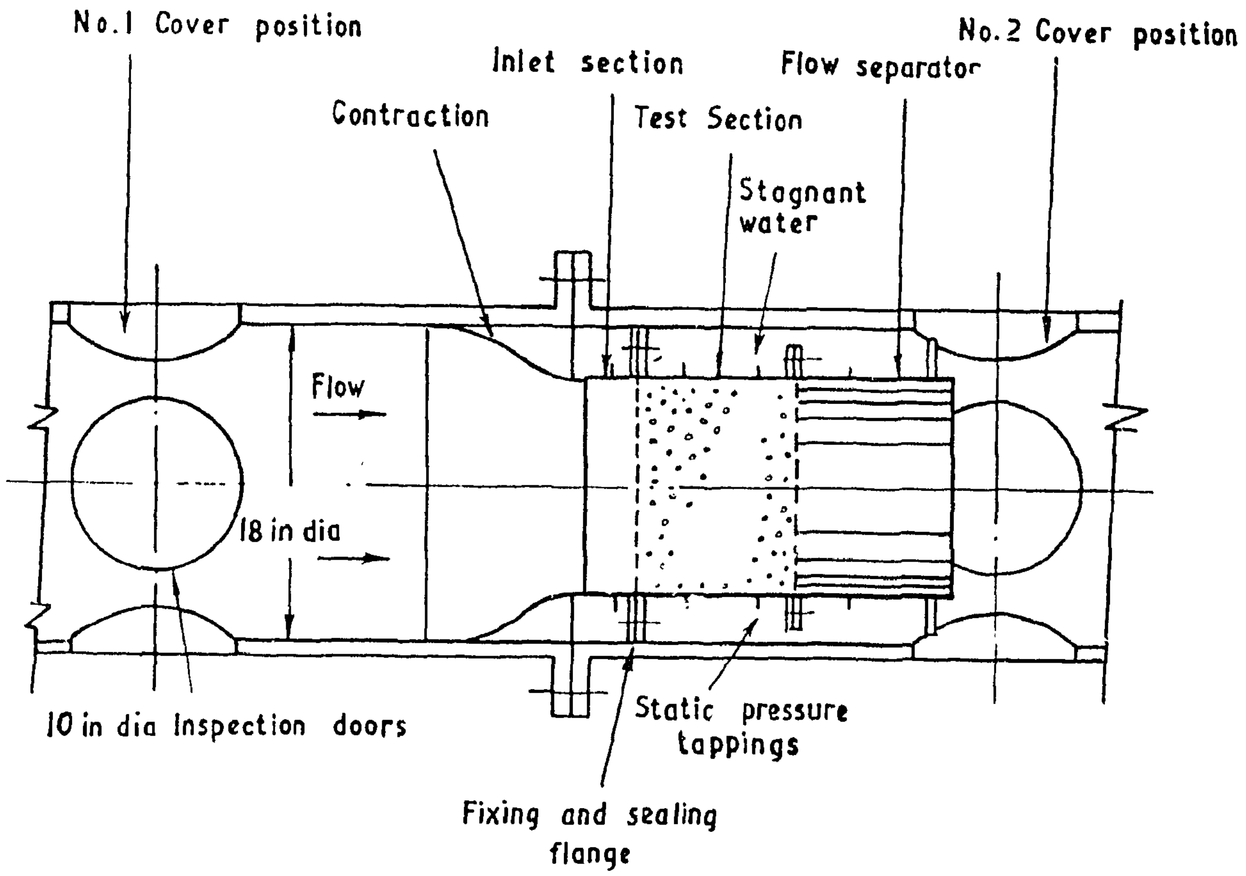

FIGURE 6. SCHEMATIC ARRANGEMENT OF TEST EQUIPMENT

P1193

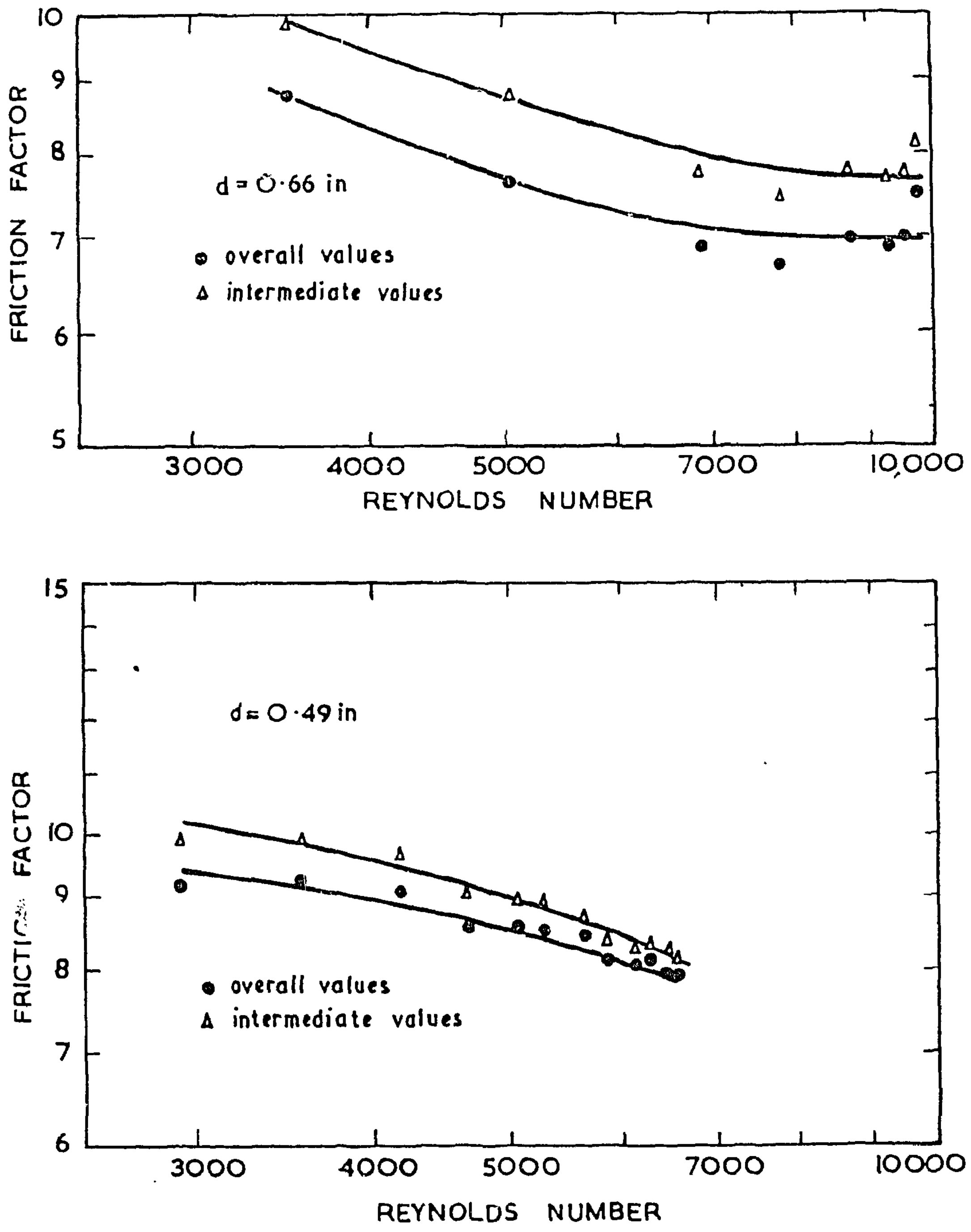

