FACTORS AFFECTING THE FORMATION OF AIR-ENTRAINMENT VORTICES AT PUMP INTAKES IN OPEN CHANNEL FLOW

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ABSTRACT

The critical submergence of an air-entraining vortex at pump intakes in a uniform open channel flow was studied. The study was achieved for different intake directions to mean flow. The mean flow has different upstream circulations. The vortices at the intakes are defined by the first observation of a persistent surface separation wave which appears at the surface downstream of the intake. The potential flow solution for the combination of a point sink and a uniform flow is considered. A comparison between the experimental results and theory is made, and an empirical formula is included which may be applied to intakes in open channel flow. Results have shown that the phenomenon is mainly characterized by the following parameters: inlet direction to mean canal flow, ratio of intake velocity to mean flow velocity, intake Froude number and upstream circulation of the mean flow. Also, it is found that the potential flow solution gives low values for the required submergence to avoid the formation of air-entrainment vortex in comparison with the experimental results.

INTRODUCTION

Water intake structures of many types are sometimes subjected to air-entraining vortices formation. Such vortices approximate the free vortex except close to the core where viscosity modifies the pattern. Hydraulic pumps and turbines are designed assuming that the flow into the machine will be axial and uniform. An intake vortex can cause a swirling flow to enter the machine, resulting in off-design operation, loss of efficiency and possibly cavitation, surging and vibration. An air-entraining vortex can also reduce the discharge into the intake. There are several means of avoiding air-entrainment vortex. The most cost-effective choice is often determined through a physical model study. The most common solution for avoiding air-entrainment is to provide sufficient submergence to the intake which it takes a suitable direction to the mean flow.

There is a need for design criteria based on analytical and experimental investigations, however, because for some projects the physical model study may not be economic due to both time and financial constraints. Several analytical and experimental investigations have been conducted for critical submergence related to intakes [1], [2], [3], [4], and [5], but non of these are applicable to vortices that occur at intake in open channel flow.

The present study set out to investigate both analytically and experimentally the critical submergence for intakes set at different directions in a uniform open channel flow. The effect of upstream circulations on the formation of the vortex was studied. The circulations were generated by means of guide vanes located upstream of the intake. It becomes clear during the course of study that the phenomenon was divisible in to several logical components. The *first* component is the flow as it approaches the intake. This approach flow is controlled by the boundaries of the canal, the generated vorticity and flow uniformity. *Secondly,* the tendency of the vortex to form at the intake depends not only on the approach vorticity but also on the intake conditions such as its direction to the mean flow, its flow rate and hence the size of its entrance. *Thirdly,* whether such vorticity will produce an air-entraining vortex depends on the submergence and also whether the intake is in a vortex forming situation.

THEORETICAL CONSIDERATIONS

Dimensional Analysis: For the purpose of the experimental study, let the critical submergence be defined as the submergence of the intake at which incipient air-entrainment is possible. Treating the critical submergence as the dependent variable, the following functional relationship may be written as follow:

$$h_c = \phi(\theta, U, v, z, x_1, x_2, \rho, \mu, \sigma, g, \Gamma) \qquad (1)$$

where h_c = critical submergence; θ = angle of inlet inclination to the mean flow direction; U = mean velocity of the mean flow upstream of the intake; v = flow velocity through intake pipe; z = distance between the inlet of the intake and channel bed level; x_1 , x_2 = distances of the intake pipe to the right and left hand side walls of the channel; d = internal diameter of the intake pipe; ρ = density; μ = dynamic viscosity, g = acceleration due to gravity, σ= surface tension and Γ= circulation.

Taking ρ, d, v as the repeating variables, the dimensional analysis of variables of Eq. (1) yields:

$$\frac{h_c}{d}=\phi_1\left[\theta,\frac{v}{U},\frac{\rho\, d\, v^2}{\sigma},\frac{\rho\, d\, v}{\mu},\frac{\Gamma}{d\, v},\frac{v}{\sqrt{g\, d}},\frac{z}{d},\frac{x_1}{d},\frac{x_2}{d}\right] \tag{2}$$

