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BEHAVIOUR OF A WATER JET IN A DIVERGING SHALLOW OPEN CHANNEL

by

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SUMMARY

An experimental study has been made of the flow emerging from a pipe (flowing full) into a diverging open channel. The channel bed was horizontal and at the level of the pipe invert. The emerging flow was at supercritical velocity at the apex of the expansion, becoming subcritical downstream. The nature and a physical explanation of the flow within the transition are the subject of this paper. Three key factors have been found to determine the resulting flow patterns, they are the angle of divergence of the side walls, the degree of submergence, and the upstream Froude number.

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Introduction

This study originated with an incidental observation during a full scale test of the low level outlet works of an old embankment dam. The two parallel outlet conduits, which flowed full, were 0.91m wide by 1.83m high and 2.44m apart. They discharged into a horizontal channel with walls diverging at 18 deg from the centreline, retaining the embankment slope. Beyond the toe of the dam the channel continued to expand for some distance before being constricted by the river banks. The outlet discharge was slowly increased to an estimated 30m^3/s while the water levels downstream were gradually rising under the influence of river channel control. Initially the jet issued symmetrically and seemed quite stable. But suddenly the jet swung across to attach itself to one wall. It remained in that position until the discharge was considerably reduced. The practical implications, in terms of scour, of confining the high velocity flow to the side of the channel were immediately obvious.

The purpose of the experimental study undertaken was to determine in general how flow behaves in such channels, and the conditions required for the observed jet attachment to occur. Further work is needed to measure the details of the flow types to obtain a fuller explanation of the fluid mechanics of the problem.

Straight walled expansions may be classified into three groups. At one extreme the expansion is long and the flow does not separate from either wall. Such expansions have a divergence angle of less than about 9 deg (3). At the other extreme are abrupt outlets where the walls may diverge at 90 deg, the flow separating at the end of the conduit. The third class of expansions have walls diverging more than 10 degrees or so, but less than some limit to be determined. In these structures, the subject of the present study, the behaviour of the flow is not defined solely by the geometry of the channel. Two flow factors have been found to be of major importance: the Froude number of the flow emerging from the conduit, and the submergence ratio (downstream depth divided by orifice diameter).

The particular geometry studied consists of a circular conduit whose invert was at or very slightly above the horizontal bed of the channel. The conduit ended at a headwall, and the straight sides of the channel were one diameter of the orifice apart at the headwall. The expansion was symmetrical about the axis of the conduit. The emerging flow was supercritical, having Froude numbers (based on orifice diameter) of 3 to 18.

The Models

Two models were constructed. The smaller one, at Imperial College, was built in a 1.83m by 1.22m shallow tank. The bed was horizontal smooth perspex. In the tank 1.22m long walls were placed at the required angle to the centreline. The inlet was a short length of 12.7mm or 19mm diameter copper tube, placed centrally in the tank opposite the outlet (fig 1). The supply, through a 25.4mm pipe, was from the main laboratory constant head tank.

A vertical head wall was fitted over and sealed to the inlet pipe. Great care was necessary to ensure the head wall was flush with the pipe end and the upstream end of the diverging walls were the correct distance from the centreline. Only the bottom and upstream end of the walls were sealed to adjoining surfaces.

The second model was built on the premises of Wimpey Laboratories Ltd. This larger model was built in a similar way to the smaller one, the expansion walls being set in a larger tank. The orifice was 104mm diameter, supplied by a 152mm diameter pipe. The outer tank was an existing harbour model with a horizontal smooth concrete floor. The movable walls were 3.66m long.

Typical flow types

Taking a typical case of a 30 deg expansion, with a Froude number of 14, the following sequence of flow conditions was observed as the tailwater level was raised. With low tailwater, the jet was undrowned, forming the well known Vee-shaped hydraulic jump across the full width of the channel. The Vee moved upstream as the downstream depth increased until the inlet pipe was drowned.

When the inlet became drowned, there was always a well defined region of back flow along each wall of the expansion. The path of the high velocity flow did not remain straight, but fluctuated over most of the width of the channel. As the downstream depth approached a submergence of 1.9, the swings of the jet would become slower until it reattached to one wall near the downstream end. The reattachment of the jet was influenced by the large swings of the high velocity core, the momentum of the resulting eddies, and shape of the basin far from the inlet pipe.

To which side of the expansion the jet reattached was arbitrary, though with any one model there usually was a bias to one side. It was observed that certain small asymmetries were crucial, for instance, the precise centring of the orifice between the upstream end of the walls. The outlet, even if far downstream, had an influence on the selection and growth of the large eddy which is part of the reattachment process.

