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SHAPE EFFECTS ON RESISTANCE TO FLOW IN

SMOOTH SEMI-CIRCULAR CHANNELS

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Synopsis

Some new experiments in smooth semi-circular channels are described and a set of accurate data about the resistance to flow is presented. At the same Reynolds numbers, the observed friction factors in the smooth semi-circular channel are not only larger than those in smooth pipes but also larger than those in smooth rectangular channels.

The results of these experiments were used to study the effects of channel shape on flow resistance and they established the effectiveness of the previously published Kazemipour's method for the case of semi-circular channels.

For convenience of application, an independent shape parameter curve was developed for semi-circular channels. However, it is shown that the shape parameter curve for semi-circular channels is transferable on to the shape parameter curve for rectangular channels by two linear, parallel shifts.

CONTENTS

1. INTRODUCTION

A large number of papers has been published on flow in pipes and open channels with smooth and rough surfaces. However, apart from studies of non-uniform flow conditions and other special studies, relatively little attention has been paid to open channels of circular cross-section in general, and semi-circular open channels in particular, where the transitional stage between pipe flow and open channel flow and the effects of changes in channel shape with depth can be studied.

Information on the variation of boundary shear, friction factor and shape effects of flowing water in a semi-circular open channel is lacking at the present stage. Some studies in pipes flowing partly full by Rohwer (1), Smith (2), Nalluri and Novak (3,4) and others, have revealed that there is a pronounced discontinuity in the discharge curves for depths greater than half the diameter. Also the flow is unstable at such depths greater than half the diameter. For such cases the flow is then variable and depends on conditions, the nature of which has not been fully determined yet. This is probably because, in a channel of circular cross-section, the variation of depth of flow changes the type of flow from approximately two-dimensional in a wide channel (low depths) through three-dimensional (medium depths) back to almost two-dimensional pipe flow (large depths). Therefore, measurements made at depths of more than half the pipe diameter may be inconclusive. However, the above limitations do not occur when the pipe is flowing at less than half the diameter, for which state the discharge is directly related to the depth. For these reasons a series of experiments with smooth semi-circular channels was designed and carried out to study the effects of channel shape on resistance in the case of semi-circular channels and these are described in this paper. The results of these experiments are of interest not only for the study of shape effects but also in providing a comparison between the resistance to flow in channels of other cross-sectional shapes and in a semi-circular one for whcin very little data is available in the literature.

The general relation between f_c, the observed friction factor in a channel or non-circular closed condiut, and the other flow parameters can be expressed by Equation 1, details of which can be found in Kazemipour (5) and Kazemipour and Apelt (6).

$$1\sqrt{f_c} = \phi \left(R_e, \frac{K_s}{R}, \frac{B}{y_{av}}, \frac{P}{B} \right) \qquad (1)$$

The symbols are defined in Appendix A.- Nomenclature.

The last two groups in Equation 1 obviously relate to the shape of the cross-section and the equation can be written as

$$1\sqrt{f_c} = \phi \left(R_e, \frac{K_s}{R}, \text{shape} \right) \qquad (2)$$

Equation 1 applies equally to flow in open channels and to flow in closed conduits and the parameters B/y_{av} and P/B represent the effects of cross-sectional shape on flow resistance in open channels and in non-circular closed conduits, compared to circular pipe flow.

For smooth turbulent flow in circular pipes, where the parameters B/y_{av} and P/B have no effect, Equation 1 reduces to that of Karman-Prandtl which is written as

$$1\sqrt{f} = 2.0 \log R_e \sqrt{f} - 0.8 \qquad (3)$$

where f is the friction factor in the pipe. It is well known that the friction factor for open channels and non-circular closed conduits, f_c, is larger than that for circular pipes, f, at the same Reynolds number and relative roughness. The larger resistance to flow in open channels and in non-circular closed conduits is attributed to the effects of the shape of cross-section on flow resistance.

A new method accounting for the effects of the shape of the cross-section on flow resistance was developed by

Kazemipour (5) and presented in an earlier paper (6). The new method which is referred to as Kazemipour's method employs a shape factor $\psi = \psi_1/\psi_2$ by which the observed values of f_c are adjusted to be equal to f at the same Reynolds number.

To obtain the value of the shape factor, ψ, it is necessary to evaluate the values of the shape parameters ψ_1 and ψ_2. ψ_1 is evaluated directly from the measured values of P and B according to the relation

$$\psi_1 = \frac{V'_*}{V_{*o}} = \sqrt{\frac{\tau'}{\tau_o}} = \sqrt{\frac{\rho g S y_{av}}{\rho g S R}} = \sqrt{\frac{y_{av}}{R}} = \sqrt{\frac{P}{B}} \qquad (4)$$

ψ_2 is a function of the (width/depth) or the aspect ratio of the cross-section and must be derived from experimental data.

The curve of ψ_2 as a function of B/y_{av} based on the data from smooth rectangular channels, which was derived previously (5,6) is reproduced here as Figure 1. The experiments in smooth semi-circular channels were designed to test the effectiveness of the ψ_2 curve drawn in Figure 1 for the case of semi-circular channels.