in which $\rho d v^2 / \sigma$ Weber number (W); $\rho d v / \mu$ = intake Reynolds number (R); Γ / dv = Kolf number (K); and $v/\sqrt{g\,d}$ = intake Froude number (F). Yildirim and Jain [6] and Padmanabhan and Hecker [7] have shown that surface tension may be important for vortices with low circulation only. The experimental study of Odgaard [3] infers that in case of air-entraining vortices in a still water body for $R > 1.1 \times 10^5$ and $W > 720$, the effects of viscosity and surface tension can be neglected. Because in the experiments the Reynolds and Weber numbers were generally larger than these criterions, they were dropped out from Eq. (2). The terms x_1 and x_2 were taken sufficiently large not to affect the flow conditions at the intake. Thus x / d can be dropped out from Eq. (2). To avoid the ground boundary layer effect and picking up the small debris from the canal bed, z / d was taken as 1.4 [2]. Guliver and Rindels [4] calculated a circulation parameter which it considers the effect of mean flow circulation. This parameter depends mainly on the angle of vanes inclination to the mean flow direction near the intake (β).

On the basis of their analysis, the angle of vanes inclination to the mean flow direction (β) can be considered instead of Kolf number (K). Considering the intake Froude number and the angle of vanes inclination to the mean flow direction (β), Eq. (2) may be reduced to:

$$\frac{h_c}{d}=\phi_2\left[\theta,\beta,F,\frac{v}{U}\right] \tag{3}$$

<u>Potential Flow Theorem:</u> On the basis of Stoke's stream function, Streeter [8] combined a uniform flow having a velocity U in x-direction with a sink flow to give the following expression for the stream function ψ as;

$$\psi=\frac{q}{4\pi}\cos\alpha+\frac{U\,r^2}{2}\sin^2\alpha \tag{4}$$

q is the "strength" of the sink and it defined as the rate of flow passing through any surface enclosing the sink; α is the polar angle, and r is the radial distance from the origin (point sink).

The condition for the stagnation point which appears in this type of fluid flow is the velocity component normal to the stream surface in steady flow is always zero. According to this definition with Eq. (4), Streeter developed the equation of the stream surface through the stagnation point as:

$$r=\frac{1}{2}\left(\sec\frac{\alpha}{2}\sqrt{q/\pi U}\right) \tag{5}$$

From which the surface is easily plotted. Such a figure of revolution is called a half-body of revolution as it extends to negative infinity, surrounding the negative x-axis.

In the case of pipe intakes in open channel flow, flow into a pipe can be approximately considered as a "point sink". In the critical conditions where the air core free vortex has not yet formed, flow is considered to be the superposition of uniform flow and point sink as shown in Fig. 1. The equation of half-body of revolution, Eq. (5) divides the flow in two regions, the flow area entering and not entering the intake. Just above the inlet of intake where α = 90° (in Fig. 5), the vertical distance from the intake level to the upper boundary of the half- body of revolution $r = h$ is;

$$h=\sqrt{q/2\pi U} \tag{6}$$

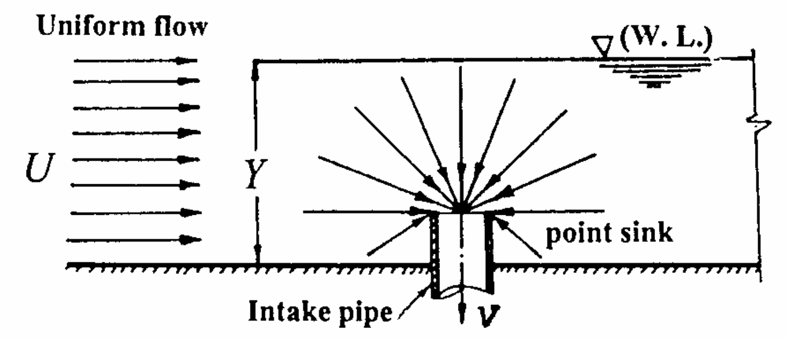


Fig. 1. Uniform flow and point sink

In case of high submergence ($h > h_c$), the upper boundary of the half-body of revolution does not reach the free surface and then the surface water above the centre of the intake can not enter the intake (Fig. 2a). At critical conditions ($h = h_c$), the stagnation point of the surface separation wave corns to just above the intake. This indicates that, at the critical conditions the upper surface of the half-body of revolution is matching gradually the surface level above the intake (Fig. 2b). From Eq. (6), the critical submergence h_c must be equal to h, then

$$h_c = \sqrt{q / 2\pi U} \tag{7}$$

Because the intake discharge can be computed from multiplying the cross section area of the intake pipe by the intake velocity v as;