FIGURE 7. FRICTION FACTORS FOR LIQUID FLOW THROUGH RANDOMLY PACKED BEDS

P1193

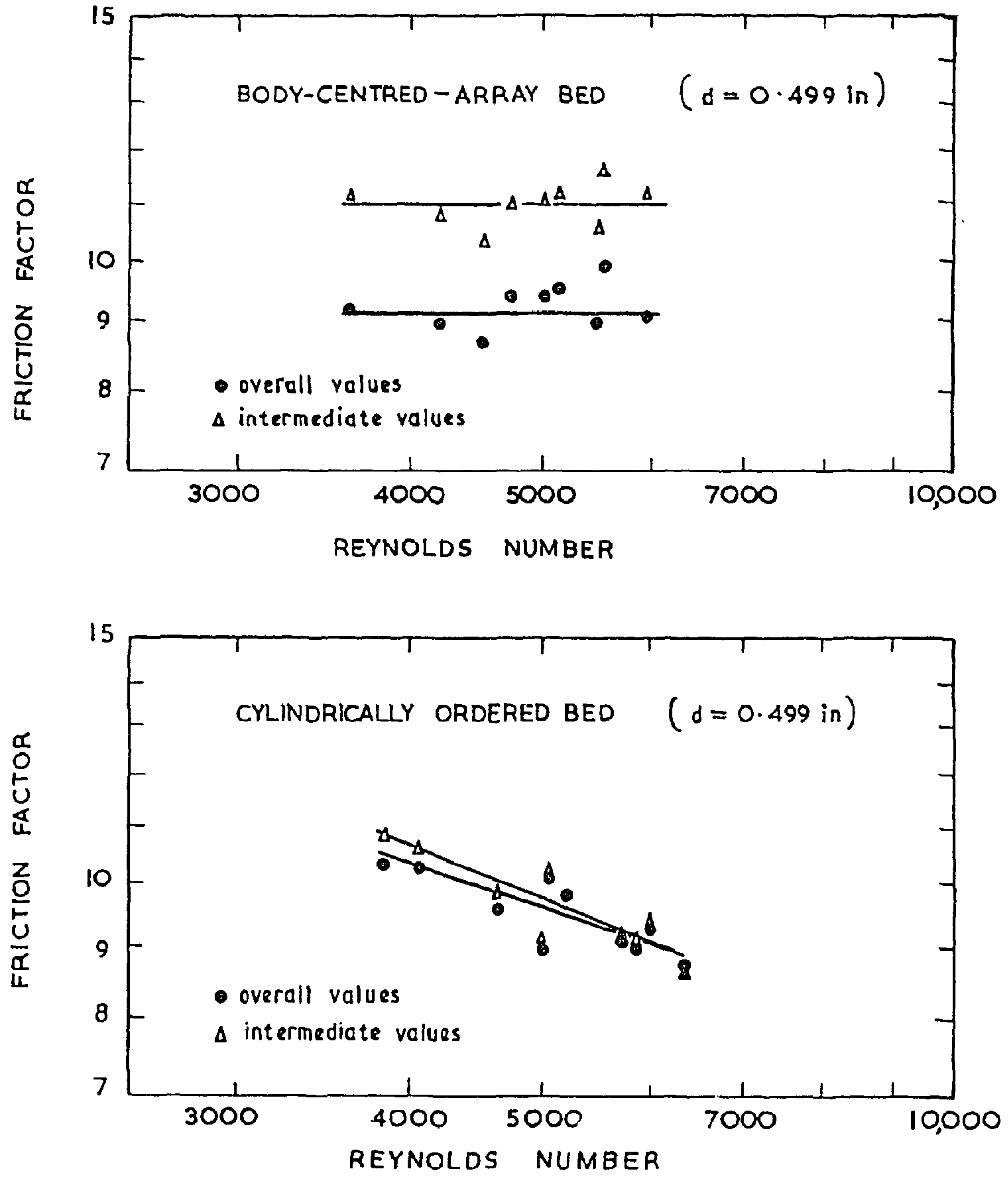