2. EXPERIMENTS

2.1 Experimental channel

An outdoor platform adjustable in slope and covered with steel formwork panels was used to support the experimental channel. The platform is 25 m long, 1.2 m wide and is carried by a steel truss. The channel consisted of five 4 m long compressed asbestos cement half pipes. The internal diameter of the half pipes which were used was 38 cm and the wall thickness of the half pipes was 21 mm. This wall thickness was large enough to guarantee no measurable deflection along the length and no change in the diameter of the half pipes under maximum load of water. The ends of the half pipes were finished square to the axis of the pipe to ensure accurate

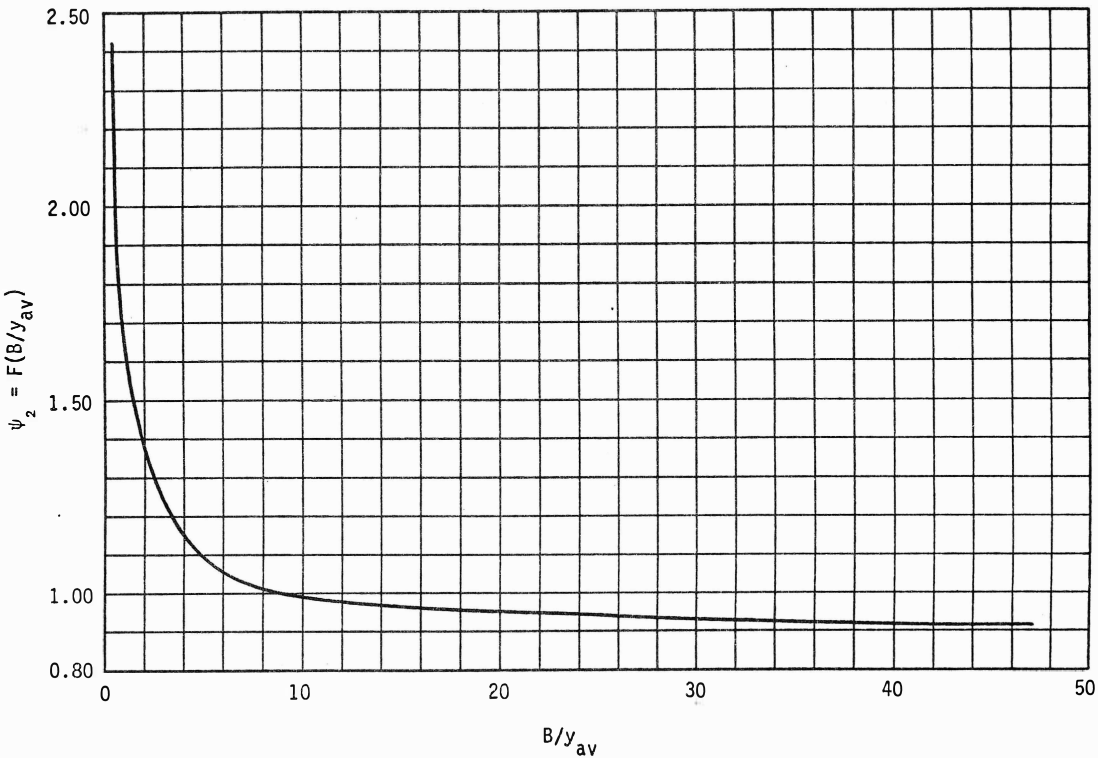

FIGURE 1 : Shape parameter, ψ_2, which reflects the effects of aspect ratio of cross section in Kazemipour's method. The curve is based on data from smooth rectangular channels.

joining. The platform was set horizontal (zero slope) first, then five 4 m lengths of half pipes were laid on the platform. Originally, the half pipes were supported by some hardwood wedges placed under them at 1 m intervals. By adjusting these wedges the half pipes were matched along the centreline and then they were joined together. The wedges were also used to set the whole channel flat at zero slope.

After all the half pipes were joined together and levelled by adjustment of the wedges, specially made frames were placed under the channel at the joints and at the mid-length of each half pipe. These frames were filled with concrete to form the main and permanent supports for the channel on the platform. When the concrete supports set and dried out, they ensured that the channel stayed in position and did not move. Then the joints were filled with a waterproof sealant, "silicone 790", to stop any leakage. A view of the channel is shown in Figure 2.

Water was upplied to the experimental channel from a tank with constant water level through three 15 cm (6") lines. Each line provided up to 20 litres per second of discharge. Water from the supply lines ran into a stilling tank, 1.2 m x 1.2 m wide and 1.5 m deep (below the bottom of the channel) before entering the channel. The entrance between the channel and stilling tank was built as a smooth semi-circular transition and was painted with epoxy resin to give it a smooth finish. The discharge from each supply line was measured by an orifice plate of 8.89 cm (3.5") in diameter. The maximum possible error in measuring the discharge using this particular orifice meter is within 1%.

An undershot sluice gate in the upstream end of the channel and an overflow weir plate at the downstream end of the channel were used to control the flow, when it was necessary. To achieve uniform flow at normal depth, adjustment of the head-gate was required when the flow was supercritical and adjustment of the tailgate when it was subcritical.

Point gauges were installed at 1 m intervals along the centreline of the channel. The gauges were held perpen-

