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Effect of Anti-Vortex Plates on Critical Submergence at a Vertical Intake

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Abstract. *One of the sources of disturbance at intakes is the occurrence of free-surface vortices with an air core. The most common solution for avoiding air-entrainment is the use of anti-vortex devices and, especially, plates for large pipe or shaft intakes. If plates are used, then, the geometry and position of them should be studied experimentally. Since only general guidance for use of plates is available, a study for the more precise placement of plates is needed. Hence, a comprehensive set of experiments have been carried out using rectangular plates with different dimensions and at various positions with respect to the vertical outlet pipe intakes and two different pipe diameters ($D = 75$ and 100 mm). The results of critical submergence with respect to the dimensions and positions of the plates are presented as graphs and equations. Thus, design guides and recommendations are provided.*

Keywords: *Air entrainment; Experimental data; Intakes; Pipe flow; Plates; Vortices.*

INTRODUCTION

Pipe intakes are used to convey water for turbines, pumps, flood routing, irrigation and other demands. When the water level above a pipe intake is low (less than critical value), strong vortices may be formed, which may lead to air-entrainment and which may cause loss of efficiency, cavitation and vibration in pumps, turbines and pipelines. An intake that is prone to vortex formation, results in a considerable entrainment of air and swirl (the conditions for vortex formation is fully discussed in [1]). Intake vortices are the result of angular momentum conservation at the flow constriction where angular velocity increases with a decrease in the cross sectional area [2]. The common solution for avoiding air-entrainment and swirl is to provide sufficient submergence to the intake. If the required approach flow conditions cannot be met to avoid swirl and air entrainment, it is economical to consider other approaches for preventing vortices at water intakes. While the effect of extreme pressure variation in a pressurized flow due to air entrainment is shown by Kabiri-Samani et al. [3], there are several means of avoiding air-entrainment where for large structures, the most cost-effective option is often determined by a physical model study. One of the most popular ways is the use of special vortex suppression devices [1]. Among the most economical and common measures of reducing the effect of air-entrainment and swirl strength, is anti-vortex plates (e.g. for shaft spillways, submerged culverts and gates). These plates can have any geometry and be used singly, in pairs or in other combinations, and perpendicularly or with an angle to the free surface flow. Ample research work has been carried out to have a better knowledge of vortex formation and critical submergence depths for vertical pipe intakes. Among the analytical approaches, the works of Odgaard [4] and Hite and Mih [5] are more relevant. However, for experimental published work, the studies can be divided into two categories. First, the understanding of free vortex hydrodynamics [6-11] and second, parameters affecting the critical submergence depth [2,7,12-16]. On the other hand, while many attempts have been made numerically to analyze the hydrodynamics of vortex and cavity development [17,18], not much published work with a numerical basis exists on air entrainment due to shaft intake.

Although much research has been carried out for

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a better understanding of swirl flow and submergence depth, there is no design criteria for anti vortex plates. Hence, in this paper, the effect of using anti-vortex plates as a means of fully reducing critical submergence depth and air entrainment is studied experimentally. Anti-vortex plates with different dimensions are used singly, in pairs and in different combinations and positions, to study the effects on critical submergence depth.

GOVERNING PARAMETERS

Important dimensionless terms which should be used for experimental studies to define the swirling flow at a pipe intake are [1]:

$$S/D: \text{ Relative Submergence,} \tag{1a}$$

$$\Gamma_N = \frac{\Gamma D}{Q}: \text{ Kolf Number,} \tag{1b}$$

$$\mathrm{F_N} = \frac{4Q}{\pi(gD^5)^{0.5}}: \text{ Froude Number,} \tag{1c}$$

$$\mathrm{R_N} = \frac{Q}{\nu s}: \text{ Reynolds Number,} \tag{1d}$$

$$\mathrm{W_N} = \frac{(Qr_0S)^2}{\sigma/(\rho r_0)}: \text{ Weber Number,} \tag{1e}$$

or:

$$S/D = f(\Gamma_N, \mathrm{F_N}, \mathrm{R_N}, \mathrm{W_N}), \tag{2}$$

where S = submergence depth; D = pipe intake diameter; Γ = circulation intensity; Q = discharge; g = gravitational acceleration; ν = kinematic viscosity; r_o = pipe intake radius $(D/2)$; σ = surface tension; ρ = density and f = a function. It should be noted that some of the dimensionless numbers have been introduced with different variables as well (Table 1). The effects of viscosity or the Reynolds number ($\mathrm{R_N}$), and the surface tension or the Weber number ($\mathrm{W_N}$), which often occur in model studies, are of major interest to many investigators. A summary of the range of influence of the two numbers by some investigators is shown in Table 1 (V is the flow velocity in pipe). As seen, different definitions and values are suggested. It seems that while the minimum values in the table should be satisfied, it would be better if the results were checked by a scale effect analysis. Also, the Swirling Parameter (SP) can be used instead of Froude and Kolf numbers [1], as:

$$SP = \Gamma_N \mathrm{F_N} = \frac{4\Gamma}{\pi(gD^3)^{1/2}}. \tag{3}$$

By employing one or a pair of anti-vortex plates for reducing the swirling flow strength, it can be concluded that critical submergence also depends on normalized plates dimensions (a/D and b/D) and positions (r/D, z/D and α). Considering that $\mathrm{R_N}$ and $\mathrm{W_N}$ are above the critical values and not influential (see Table 2) and that the value of the critical submergence depth is directly represented by $(S/D)_{cr}$, it can be seen that:

$$\left(\frac{S}{D}\right)_{cr} = f\left(SP, \frac{a}{D}, \frac{b}{D}, \frac{r}{D}, \frac{z}{D}, \alpha\right). \tag{4}$$

Table 1. The values for $\mathrm{W_N}$ and $\mathrm{R_N}$ to affect results.

Reference	Weber No. ($\mathrm{W_N}$)	Reynolds No. ($\mathrm{R_N}$)
Daggett and Keulegan [6]	$V^2\rho D/\sigma \leq 120$	$Q/(\nu D) \leq 3 \times 10^3$
Anwar et al. [7]	$V^2\rho D/\sigma \leq 120$, $V^2\rho S/\sigma \leq 100$	$Q/(\nu S) \leq 10^4$
Jain et al. [8]	$V^2\rho D/\sigma \leq 120$	$\mathrm{R_N/F_N} = (gD^3)^{0.5}/\nu \leq 5 \times 10^4$
Padmanabhan and Hecker [9]	$V^2\rho D/\sigma \leq 600$	$VD/\nu \leq 7.7 \times 10^4$
Odgaard [4]	$V^2\rho D/\sigma \leq 720$	$VD/\nu \leq 1.1 \times 10^5$

Table 2. Minimum values of $\mathrm{R_N}$ and $\mathrm{W_N}$ for present study.

$\mathrm{R_N}$			$\mathrm{W_N}$		
	D = 75 mm	**D = 100 mm**		**D = 75 mm**	**D = 100 mm**
$Q/(\nu S)$	74322	123869	$V^2\rho D/\sigma$	147	169
VD/ν	29264	39019	—	—	—
$Q/(\nu D)$	24773	30967	—	—	—
$\mathrm{R_N/F_N} = (gD^3)^{0.5}/\nu$	71719	110419	—	—	—

EXPERIMENTAL EQUIPMENT AND TEST VARIABLES

Tests were conducted in a cylindrical tank, 1.0 m in diameter and 0.8 m in hight. The circulated water was pumped from a large sump and the discharge was measured by an electronic flowmeter (while passing through the pipe) and checked by a rectangular sharp crested weir at the end of the flume before returning to the sump. Flow enters the tank horizontally and uniformly through a set of vanes. These vanes were set at specific angles to provide the desired entrance circulation parameters, i.e. the ratio of tangential to axial velocity. The flow discharges through a vertical shaft or pipe intake, 0.35 m in height, at the center of the tank. For preventing negative pressure and reducing the suction effect at the entrance of the inlet, air vents are used so that the tests are conducted under atmospheric pressure at the inlet. Figure 1 shows the experimental setup.