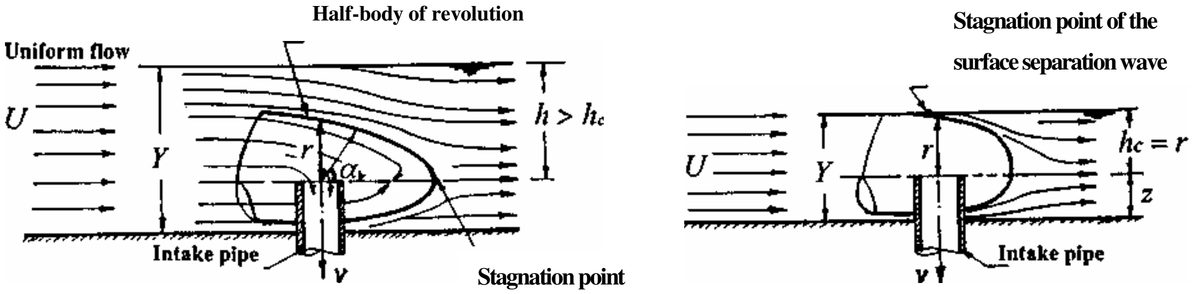
$$q = v \pi d^2 / 4 \tag{8}$$

Then from Eqs. (7) and (8) with some arrangements we can obtain

$$\frac{h_c}{d} = \sqrt{\frac{1}{8} \frac{v}{U}} \tag{9}$$

Equation (9) can be written in general form as;

$$\frac{h_c}{d} = a \left(v/U \right)^b \tag{10}$$



a) Before critical conditions. b) At critical conditions.

Fig. 2. Combined uniform flow with a point sink

EXPERIMENTAL FACILITIES

Experiments were conducted in a rectangular flume. The flume shown in Fig. 3 has 18 m long, 30 cm wide and 50 cm deep. It consists of stilling basin, a transition zone and a test section. Flow was pumped from an underground sump and re-circulated. Water depth through the flume was controlled by a downstream flapping gate. The rate of inflow was measured by an orifice meter located on the pipe line of the re-circulated flow. The discharge leaving the flume through the intake was measured by means of a calibrated flow meter. The stilling basin was designed to produce a fairly straight uniform flow out of this section. This was achieved with a 0.5 m horizontal diffuser plate shown in Fig. 3. A transition zone of 8.0 m was used to damp any large scale eddies. Visual observation was made possible by installation the two sided-glass walls of the flume. The intake inlet was centrally placed at a distance 7.0 m upstream from the downstream flapping gate.

In order to control and predetermine the flow approach angle and hence the circulation to the test section, a guide vanes were located 30 cm upstream the intake centerline. The vanes were 10 cm length with thickness of 0.15 cm and a spacing of 10 cm. Each van had pivots at its top and bottom in order to vary approach flow angle (β) between 15° to 45°. Intake pipes with different internal diameters varying from 2.54 cm to 6.35 cm were used. Five different inlet configurations were studied in some details: an inlet near the flume bed at with angle $\theta = 0°$ to the far upstream mean flow direction; an inlet at $\theta = 90°$, $\theta = 180°$ to mean flow; vertically upwards and vertically downwards oriented intakes.