Reattachment allowed the jet to divide the flow area into two regions: a large slowly recirculating area having a nearly horizontal water surface; and a smaller region between the jet and the wall to which it was reattached containing a trapped eddy. Since the jet effectively blocks flow between the two regions, a pressure difference may be sustained. The magnitude of this differential pressure controls the curvature of the jet and hence the distance along the wall to the reattachment point. As the submergence increases, the pressure difference increases so making the reattachment distance and the trapped eddy smaller. This trend is accentuated by the eddy becoming more vigorous and shallower.

At a submergence of 3.5 the separation zone was a minimum size and depth. The flow in the zone changed. No longer was there any flow towards the inlet, so that all the water entrained along the concave side of the jet had to come over the top. To this cross-flow the jet acted as a weir having a crest sloping upwards away from the orifice as the jet expanded towards the surface. The combination of weir flow over the rapid, entraining jet flow produced a noisy and disturbed surface. As the submergence increased, more water flowed over the "weir" without a matching increase of entrainment from the separation zone. The depth there increased as did the reattachment distance.

The reattached flow just described was that observed in the full scale test. Without doubt it is undesirable. The very turbulent high velocity core is held close to one wall and penetrates a long distance downstream. Most of the expensive structure is filled with a harmless, but quite useless eddy. Even with the smaller velocity of a subcritical inlet flow, Smith and Yu (3) found this flow scoured the downstream channel undesirably.

Quite suddenly at a submergence of about 4.5 the low pressure zone completely filled, the noise and surface disturbance ceased and the jet broke free from the wall to swing violently from side to side creating alternating eddies nearly filling the expansion as they progressed downstream. These eddies were accompanied near the orifice by pressure differences across the jet, resulting in strong intermittent crossflows which appreciably disturbed the water surface. Only when the submergence was increased to about 6.6 were these pressure differences suppressed, resulting in a steadier flow similar to that at an abrupt expansion.

The flow conditions just described are typical for the range of discharge, model geometry and size tested. Figure 2 is a plot showing submergence ratio for each type of flow, plotted against inlet Froude number for three sizes of inlet. All these points were obtained with a slowly rising tailwater. Considerable hysteresis occurs, so that lower values of submergence would be obtained with a falling water level. The solid lines and all points refer to a 30 deg expansion. For a 20 deg expansion the only significant change is shown by the dotted line defining the submergence where the reverse flow in the separation zone is suppressed.

Angle of Divergence

Figure 3 shows the effect of increasing the divergence angle. For all values of orifice diameter and Froude number tested, the jet would not reattach for a wall angle greater than 38 deg. This limit may be compared to the 50 deg limit reported by Bourque and Newman (2) for two dimensional flow.

In the case of flow with a free surface, reattachment occurs with a submergence greater than unity, implying that some water can always flow over the jet near the orifice into the separation zone. Therefore any small pressure difference built up by the Coanda effect would be reduced, so reducing the maximum wall angle for reattached flow.

Velocities in the channel

Time mean velocity profiles were obtained for several cross-sections for each flow type; just submerged, reattached, and deeply submerged. The divergence angle was 30 deg and inlet Froude number 14.

At a submergence of 1.0, the inlet just drowned, the maximum velocity in the channel remained high, being 50 per cent of the inlet velocity 46 diameters downstream. This implies that the jet was not entraining as much fluid as a two-dimensional or axisymmetric jet, a characteristic of near surface jets noted by Streiff (4).

With a deeply submerged inlet, the maximum velocity was reduced much more rapidly. In the first 42 diameters downstream of the orifice the velocity was reduced by 89 per cent with a submergence of 3.0, and 92 per cent with 4.4. This rate of reduction is broadly comparable to that obtained with axisymmetric jets (1).

The different behaviour of the more deeply submerged jets is significant in terms of distance from the orifice that scour protection would be needed. But if one considers the cost of a containing structure to achieve a particular reduction of velocity, the submergence must be allowed for. One may imagine, for purposes of comparison, an expansion with the same submergence as the model, and having at each section downstream of the orifice a velocity equal to the measured maximum. Then, the divergence would have an expansion angle of only 1.1 deg when the submergence is 1.0, 2.3 deg when 3.0 and 2.0 deg when 4.4. One may conclude from this that any transition of the type studied in which the flow breaks away from one or both sides at the orifice is a very inefficient velocity reducer.