The test variables, as shown in Table 3 and Figure 2, were discharge, intake diameter, anti-vortex plate dimensions (rectangular), positions (r = horizontal distance from pipecentre to the side of the plate, z = vertical distance from top of the pipe to the centre of the plate) and the angle between the two plates with a plan view (α as in Figure 2). The dimensions of plates are taken as multiples of the inlet pipe diameter (D), and shown as width by height (i.e., $2D \times D$ means a plate which has $2D$ width or horizontal dimension and D height or vertical dimension). The first set of tests were done using one plate placed under different conditions. Then, the second set of tests were done for two plates in different positions as well as different α.

RESULTS

In this study, the discharge was chosen such that the effect of viscosity and surface tension would be small and, thus, $\mathrm{R_N}$ and $\mathrm{W_N}$ are omitted (Table 3). The results in the table are minimum values. Comparing these values with the ones in Table 1, minimum values are satisfied and the assumption of not including $\mathrm{W_N}$ and $\mathrm{R_N}$ in the results is acceptable. Hence, the most significant and relevant parameters involved in this situation, as discussed previously, are Froude number, circulation number or Kolf number and relative depth (or critical submergence depth). It is not possible to

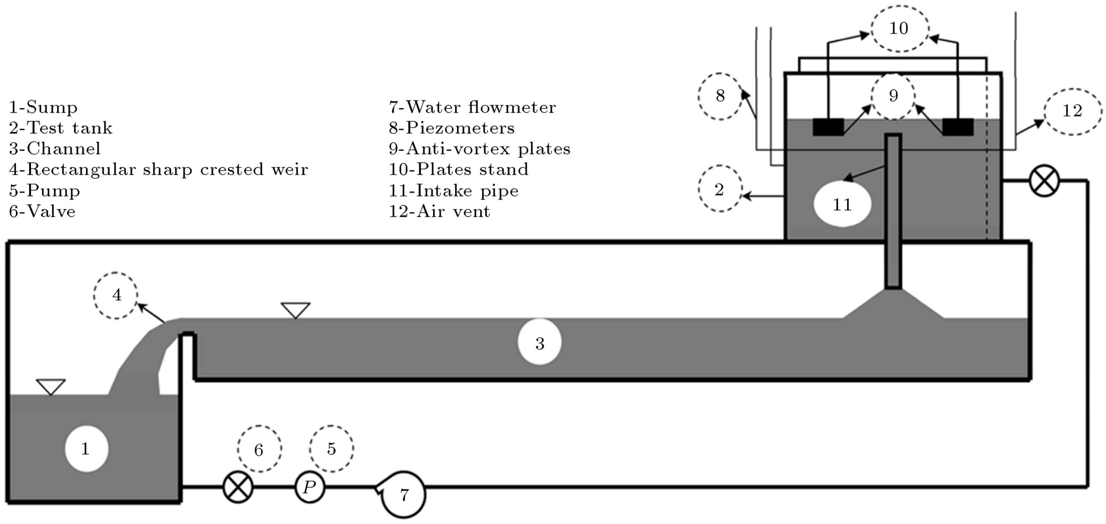

Figure 1. Schematic of experimental setup.

Table 3. Test variables.

Q (m^3/hr)	D (mm)	Plates Dimensions $a \times b$ (Width×Height)*	Plate Position		Plates Angles $\alpha°$
			r (From Edge of Plate)	z (From Center of Plate)	
6-34	75, 100	$D \times D$, $D \times 2D$, $D \times 3D$, $2D \times D$, $2D \times 2D$, $2D \times 3D$, $3D \times D$, $3D \times 2D$	$0.5D$, D, $1.5D$	D, $0.5D$, 0, $-0.5D$, $-D$, $-1.5D$	180, 135, 120, 90, 60, 45

* For 75 mm pipe complete range of plates and for 100 mm pipe only some of the plates have been tested. Overall 12 plates have been used (8 for 75 mm, and 4 for 100 mm pipe).