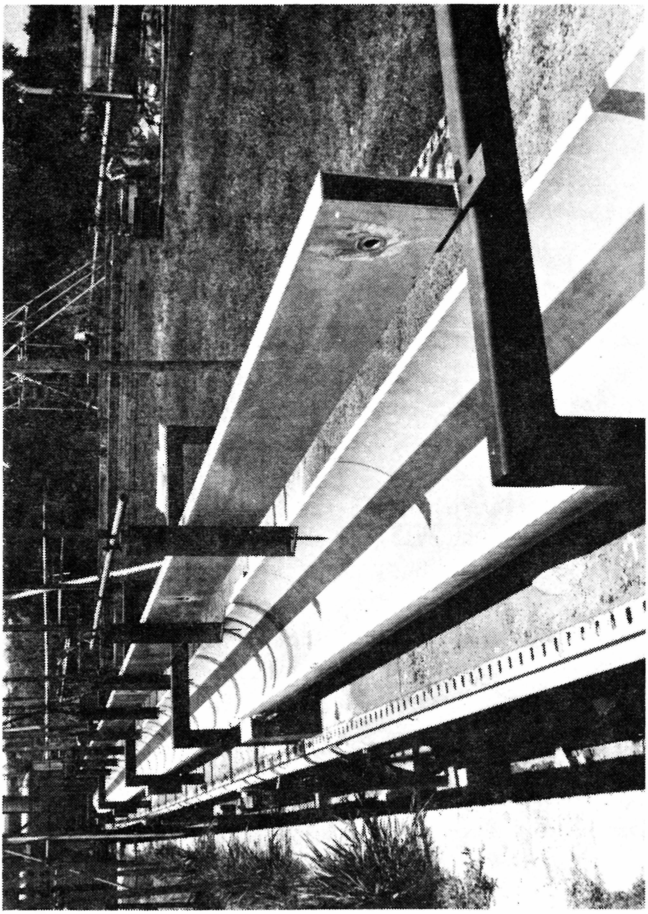

FIGURE 2 : A view of the experimental channel

dicular to the bottom of the channel at all times. The resolution of these point gauges is 0.1 mm.

2.2 Procedures for Establishing Uniform Flow and Normal Depth

The condition of steady uniform flow is seldom encountered either in the field or in the laboratory. The depth of flow for steady uniform flow, known as the normal depth is very useful for analysis of flow profiles in open channels but is extremely difficult to measure with accuracy. In determining normal depths in the laboratory it is essential that steady uniform flow be attained as closely as possible. The water surface profile should reach equilibrium, as far as can be determined by the precision of setting and reading of the point gauges. For some conditions of flow in these experiments, it took more than an hour to reach such an equilibrium condition.

After the flow is steady, it is even more difficult to be sure that it is uniform. For mild channel slopes, uniform flow at normal depth is the upstream asymptote to the M_1 and M_2 backwater curves. Backwater curves of M_1 and M_2 types corresponding to slightly different tail-gate settings may be very nearly parallel to the bottom, and yet have an appreciably different depth of flow, especially in cases where the slope of channel is very small. The uniformity of the flow cannot safely be determined by reading gauges at each end of the channel, for the error in setting and reading only two gauges, especially if the channel is short, may seem to indicate uniform flow, whereas actually the flow may be well along an M_1 or M_2 curve, and the apparent uniform depth far from the desired normal depth.

To a lesser degree, the same thing is true for flow on steep slopes where uniform flow at normal depth is the downstream asymptote to the S_1 and S_2 backwater curves. Although the S_1 and S_2 backwater curves are not nearly as long as the M_1 and M_2 curves, there are tendencies to have standing waves on the surface that make accurate setting of point gauges more difficult.

In determining the normal depths in the present investigation, initially the profiles were obtained both below and above the normal depth, each profile being for a steady flow condition. However, it was found that, this procedure led to the following problems and difficulties:

(i) As M_1 and M_2 profiles, or S_2 and S_3 profiles for that matter, had to be taken with different tail-gate or head-gate settings, the water level at the stilling tank in the upstream end of the channel was affected and, therefore, the flow rate was different for M_1 and M_2 and S_2 and S_3 profiles.

(ii) Velocity measurements had to be made in steady uniform flow conditions and at normal depth. Therefore they could not be taken on M_1, M_2 or S_2, S_3 profiles.

To eliminate these problems, it was decided to achieve accurately the actual asymptote of M_1 and M_2 or S_2 and S_3 profiles, even though this was time consuming and difficult. This could be achieved through a process of trial and error and patience by manipulating the control gate settings until the slope of the water surface profile equalled the slope of the channel bed. However, each asymptote was checked against the profiles below and above it and in case of doubt the measurements were repeated until the satisfactory result was obtained. In general, no measurement was taken until the flow became steady and it took not less than an hour for each run to be completed.

All of the normal depth measurements were taken as described above, examples of the results of the process being given in Figure 3. Figure 3(a) shows a typical set of profiles of subcritical flow and Figure 3(b) shows a typical set of profiles of supercritical flow in the channel. The different curves in Figure 3(a) were obtained from different settings of the tail-gate at the downstream end of the channel and those of Figure 3(b) from different settings of the head-gate at the upstream end.