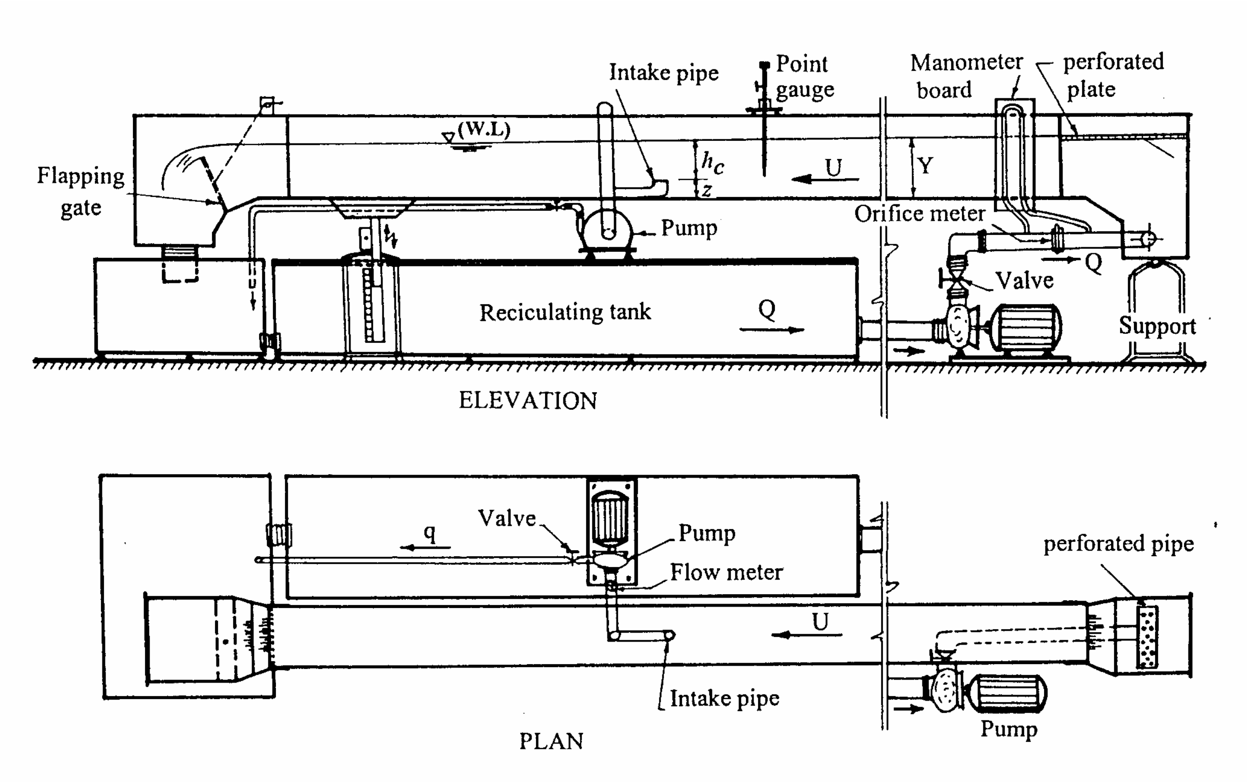


Fig. 3. Experimental Set-Up

MEASUREMENT TECHNIQUES AND OBSERVATIONS

After placing one of the intake pipes with the required direction to the mean flow direction and giving the required discharge to the flume by means of the valve, the intake discharge was selected. Observation for 0.5 - 1.0 hour (depending on the flume and intake flow rates) was made to see whether or not any free vortex developed. If no air-entrainment occurred during this time, the rear gate was lowered for some very small amount (submergence was decreased). These steps were repeated very carefully until the air-entrainment free vortex developed. When the air-entraining vortex developed, the measurements related to flume discharge Q, intake discharge q, critical submergence h_c and uniform flow depth Y were made. This experiment was conducted for 5-8 different discharges of uniform flow and intake. The aforementioned steps were repeated for all intake pipes and directions to the mean flow.

As the experiment was approaching the critical condition for the air-entraining free vortex from a large submergence, the following events were observed: when the critical condition was approached a surface separation wave appears at the surface downstream of the intake, as in Fig. 4a. In the case of low critical submergence, it has been observed that the region within the surface separation wave is a depression. The surface separation wave has a stagnation point at the surface. When the critical submergence is large, the separation wave is so small and it can be visible by potting some dye at the upstream water surface of the intake. When the stagnation point is at downstream edge of the intake, there is no obvious sign of dimples. If the submergence decreases a little more, the stagnation point of the surface separation wave moves upstream towards the center of the intake and widens a little more, but still no obvious sign of dimpling. If the submergence is lowered slightly the stagnation point moves to just above the center of the intake as in Fig. 4b. At this stage, small visible dimples appear as a first sign of the free vortex. These dimples originated from the separation point of the surface separation wave. An air-entraining free vortex develops in this stage. Just before the air entraining free vortex takes place, the surface separation wave front moves to just above the upstream edge of the intake. In front of the stagnation point, there develop some surface reflection ripple waves. In all cases, as the surface separation wave front moves upstream it widens and the air entraining vortex occurs. When the velocity of the uniform flow becomes very small, the surface separation wave widens and then spans across the entire width of the channel as in Fig. 4c. In this case due to velocity gradient (vorticity), weak vortices develop at the surface on the right-hand side of the separation wave and move towards the intake.