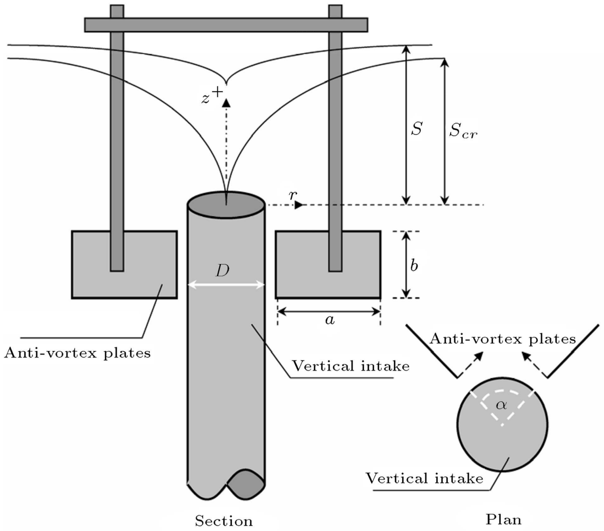

Figure 2. Plates and pipe intake geometry and position.

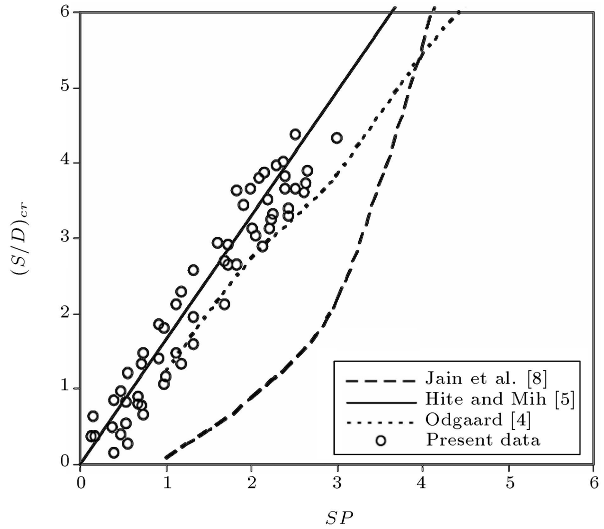

Figure 3. Critical submergence versus SP (equations in Table 4).

show the results of all the tests and, hence, samples representing typical or, sometimes, extreme values are presented in the graphs and figures. However, the final conclusions include all the measured data. In Figure 3, the results of critical submergence depth, $(S/D)_{cr}$, versus Swirling Parameter (SP) is checked with previous published works (Table 4). The agreement between observed results and those of previous works [4,5] can be seen.

On the other hand, to check if the diameter of the tank was large enough for avoiding the wall effect and the flow field representing the swirling vortex, the theoretical tangential velocity was checked with the measured, using a pitot tube (Figure 4). The figure illustrates two important points. First, the velocity profile is well matched with theoretical values [1] and expected flow field; second, the tank is large enough for the flow field, and the velocities near the wall, except at the vicinity of the entrance, were almost zero with a minimum wall effect.

Now, the effect of anti-vortex plates is checked on the critical submergence depth. Thus, the results from the different sizes and positions of the plates are analyzed. In this case, the non-dimensional factor in Equation 4 should include the plate variables too. With a trial and error methodology and using all the observed data, the relation for Equation 4 can be found.

Table 4. Critical submergence relations used in Figure 3.

Reference	Relation
Jain et al. [8]	$(S/D)_{cr} = 5.6(\Gamma_N^{0.84}\mathrm{F_N})^{0.5}$
Hite and Mih [5]	$(S/D)_{cr} = 1.65\Gamma_N\mathrm{F_N}$
Odgaard [4]	$(S/D)_{cr} = 48\Gamma/\mathrm{F_N}(gD^3)^{0.5}$