FIGURE 8. FRICTION FACTORS FOR LIQUID FLOW THROUGH REGULARLY PACKED BEDS

P1193

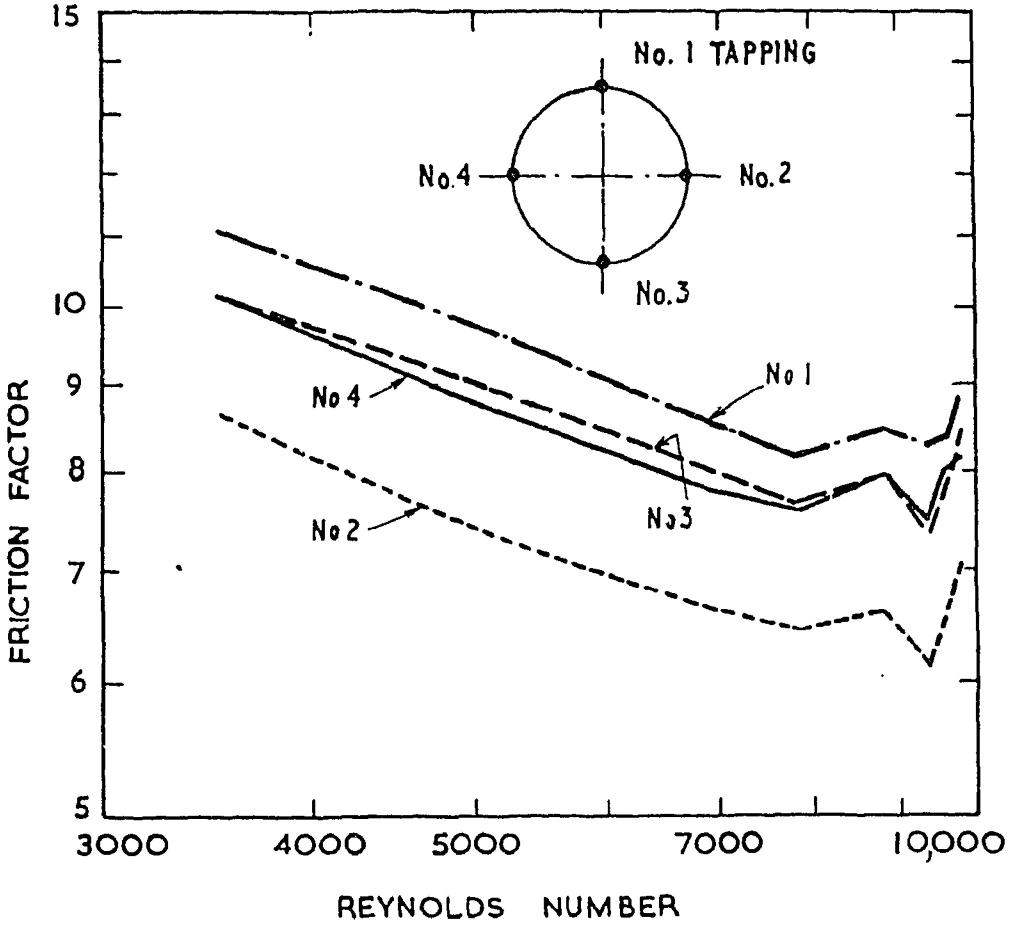

FIGURE 9. INTERMEDIATE FRICTION FACTORS FOR LIQUID FLOW THROUGH RANDOMLY PACKED BEDS (MARBLE DIAMETER 0.66 in.)