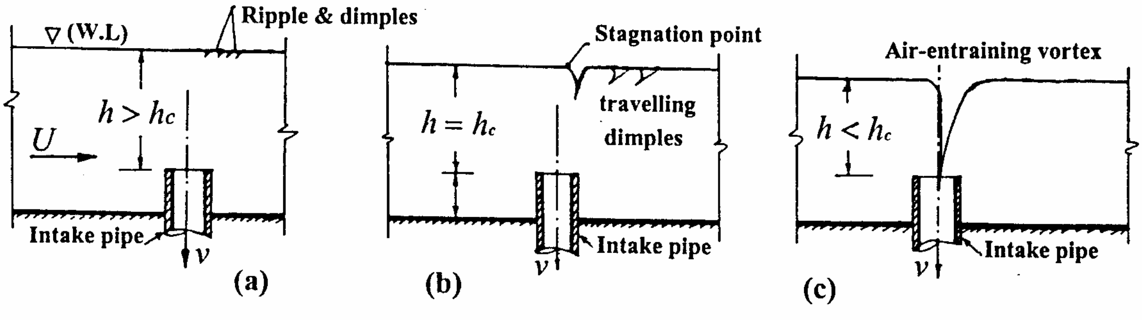


Fig. 4. Development of Air-entrainment vortex

When these surface vortices reach just above the center of the intake, an air-entraining vortex occurs. The critical submergence is the submergence corresponding to the case where the stagnation point moves to just above the center of the intake as in Fig. 4b. This is the stage in which the first dimple from which the air-entraining vortex originates and the surface particle just above the center point of the intake starts to get the chance to enter the intake, it should be avoided in most pump and turbine intake designs.

RESULTS AND DISCUSSION

The critical submergence was measured over a range of intake Froude number from 1.0 to 18.8 at 10 arrangements of the intake direction to mean flow and approach flow angle. In all, 160 individual measurements of critical submergence were made. The distances between the intake and the side walls were always more than 2.4 times the intake diameter. The walls did not greatly impede swirl development over the intake. The data, therefore, should be seen as giving maximum values of submergences that will assure no air-entrainment vortices.

The measurements are plotted in Fig. 5 as h_c / d versus v / U for five inlet configurations of its direction to the mean flow. From this figure we can see, in general, the strong effect of the v / U ratio for determining the appearance of inlet vortex. Where, the h_c / d ratio increases with the increase of v / U ratio. This means that for high values of intake velocity and low values of the velocity of the mean flow, an unstable situation must occur because the kinetic energy of the mean flow is small in comparison with that of the intake inlet. Only, a suitable vortex can establish equilibrium by dissipating the energy difference $(v^2 - U^2) / 2g$ between the intake inlet and the mean flow due to the produced swirl velocity. For high v / U values, the energy difference $(v^2 - U^2) / 2g$ is high, then a strong vortex must form and a high submergence is required to avoid its formation. As the value of v / U decreases, the energy difference decreases and consequently the required submergence decreases.

As discussed before in potential flow theorem and from Fig. 5 with Table 1, the relationship between h_c / d and v / U takes the exponential form of Eq. (10). From the experimental results shown in Fig. 5, the constants a and b in Eq. (10) are mainly depending on the intake orientation to mean flow and the produced circulation in open channel flow upstream the intake.