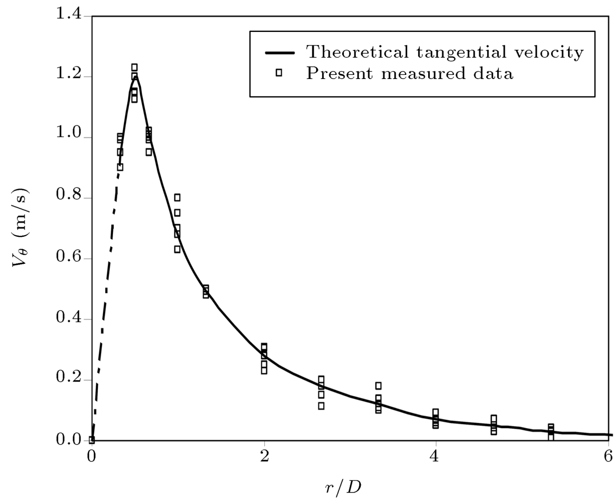

Figure 4. Example of tangential velocity versus nondimensional radial distance.

The suggested relation from these results is:

$$\left(\frac{S}{D}\right)_{cr} = \frac{1.65(SP)}{22.5} \times \left(-0.053\frac{a}{D} + 1.431\right) \times \left(-0.18\frac{b}{D} + 1.445\right)\left(0.5 - \frac{r}{D} + 1.67\right) \times \left(0.31\left(\frac{z}{D}\right)^2 - 0.2\frac{z}{D} + 1.63\right) \times (-0.07\alpha + 1.6), \tag{5}$$

where α is in radian and a and b are the length and width of a single plate, respectively. Also, the limitations to the equation are $\pi/4 \leq \alpha \leq \pi$, $a/D \leq 3$, $b/D \leq 2$, $r/D \leq 5$, and $|z/D| \leq 3$. The equation is

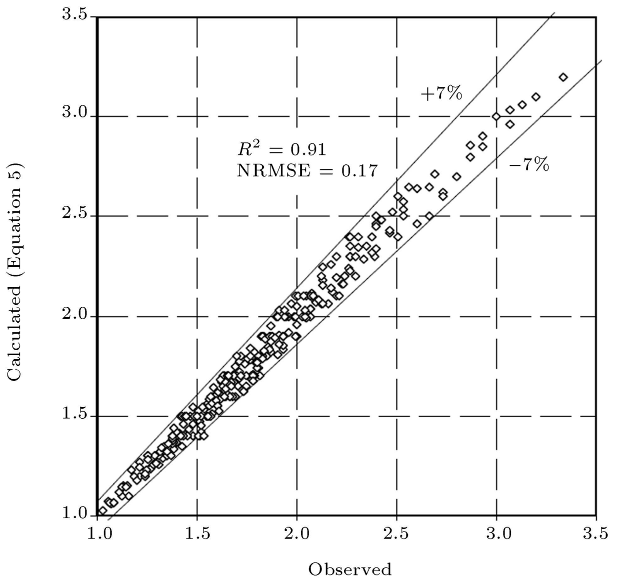

Figure 5. Critical submergence $(S/D)_{cr}$.

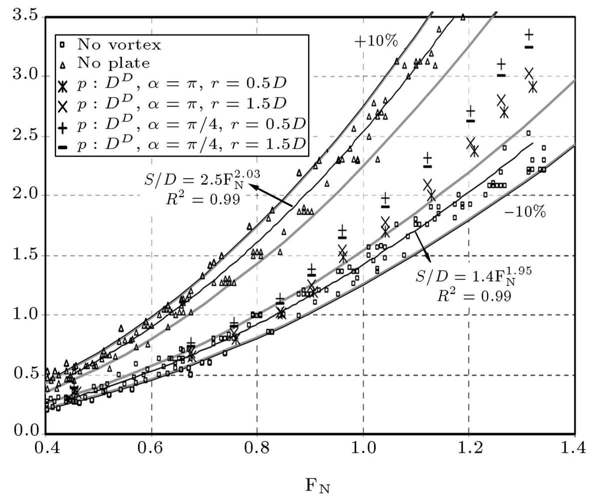

Figure 6. $(S/D)_{cr}$ versus $\mathrm{F_N}$ with free vortex, partially reduced vortex and without swirling flow from present study.