P1193

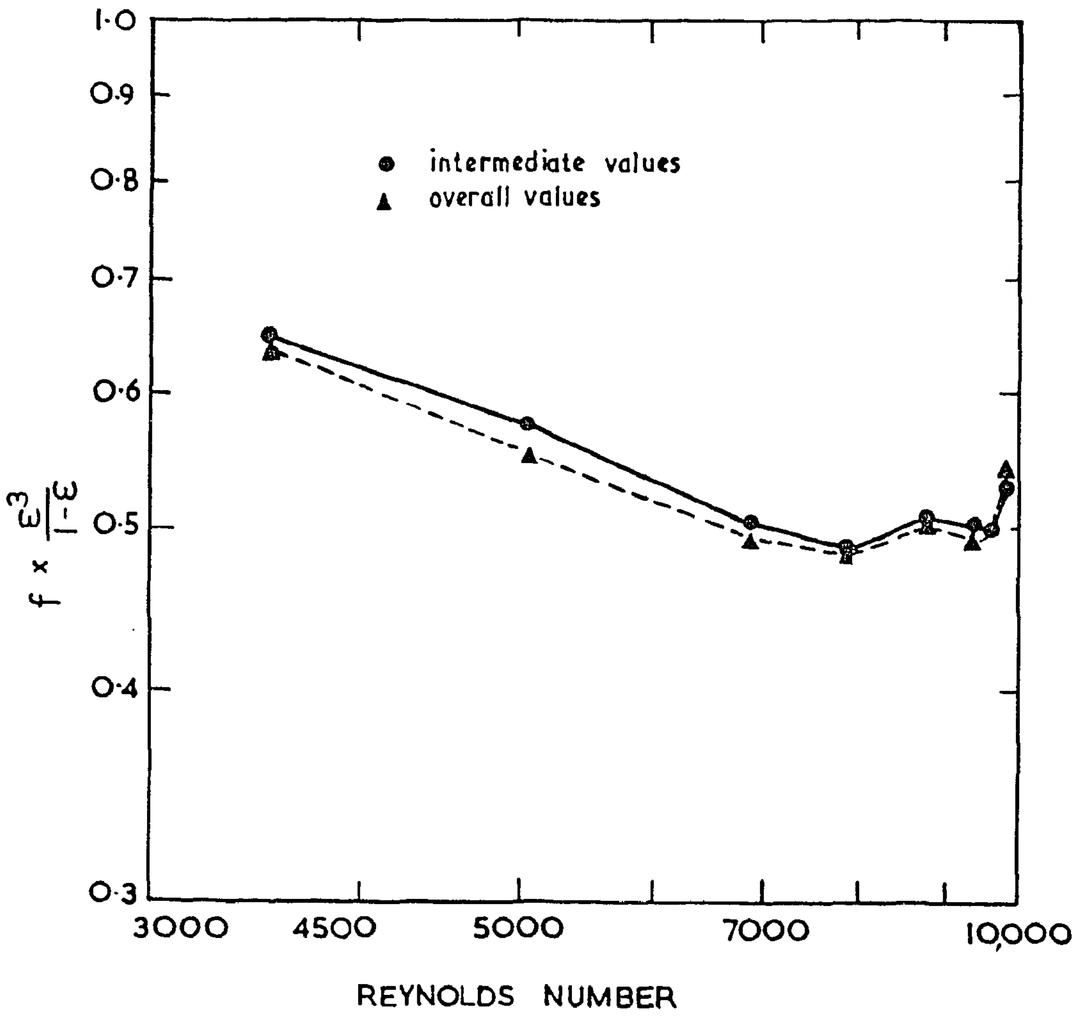

FIGURE 10. COMPARISON OF CORRECTED INTERMEDIATE AND OVERALL FRICTION FACTORS FOR 0.66 in. DIAMETER RANDOM PACKING

P1193