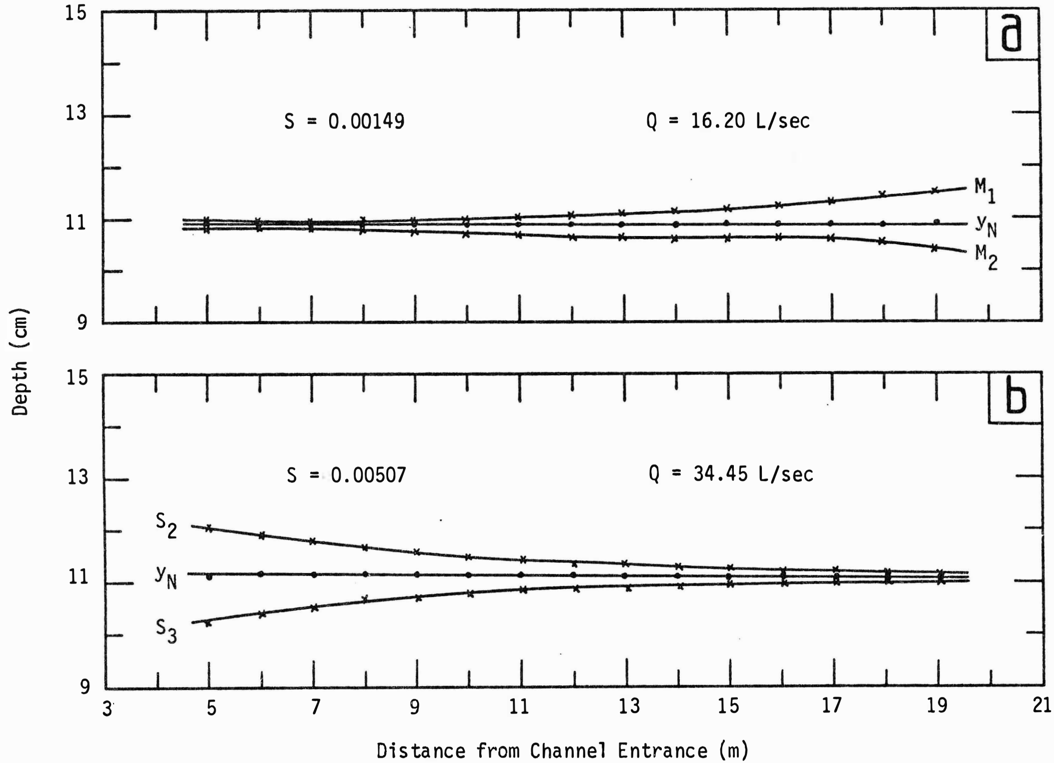

FIGURE 3 : Achievement of uniform flow and normal depth for (a) subcritical flow and (b) supercritical flow in the present experiments

In general the following conditions for accuracy of measurement of the normal depth were met with the procedure described above:

(i) The normal depth was accepted when the deviation of any point on the asymptote from the overall average value of all measurements of the normal depth was within 1%.

(ii) The difference in depth between the asymptote and the M_1 and M_2 profiles or S_2 and S_3 profiles on either side of it was about 1 mm. This is shown on Figure 3.

2.3 Experimental Procedure

Altogether 75 tests were made for subcritical and supercritical flows in the smooth semi-circular channel. From a total of 75 runs, 42 runs were in subcritical and 33 runs (including those with $F_r = 1$) in supercritical flow conditions with Froude numbers F_r, ranging from 0.31 to 1.33 based on the measured normal depth and from 0.40 to 1.60 based on y_D, where y_D is the depth of flow in an equivalent rectangular channel whose width is equal to the diameter of the semi-circular channel with the same flow area. Only 15 m of the working length of the channel was taken as the test section. The first station in the test section where a point gauge was installed was 5 m from the entrance and the last station was about 2 m from the downstream end of the channel. Flow rates ranged from 3.78 to 49.52 litres per second covering 75 runs which were made on 7 different slopes, ranging from 5.15×10^{-4} to 6.04×10^{-3}. Uniform conditions for subcritical and supercritical flows were achieved by manipulating the settings of tail-gate and head-gate respectively and checking the water surface profiles with the point gauges at all of 15 stations, until the water surface profile became parallel to the channel bed, i.e. all of the point gauges showed the same depth within the measuring accuracy, following the procedure described in the previous section. Under uniform flow conditions, the depth at each station was read directly from the point gauge at that station and the normal depth,

y_N, for the run, was taken as the height above the invert of the channel of the line of best fit to the individual values of the depth in each station of the test section. The deviation of any individual depth read from the point gauges from the value of the normal depth so obtained was within 1%.

The water surface profile along the channel was obtained for each run by adding the value of bed level, z, at each station to the value of the measured depth at that station.

The water temperature, T, was measured for each run, with an ordinary laboratory mercury thermometer, mounted in the channel at the downstream end, beyond the test section.

Point velocity measurements were made on many verticals spaced across a section normal to the flow in the region of fully established flow, half way through the test section of the channel. The measurements were made for some of the runs in both subcritical and supercritical flow ranges, using a small current meter (OTT current meter, type 10.152) with the propellers having diameters of 3 and 5 cm.

2.4 Calculations of Flow Parameters in Semi-circular Channel

In addition to the measured data, some of the flow parameters for the semi-circular channel were calculated from Figure 4 as

cross-sectional area $$A = r^2(\theta - \frac{\sin 2\theta}{2}) \tag{5}$$

wetted perimeter $$P = 2r.\theta \tag{6}$$

hydraulic radius $$R = A/P = r(\frac{1}{2} - \frac{\sin 2\theta}{4\theta}) \tag{7}$$

top width $$B = 2r \sin\theta \tag{8}$$

where r is the radius of semi-circular channel,

θ is the angle shown on Figure 4.

$$\cos\theta = \frac{r - y_N}{r} \tag{9}$$

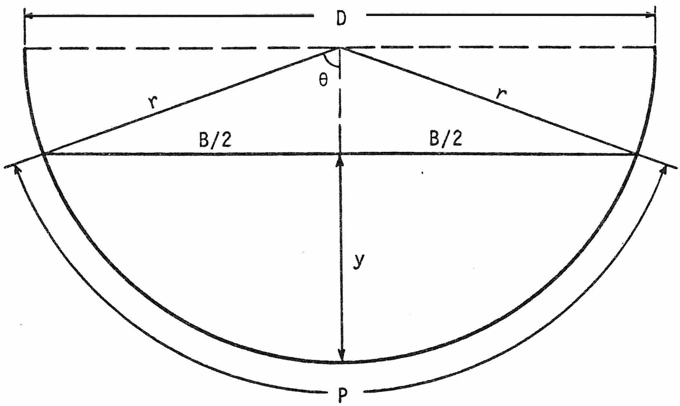

FIGURE 4 : Geometric parameters in the semi-circular channel

3. PRESENTATION AND ANALYSIS OF THE EXPERIMENTAL RESULTS

In the test with the smooth semi-circular channel the Reynolds numbers varied from 70,000 to 477,000 for the range of discharges tested. In this range of Reynolds numbers the friction factor, f_c, varied from 0.0152 to 0.0249. The complete details of the experimental results are given by Kazemipour (5). The variation of friction factor with Reynolds number is shown in Figure 5. It can be seen in Figure 5 that there is good consistency in the experimental results and that there is no obvious difference between the results from subcritical flows and those from supercritical flows. Further, it is clear from Figure 5 that the friction factor for the channel is greater than