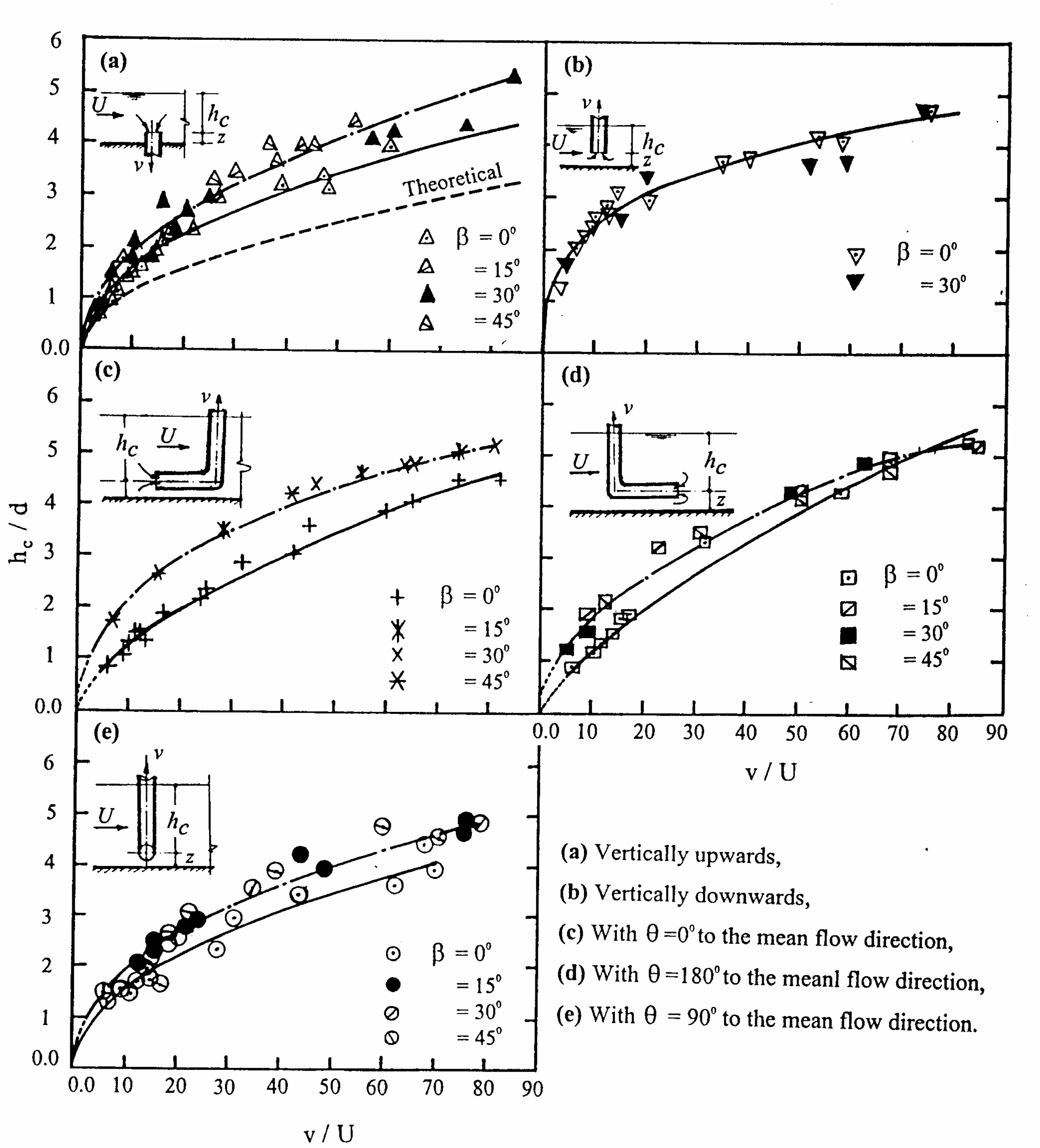


Fig. 5. Variation of critical submergence for different intake orientations to the mean flow direction

For vertically oriented intakes, the case of vertically downward (Fig. 5b) gives high values of h_c/d in comparison with the case of vertically upward and also with other studied cases for the same values of v/U. This may due to, for the vertically downward orientation; the intake pipe vertically penetrates the surface of the flume flow. As the flow passes the intake pipe, surface vortices (dimples or trailing vortex) emerge around the periphery of the intake pipe, which stimulates the occurrence of the air-entrainment vortex. The same effect is noticed for the oriented intake by $\theta = 180°$ to the mean flow direction (Fig. 5d), especially for the high values of v/U where the flow can carry the trailing vortex which becomes stronger to the location of the inlet of the intake. But at low values of v/U, the trailing vortex becomes weak to reach the inlet. The case of oriented intake with $\theta = 90°$ (Fig. 5e) gives similar results of vertically upwards oriented intake (Fig. 5a). When the inlet facing at $\theta = 0°$, as shown in Fig. 5c, and because the intake velocity in the same direction of the mean flow, the results for low values of v/U is higher than that of the case (d) in Fig. 5.

Table 1. The constants found in Eq. (10) predicted from the experimental results

Test conditions	Constant	Theoretical	Intake Orientation to Mean Canal flow				
			Vert.-up	Vert-down	θ = 0°	θ = 180°	θ = 90°
Without guide vanes	*a*	0.3536	0.485	1.235	0.27	0.23	0.485
	b	0.5	0.5	0.306	0.65	0.72	0.5
With guide vanes	*a*	-	0.582	1.235	0.86	0.582	0.55
	b	-	0.5	0.306	0.41	0.5	0.5