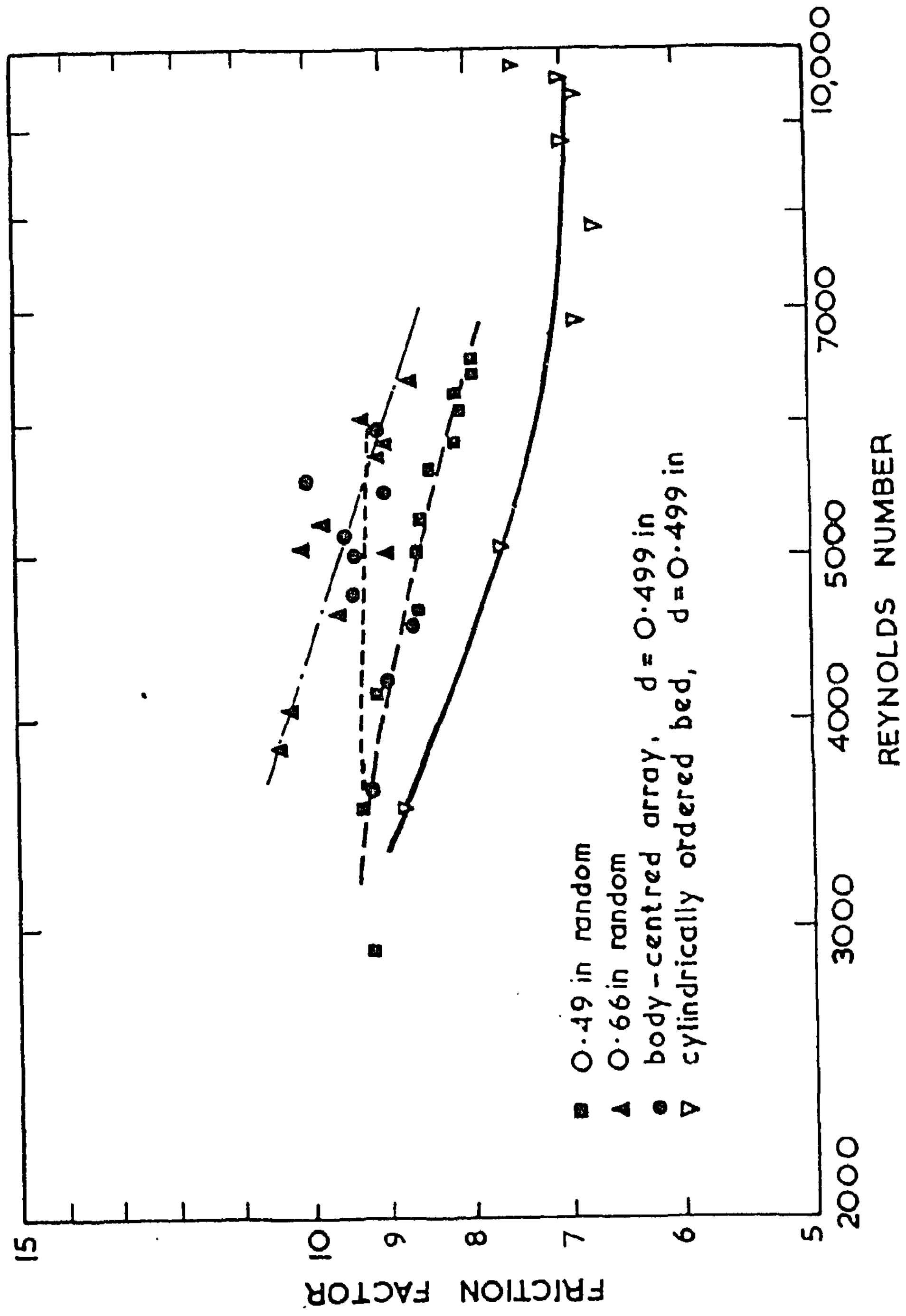

FIGURE 11. OVERALL FRICTION FACTORS FOR ALL BEDS

P1193

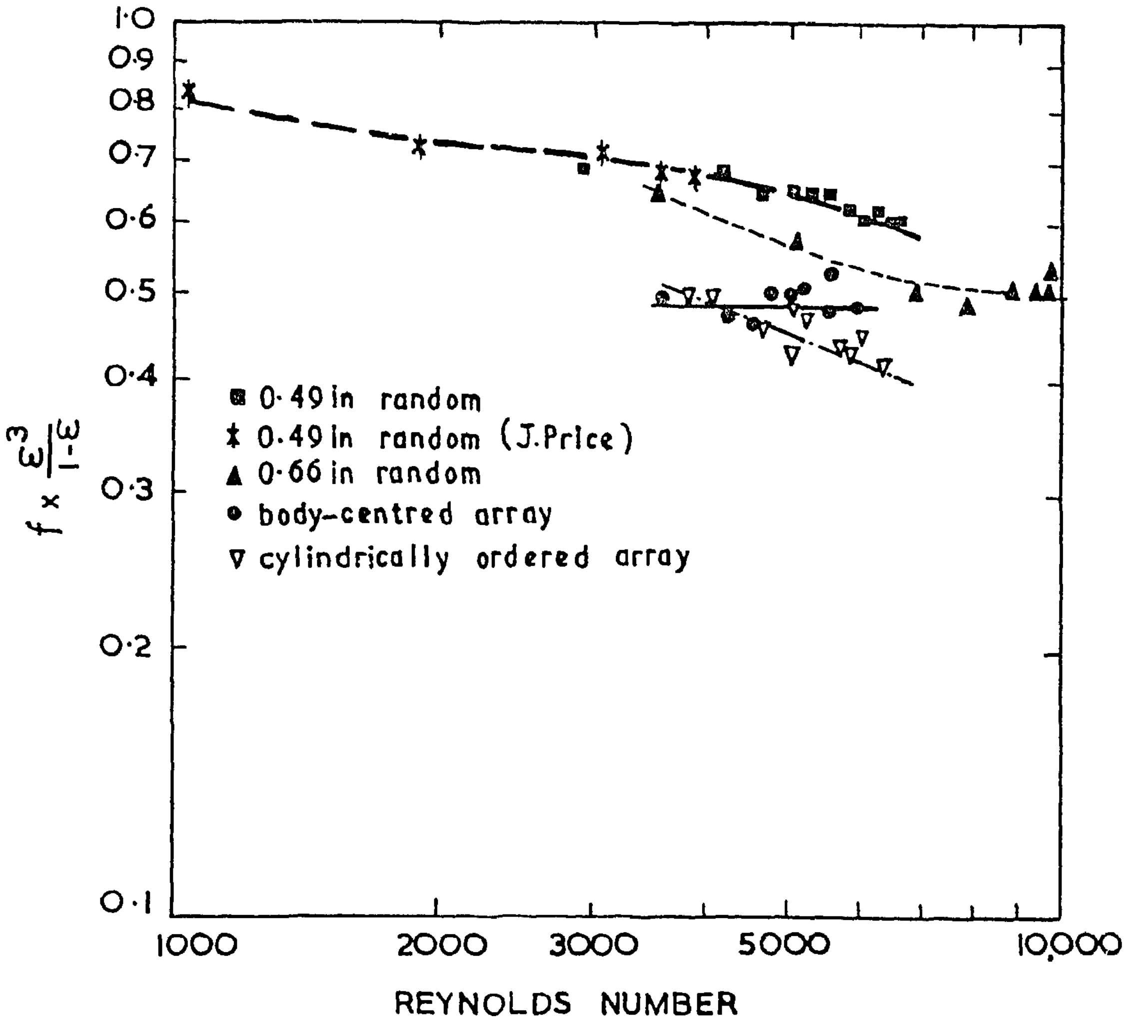

FIGURE 12. BLAKE'S FRICTION