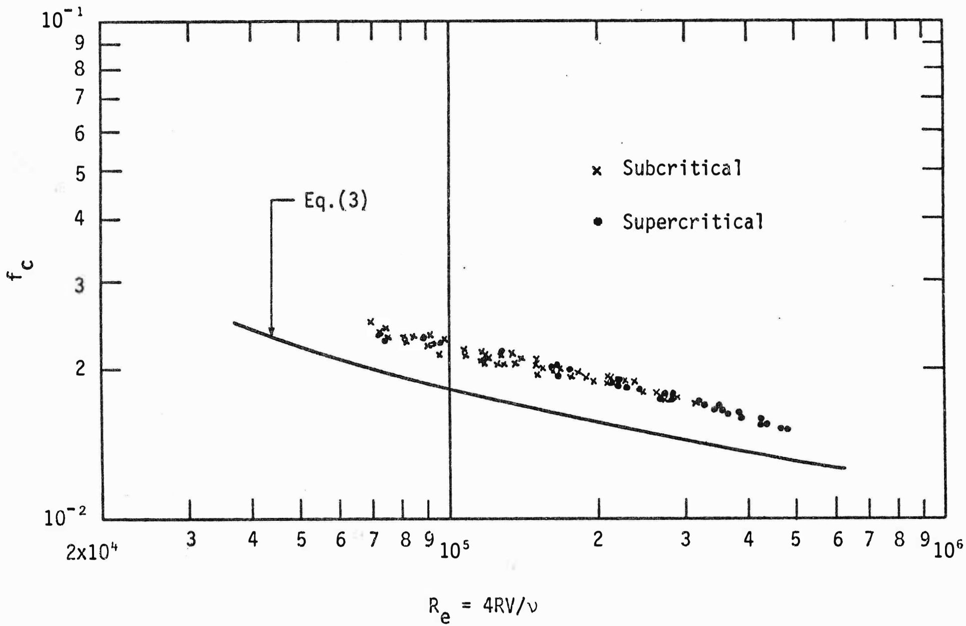

FIGURE 5 : Variation of friction factor with Reynolds number in smooth semi-circular channel

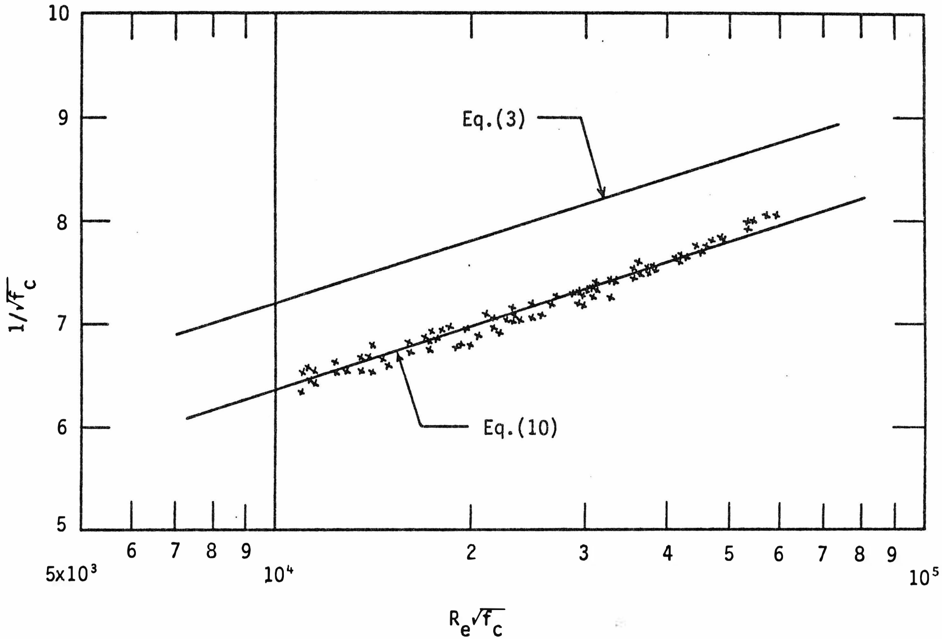

FIGURE 6 : Flow resistance in smooth semi-circular channel; data before adjustment for shape effects

that for a smooth pipe at the same value of Reynolds number. The results are shifted from the smooth pipe curve (Equation 3) by about the same amount over the range of Reynolds numbers covered in the present experiments.

The experimental results are plotted in the form of $1/\sqrt{f_c}$ against log $(R_e\sqrt{f_c})$ in Figure 6. For comparative purposes, Equation 3 for turbulent flow in smooth pipes is also shown on this figure. The line drawn through the channel data, has the equation

$$1/\sqrt{f_c} = 2.0 \log R_e\sqrt{f_c} - 1.62 \qquad (10)$$

which differs from Equation 3 only in the magnitude of the additive constant. Further, not only are the friction factors greater than those of smooth pipes, but comparison of these results with the results from the smooth rectangular channel (7) reveals that the friction factor for the smooth semi-circular channel is even greater than that for the smooth rectangular channel at the same Reynolds number. The greater resistance to flow in the semi-circular channel compared to pipe flow and also compared to the rectangular channel can only be attributed to the pronounced effects on flow characteristics in general and on the friction factor in particular as the shape of the semi-circular channel changes continuously with changes in depth.

Because of everchanging shape of flow section with depth in the semi-circular channel and also because of the fact that it is customary to use the diameter of a semi-circular channel in place of the top width in other channels, it was decided to draw a curve similar to that of Figure 1, specifically for the semi-circular channel. In order to do this the data of the smooth semi-circular channel were processed in line with Kazemipour's method (5,6) in the following section.