Conclusion

The experimental study of the flow from a conduit into a symmetrical open channel expansion with subcritical flow downstream has shown, within the range tested:

(1) That for walls angled more than a few degrees to the centreline the flow will separate from at least one wall, maintaining a high velocity.

(2) In all cases in which the flow separates from one or both walls, the reduction in maximum velocity could theoretically be obtained by an expansion having the same downstream depth and a wall angle of less than 2.3 deg.

(3) The conduit outflow may reattach to one wall if the downstream depth is within the limited range shown on figure 2;

(4) The conduit outflow will not reattach to either wall if the walls are angled 38 deg or more from the centreline.

Acknowledgements

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References

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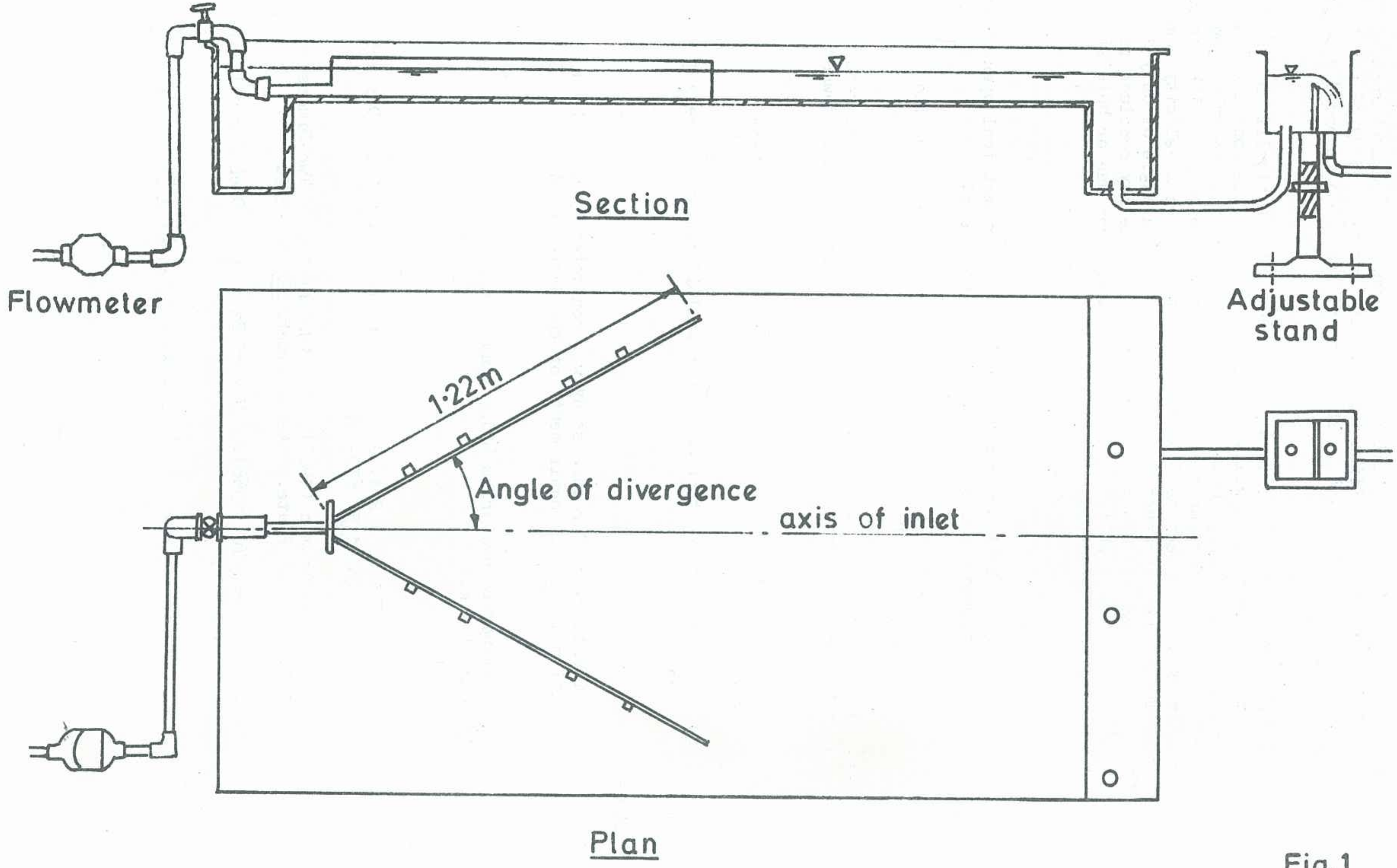
Section
Flowmeter
Adjustable stand
1·22m
Angle of divergence
axis of inlet
Plan