A number of researchers have experimentally investigated the free surface vortex formation at an outlet in a tank with still water body or with a given circulation. The circulation was controlled using vanes or jets issuing water from the side of the tank. Gulliver and Rindels [4] have used vanes located upstream of a typical vertically arranged hydroturbine intake structure to produce a circulation in the approach channel (headrace). Whereas the effect of the structures near the intakes (guide walls in a pump sump, bridge piers in open channels ... etc) on the mean flow circulation and consequently the formation of air-entrainment vortex is generally unknown, a guide vanes representing the effects of these structures and many of the hydropower facilities were used upstream the intake. From Fig. 5 one can clearly see the significant increase in the required submergence to avoid the formation of air-entraining vortex with the increase of mean flow angle (β) from 15° to 45°. This increase in the critical submergence may be due, for example, to the formation of the trailing vortices behind the guide vanes upstream the intake. These trailing vortices propel each others and amplified, and rarely destroyed themselves and vanish before reaching the intake inlet. If the trailing vortex reaches the intake inlet, it stimulates the occurrence of the air-entrainment vortex. Another reason for increasing the required submergence is the acceleration given to the generation of radial flow at the intake. It was found in the cases where the intakes penetrate the water surface; the effect of inflow angle on the critical submergence is smaller than the other cases because the intake pipe itself approximately gives the same effect of guide vanes in producing the trailing vortices near the intake inlet. Also, it is observed that, for the given location of the guide vanes, an interference in the results of the required submergence to avoid the inlet vortex with changing the inflow angle (β) from 15° to 45°.

From the theoretically given and experimentally predicted relationships between the h_c/d and v/U with Fig. 5, a difference between the theoretically required submergence and the experimentally one is seen. In comparison with the two studied categories (without and with mean flow angle (β)), the potential flow theory gives low values of the critical submergence, especially for high values of v/U. This is because the theory does not take into consideration the presence of mean flow circulation and the surface tension effects. Also the presence of the periphery of the intake pipe in the uniform flow affects the experimental results. Because of the vortex formation at such intakes is a transition phenomenon from being uniform flow to radial flow. Such transition and unstable situation is subjected to an experimental error. This is a usual source of error in experimental results and could account for some scatter in the data.

Plotted in Fig. 6 is a dimensionless parameter h_c/d versus the intake Froude number (F) for the case of vertically upward oriented intake. A comparison between the results of present study and the results of Gulliver and Rindels [4] for the vertical intake with headrace channel is shown in this figure. The comparisons are made for inflow angles (*β*) equaling to 15°, 30° and 45°. From this figure, we can see that the increase of intake Froude number increases the corresponding h_c/d values. This may due to the increase of kinetic energy difference between the intake and the mean flow. Also, the effect of inflow angle is clearly seen in both Gulliver and Rindels [4] and results of the present study where the increasing of the inflow angle -within the study range- stimulates the occurrence of intake vortex. As a result, the critical submergence needed to avoid such vortices must be increased. From these comparisons, the study of Gulliver and Rindels [4] gives higher submergence than the present study. The reason of this difference may due to the effect of the distance from the intake to the dead end of the channel where in the study of Gulliver and Rindels [4], this distance is small. As this distance becomes smaller the effects of viscosity and surface tension starts to be important [4].