4. ANALYSIS OF SHAPE EFFECT

4.1 Construction of Curve of ψ_2 Versus D/y_D for Semi-circular Channel

The diameter of the semi-circular channel, D, was used instead of the top width of the channel for all cases of varying depths. Therefore the effective depth of flow for each run was simply calculated as

$$y_D = A/D \tag{11}$$

where A is the actual area of the flow.

The data were processed in the following way:

(i) The value of ψ_1 was calculated as

$$\psi_1 = \sqrt{P/D} = \sqrt{\theta} \tag{12}$$

(ii) For each data point the pipe friction factor, f, at the same value of Reynolds number was calculated from Equation 3.

(iii) The value of f_1 was calculated from the experimentally determined value of f_c as $f_1 = f_c/\psi_1$.

(iv) The value of ψ_2 was then obtained from $\psi_2 - f/f_1$.

(v) The values of ψ_2 so calculated were plotted against D/y_D in Figure 7.

It is seen from this figure that the data points follow a well defined curve. The point corresponding to full pipe flow on this figure has the value of $\psi_2 = 1.772$ at $D/y_D = 1.273$. This is because for a pipe running full the shape factor ψ must be unity. But, as $\theta = \pi$, so from Equation 12 $\psi_1 = \sqrt{\theta} = 1.772$. Therefore, according to the

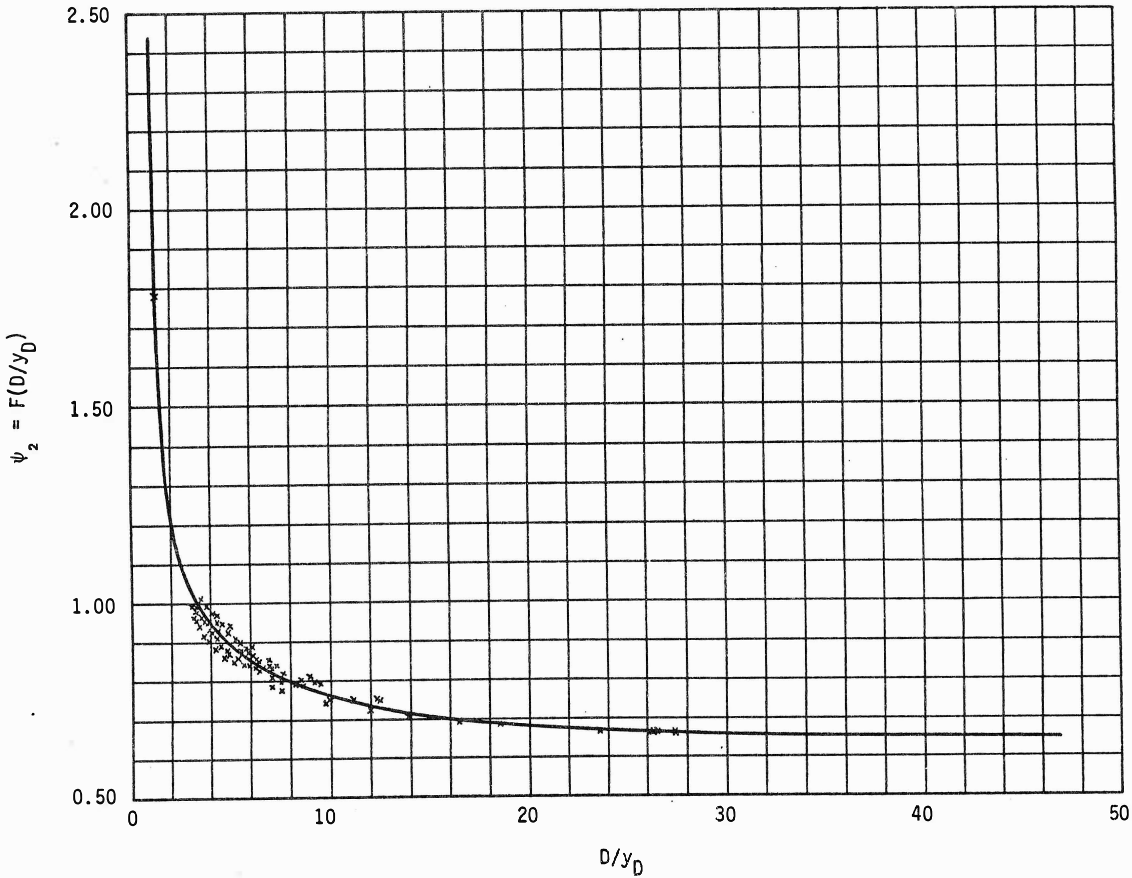

FIGURE 7 : The parameter, ψ_2, which reflects the effects of aspect ratio, D/y_D, for semi-circular channels in Kazemipour's method.

relation $\psi = \psi_1/\psi_2$, ψ_2 must be equal to ψ_1 having the value of 1.772. However, to keep the continuity of calculations, D/y_D for full pipe flow was calculated as

$$D/y_D = D/(A/D) = D^2/A = 4/\pi = 1.273 \tag{13}$$

It is proposed that the curve for ψ_2 in Figure 7 will apply to all cases of flow in smooth semi-circular channels. Before comparing the curve of ψ_2 for the semi-circular channel with the one in Figure 1 for rectangular channels it is necessary to check its effectiveness in shifting the experimental data points drawn in Figure 6 on to the line of Equation 3 for turbulent flow in smooth pipes.

4.2 Application of Kazemipour's Method to the Data of Smooth Semi-circular Channel

For given values of D/y_D, the mean values of ψ_2 were taken from the curve drawn on Figure 7 for all data points of the experiments in the smooth semi-circular channel. The values of ψ_1 were calculated from Equation 12. Then the shape factor $\psi = \psi_1/\psi_2$ for each data point was calculated and the modified friction factor, f_*, was obtained from the observed friction factor f_c and the shape factor, ψ as $f_* = f_c/\psi$.