Fig. 1

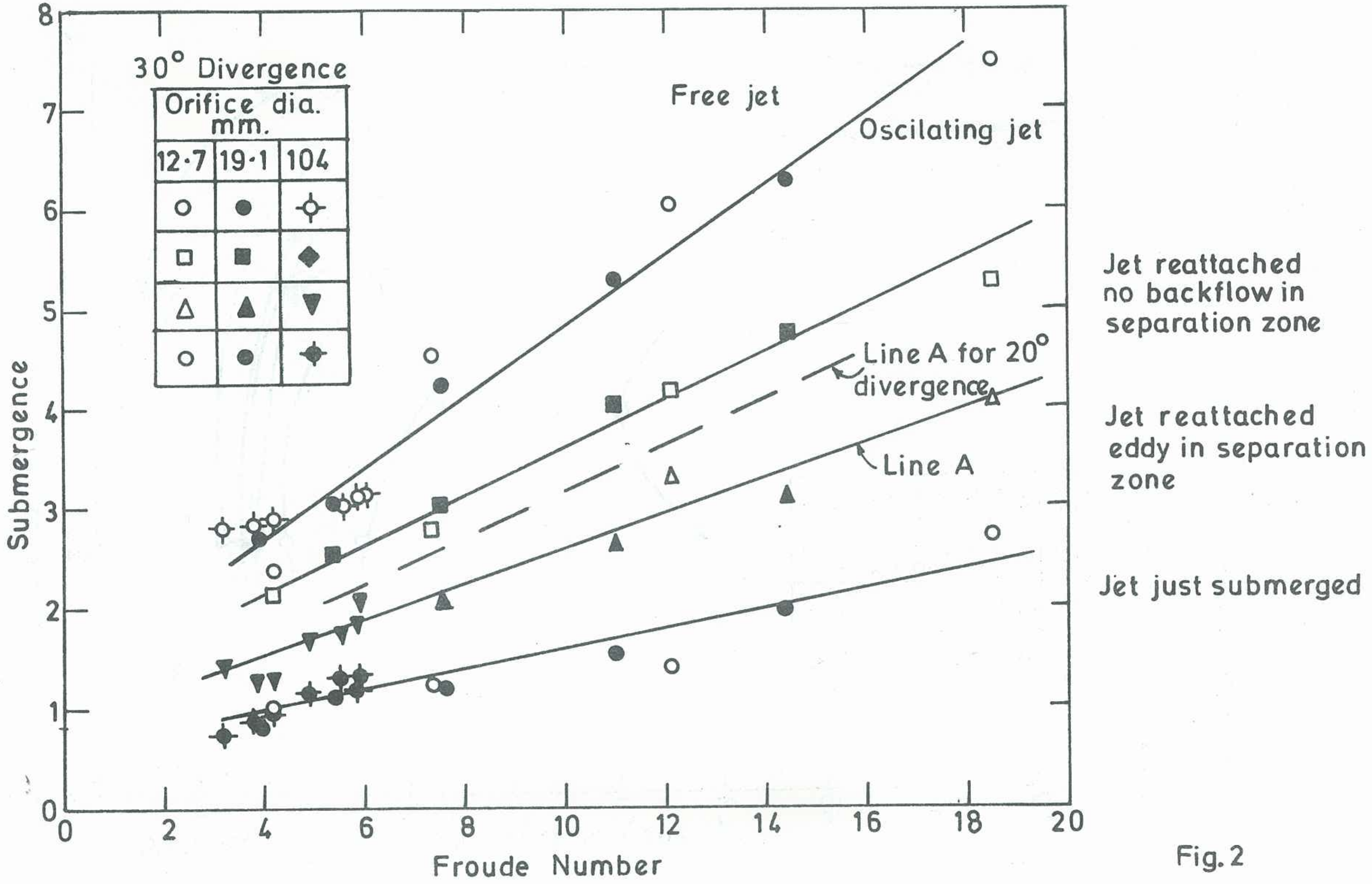
30° Divergence
Orifice dia. mm.
12·7
19·1
104
Free jet
Oscilating jet
Line A for 20° divergence
Line A
Jet reattached no backflow in separation zone
Jet reattached eddy in separation zone
Jet just submerged
Submergence
Froude Number
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
16
18
20