FACTORS (OVERALL) FOR ALL BEDS

P 1193

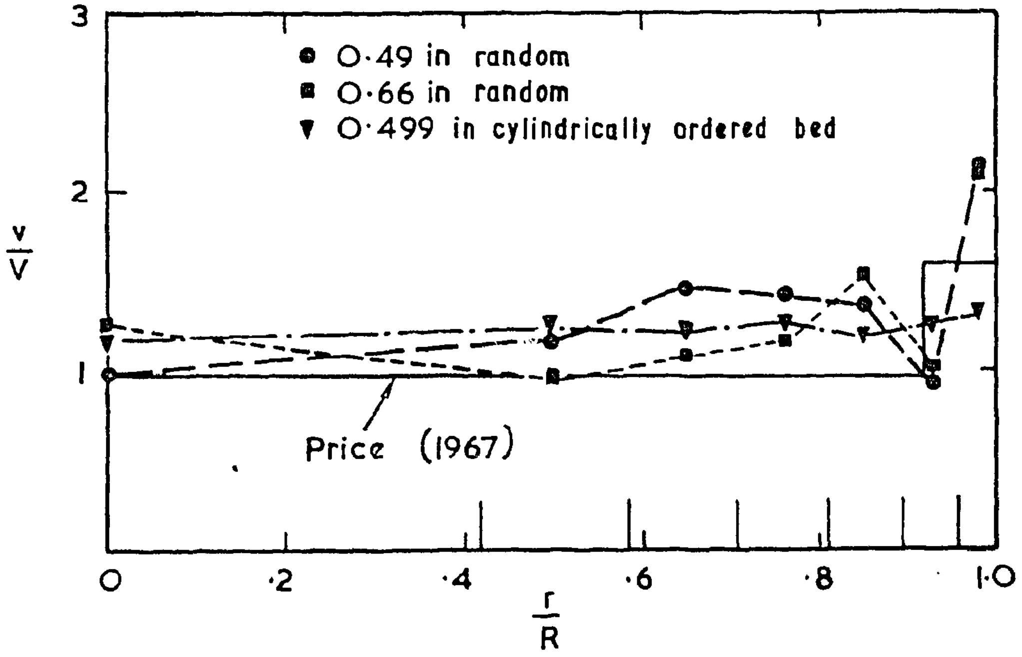

FIGURE 13. FLOW DISTRIBUTIONS DOWNSTREAM FROM TEST BEDS. COMPARISON WITH PRICE (1967)

P 1193