The modified friction factor, f_*, is plotted as $1/\sqrt{f_*}$ against $\log\ (R_e\sqrt{f_*})$, together with Equation 3 for pipe flow in Figure 8. It can be seen from Figure 8 that the data have been shifted well onto the line of Equation 3 for pipe flow; i.e. the modified friction factor f_* has the same value as f at the same Reynolds number.

5. COMPARISON AND GENERALISATION OF ψ_2 CURVES FOR RECTANGULAR AND SEMI-CIRCULAR CHANNELS

It was shown in the previous sections that the shape effect on resistance is larger for the smooth semi-

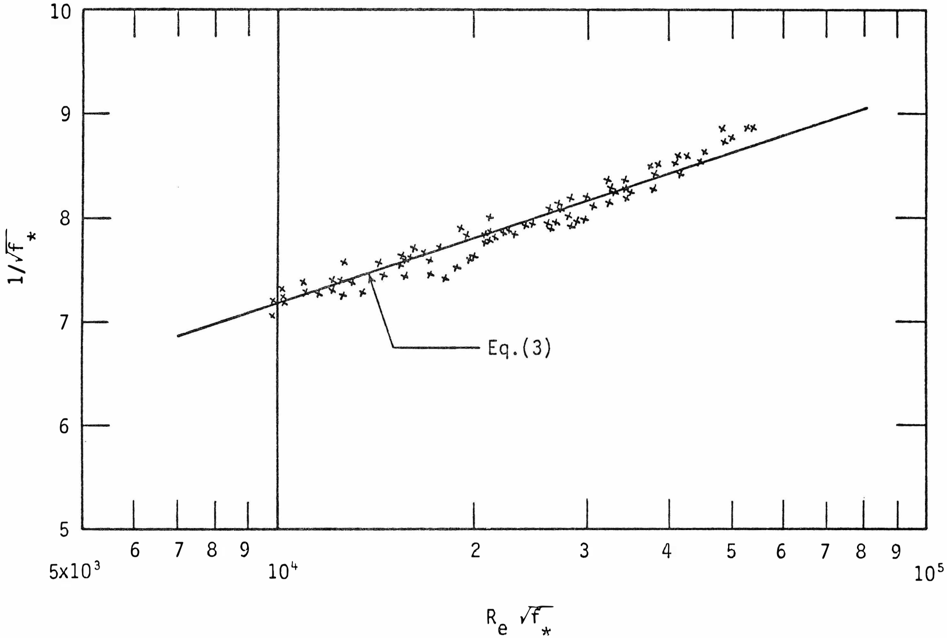

FIGURE 8 : Kazemipour's method applied to smooth semi-circular channel; data after adjustment for shape effects

circular channel than for the smooth rectangular channel. The shape factor ψ is derived from ψ_1 and ψ_2 as ψ_1/ψ_2. ψ_1 is calculated directly from the data, but ψ_2 is a function of the aspect ratio of the cross-section. Therefore it is only necessary to generalise the ψ_2 curves for rectangular and semi-circular channels.

The ψ_2 curves drawn in Figures 1 and 7 are very similar. For the purpose of further comparison both curves are replotted together on Figure 9. The curve for semi-circular channels lies generally below and to the right of the one for rectangular channels. It must not be forgotten that the diameter, D, instead of top width, B, has been used in the construction of ψ_2 curve for semi-circular channels. However, it is possible to combine the two curves into one by shifting the curve for semi-circular channels onto the curve for rectangular channels. This is done simply by two linear shifts; first a shift upward for 0.275 units of ψ_2, keeping the horizontal axis parallel and then a shift to the left for 0.8 units of width/depth axis, keeping the vertical axis parallel. When shifted in this way the ψ_2 curve for the semi-circular channel becomes identical with that for the rectangular channel. Therefore, the ψ_2 curve drawn in Figure 1 for the rectangular channels can be used for semi-circular channels if the following procedure is used:

(i) Calculate the value of D/y_D for the semi-circular channel.

(ii) Subtract 0.8 from the value obtained in (i) to get the equivalent value of B/y in a rectangular channel.

(iii) For this value of B/y obtain the value of ψ_2 from the curve in Figure 1.

(iv) Subtract 0.275 from the ψ_2 value so obtained in (iii). The result is the same as the value of ψ_2 taken from the curve of Figure 7 for the value of D/y_D given by (i) above.