Fig. 2

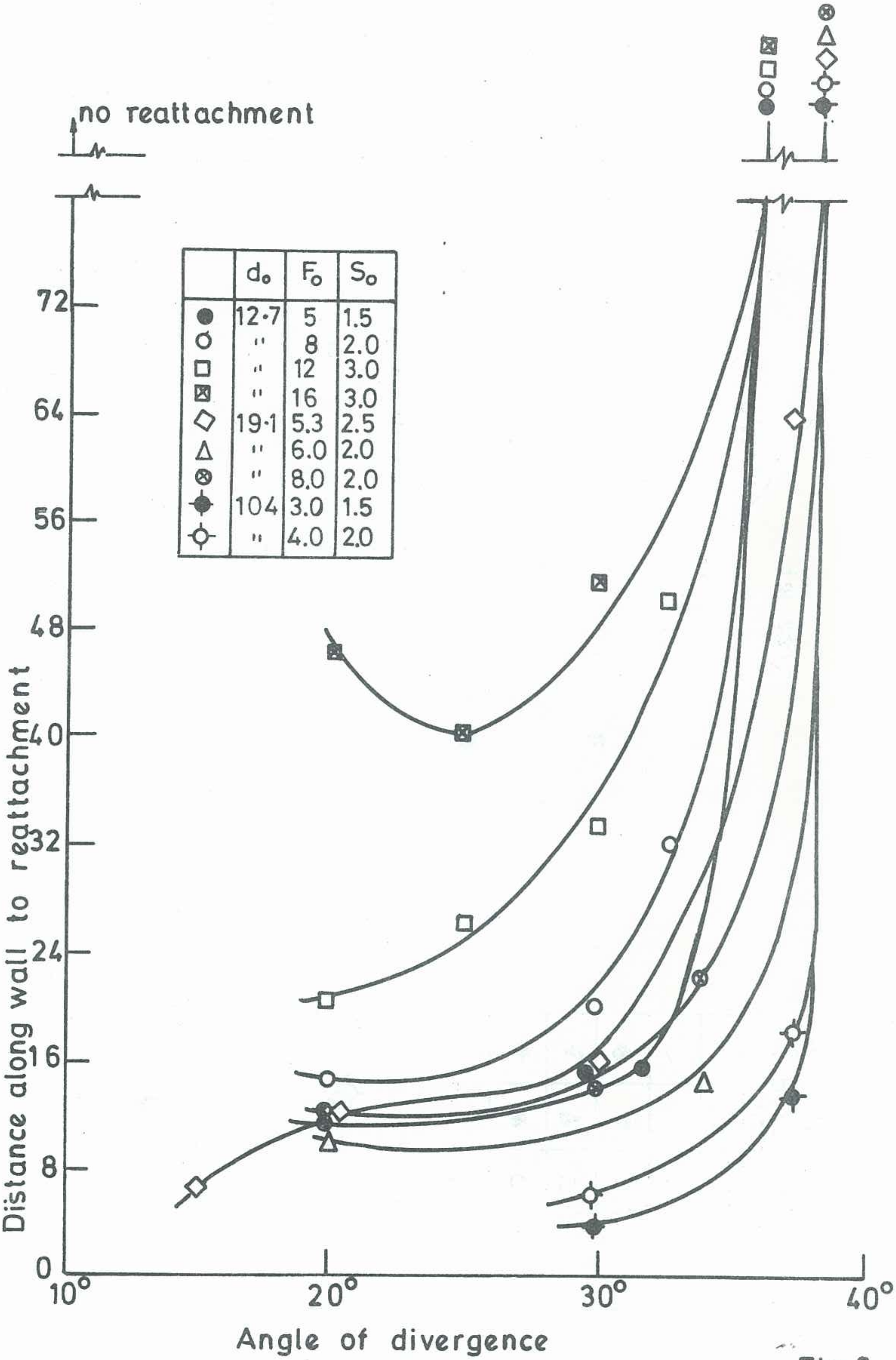
no reattachment
d₀ F₀ S₀
● 12·7 5 1.5
○ " 8 2.0
□ " 12 3.0
⊠ " 16 3.0
◇ 19·1 5.3 2.5
△ " 6.0 2.0
⊗ " 8.0 2.0
-●- 104 3.0 1.5
-○- " 4.0 2.0
Distance along wall to reattachment
0
8
16
24
32
40
48
56
64
72
10°
20°
30°
40°
Angle of divergence

Fig.3