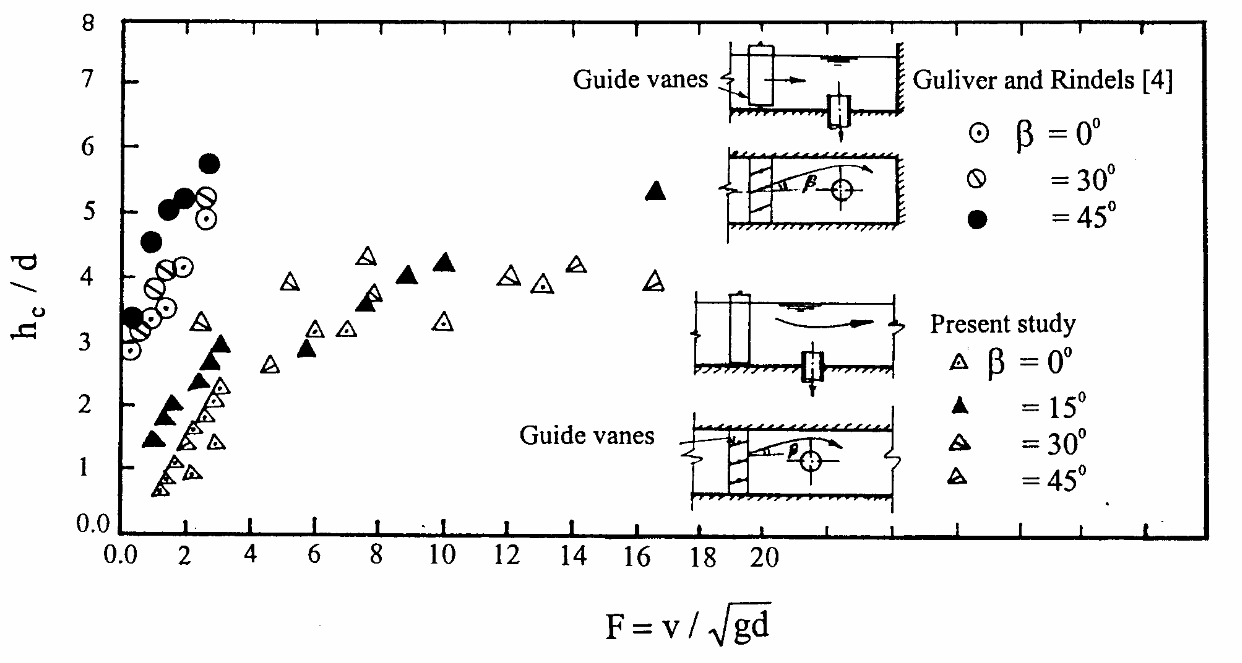


Fig. 6. The variation of h_c / d versus intake Froude number (*F*)

CONCLUSIONS

The required submergence to avoid the formation of air-entrainment vortices at intakes in open channel flow was studied theoretically and experimentally. The theoretical study is based on the potential flow solution of the combination of a point sink with uniform flow.

From the results of this study the following conclusions may be drawn:

1- The ratio of the velocity of intake flow to that of the mean flow is an important parameter for determining the appearance of inlet vortex.

2- The direction of the intake inlet to the mean flow has major effects on the required submergence to avoid the inlet vortex.

3- The presence of guide vanes, which are simulated the guide walls in pump sump and bridge piers, stimulate the occurrence of inlet vortex.

4- The potential flow solution gives low values of the required submergence to avoid inlet vortex in comparison with the experimental results.

5- Both the theoretical and the experimental results give an exponential form of the relation-ship between h_c/d and v/U as: $h_c/d = a(v/U)^b$, the values of the constants a and b are listed in Table 1.

6- The required submergence for intakes in open channel flow is lower than that the required for intakes in a headrace channel, the results of both configurations can be used for intakes in the irrigation canal.

NOMENCLATURE

The following symbols are used in this paper:

d = internal diameter of the intake pipe;

F = intake Froude number;

g = acceleration due to gravity;

h = vertical distance from intake inlet to water surface (submergence);

h_c = critical submergence (critical value of h);

K = Kolf number;

q = intake discharge;

R = intake Reynolds number;

r = radial distance from the center of the intake inlet (point sink);

U = mean velocity of canal flow upstream of the intake;

v = flow velocity through the intake pipe;

W = Weber number;

x_1 = horizontal distance of intake to right hand side wall of canal;

x_2 = horizontal distance of intake to left hand side wall of canal;

z = distance between the inlet of the intake and the canal bed;

α= angle between horizontal axis and radial direction at the original (point sink);

β= angle of vanes inclination to mean open channel flow;

Γ= circulation;

θ= angle of inlet inclination to mean flow;

μ= dynamic viscosity;

ρ= density;

σ= surface tension; and

ψ= stream function.

REFERENCES

1- Jain, A. K., Ranga Raju, K. G., and Garde, R. J., "Vortex formation at vertical pipe intakes", J. Hyd. Div., ASCE, 100(10), 1429-1448, 1978.

2- De Siervi, F., Viguier, H.C., Greitzer, E. M., and Tan, C. S., "Mechanisms of inlet-vortex formation", J. Fluid Mech., 124, 173-207, 1982.

3- Odgaard, A. J., "Free surface air core vortex", J. Hyd. Div., ASCE, 112(7), 610-620, 1986.

4- Gulliver, S. J., and Rindels, A. J., "Weak vortices at vertical intakes", J. Hyd. Div., ASCE, 113(9), 1101-1116, 1987.

5- Kite, J. E. and Mih, W. C., "Velocity of air-core vortices at hydraulic intakes", J. Hyd. Div., ASCE, 120(3), 284-297, 1994.

6- Yildirim, N. and Jain, S. C., "Surface tension effect on profile of a free vortex", J. Hyd. Div., ASCE, 107(1), 132-136, 1981.

7- Padmanabhan, M. and Hecker, G. E., "Scale effect in pump sump models", J. Hyd. Div., ASCE, 110(11), 1540-1556, 1984.

8- Streeter, V. L., "Fluid Mechanics", McGraw-Hill Book Co., New York, 360-374, 1966.