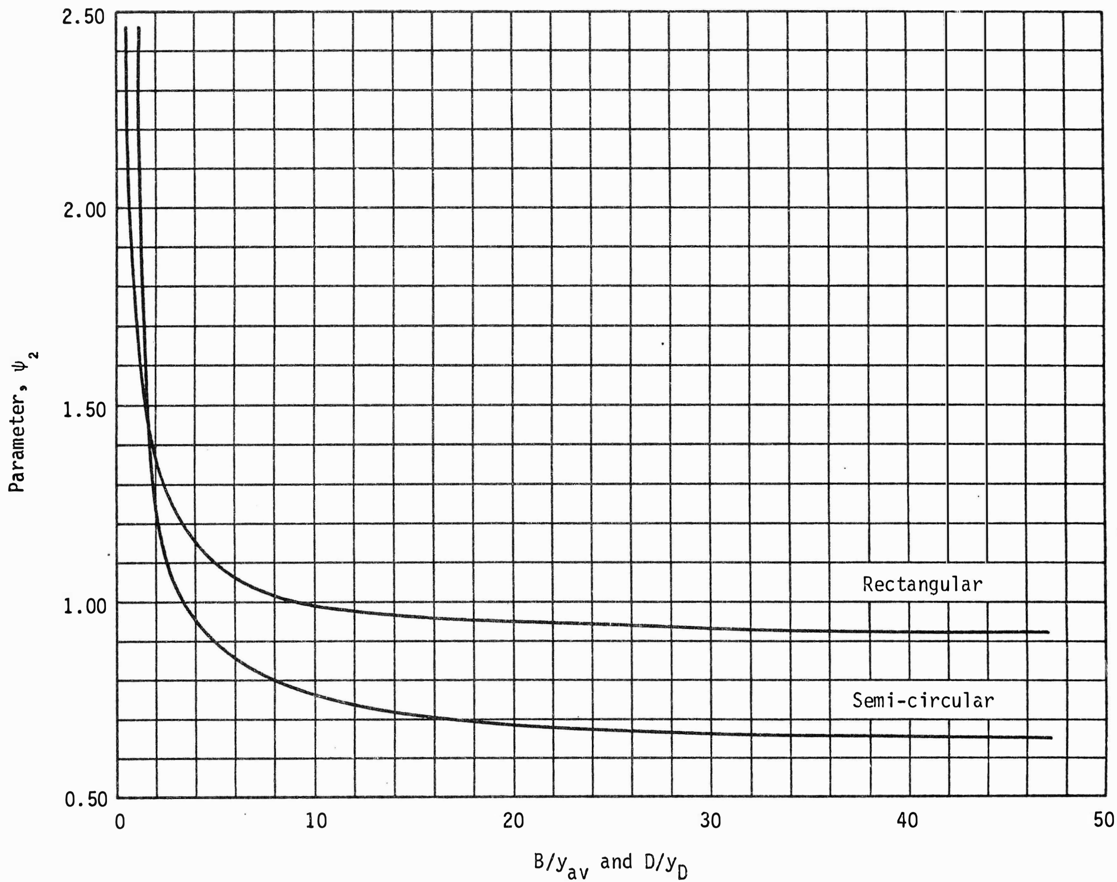

FIGURE 9 : Comparison of the ψ_2 curves for rectangular and semi-circular channels

The procedure followed above indicates that, with a simple modification, the ψ_2 curve in Figure 1 does equally apply to semi-circular as well as rectangular channels. This result in itself is a further indication of the generality of Kazemipour's method and the effectiveness of the shape factor. Moreover, it was demonstrated in (6) that the curve of ψ_2 in Figure 1, can be used to take account of the shape effects in open channels with other shapes of cross-sections.

6. CONCLUSION

Experiments with smooth semi-circular channels have been described in this paper. The choice of a semi-circular channel was made in order to study the effects of the shape on flow resistance in a channel which exhibited wide variations of cross-sectional shapes and of types of flow as the depth varied.

Valuable sets of consistent results were collected from the tests in the smooth semi-circular channels for which little or no data exists in the literature. The results of the tests showed that, at the same Reynolds number, the resistance to flow in smooth semi-circular channels is not only larger than that in smooth pipes, but even larger than that in smooth rectangular channels.

The larger resistance to flow in the semi-circular channel is due to the ever-changing shape of the cross-section as the depth changes. Because of this the results of the tests in the smooth semi-circular channel were used to derive a ψ_2 curve for semi-circular channels similar to that derived for rectangular channels. By using the newly constructed ψ_2 curve, the effectiveness of Kazemipour's method in shifting the data of the smooth semi-circular channel onto the line of Equation 3 for smooth pipe flow was demonstrated.

It was shown that the ψ_2 curve for semi-circular channels was transferable on to the ψ_2 curve for rectangular channels by two linear and parallel shifts. As a result, with a simple modification, the general ψ_2 curve in Figure 1 can be used for semi-circular channels as well as for rectangular channels.

It has been demonstrated that the application of Kazemipour's method shifts the experimental resistance data for flow in smooth open channels on to the universal diagrams for smooth circular pipes. The shape factor ψ establishes a simple correlation between the flow in circular pipes and open channels and permits the friction factor and the average velocity of the flow in the channel to be calculated from the universal resistance formulae and diagrams for circular pipes.

APPENDIX A. - NOMENCLATURE

Symbol	Meaning
A	flow cross-sectional area in channel
B	top width of cross-section
D	diameter of semi-circular channel
F	denotes a function
F_r	Froude number
f	pipe friction factor
f_1	$= f_c/\psi_1$
f_c	channel friction factor
f_*	channel friction factor adjusted by Kazemipour's shape factor $= f_c/\psi$
g	acceleration due to gravity
K_s	equivalent roughness size
log	common logarithm to base 10
P	wetted perimeter of flow cross-section

Symbol	Meaning
R	hydraulic radius of cross-section
R_e	Reynolds number = $4RV/\nu$
r	radius of semi-circular channel
S	slope of uniform flow
T	water temperature
V	average velocity of flow
V_{*o}	shear velocity corresponding to τ_o
V'_o	shear velocity corresponding to τ'
y	depth of flow in channel
y_{av}	average depth of flow in channel = A/B
y_D	depth of flow in an equivalent rectangular section having the width equal to the diameter of semi-circular channel with the same flow area as in semi-circular channel
y_N	normal depth of uniform flow
z	elevation of the bed
2θ	the angle subtended at centre of circle by arc of length P
ν	kinematic viscosity
ρ	density
τ_o	average boundary shear stress
τ'	boundary shear stress corresponding to y_{av}
ϕ	denotes a function
ψ	shape factor in Kazemipour's method
ψ_1	a shape parameter which reflects effects of non-uniform distribution of shear stress as shape of cross-section departs from an infinitely wide rectangle = $\sqrt{P/B}$
ψ_2	a shape parameter reflecting the effects of aspect ratio, B/y_{av} or D/y_D, on open channel flow resistance

APPENDIX B. - REFERENCES

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