verified by observed data in Figure 5. The deviation of ±7% between the calculated and observed values of $(S/D)_{cr}$, $R^2 = 0.91$ and NRMSE = 0.17, for so many variables and data points, is acceptable. Although the proposed equation is for a pair of symmetrical plates, it has been checked by the authors that the equation can also be used for asymmetrical plates. In this case, the position of each plate can be used in the formula and, then, the average of the two values multiplied by 1.1 should produce the result. Also, for a single plate, the value from Equation 5 should be divided by 0.6, while $\alpha = \pi$. Another presentation of the results showing the effect of anti-vortex plates with non-dimensional values of $(S/D)_{cr}$ and $\mathrm{F_N}$, is given in Figure 6. In this figure, the relation between $(S/D)_{cr}$ and $\mathrm{F_N}$, for the cases of using anti-vortex plates (no-vortex) and no-plate (fully circulating flow condition) is plotted. It can be seen that by using the anti-vortex plates and completely omitting the vortex, the critical submergence of flow is reduced compared with the free vortex flow condition.

Another important result of this study is the validation of the model scale and the sensitivity analysis, since two different pipe sizes (75 and 100 mm) and different dimensionless parameters were used. The same trend and the good correlation between the results have been observed, which is encouraging for both pipe sizes. The results from the two pipe intakes show that the smaller pipe diameter is large enough to avoid insignificant forces and, also, that the flow conditions for the experiments have been suitable. Also, sensitivity analyses have been done among different important parameters affecting critical submergence depths. After the analysis of different parameters, using experimental data, the best fit has been resulted as Equation 5.

CONCLUSIONS

For reducing the critical submergence depth at vertical pipe intakes and omitting the swirling flow, anti-vortex plates can be used. Equation 5 can be used while knowing flow conditions (Γ_N and $\mathrm{F_N}$), required submergence depth (Figure 6), pipe diameter and symmetrically positioned plate positions. Also, for a single plate and for non-symmetrical positions, the suggestions using the equation are given. It should be noted that the proposed conclusion is made with the present experimental set-up. There is no doubt that many more experimental models with different set-ups from different research will be needed, in order to finalize and achieve a generalized equation.

NOMENCLATURE

A_p	area of a single plate (m^2)
$a \times b$	anti-vortex plates dimensions (m^2)
D	pipe intake diameter (m)
$\mathrm{F_N}$	Froude number
f	function
g	gravitational acceleration ($\mathrm{m/s^2}$)
$\mathrm{R_N}$	Reynolds number
r	radial distance (m)
r_0	pipe intake radius (m)
Q	discharge of intake pipe ($\mathrm{m^3/s}$)
Q_0	reference discharge ($\mathrm{m^3/s}$)
V	pipe velocity (m/s)
V_θ	tangential velocity (m/s)
S	submergence depth (m)
S_{cr}	critical submergence (m)

S_∞	water depth far from the intake (m)
SP	swirling parameter
W_N	Weber number
z	axial distance (m)
α	anti-vortex plates angle (rad.)
Γ	circulation intensity (m^2/s)
Γ_N	Kolf number
ν	kinematic viscosity (m^2/s)
ρ	water density (kg/m^3)
σ	surface tension (N/m)

Subscripts

nv	no vortex or flow through pipes without any visible vortex or swirling flow when using the anti-vortex plates
np	no plate when the flow is natural or has free swirl
cr	critical

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BIOGRAPHIES

S.M. Borghei was born in Tehran, Iran on 23 Dec, 1954. He received his BS in civil engineering in 1977, and his PhD in hydraulic engineering in 1982 from Nottingham University in the UK. Dr Borghei began his academic career at Sharif University of Technology, Iran, in 1983 and became professor in 2006. His main research interests include experimental and physical modeling of hydraulic structures, and river engineering. He has published and presented, respectively, more than 100 papers in scientific journals and at conferences in these areas of interest.

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Dr Kabiri received the 2008 "Elite National Foundation" for being ranked the highest of all PhD graduated students in the civil engineering department of Sharif University of Technology and the 2006 "Tavakkoli Award" due to his applicable research in two-phase flow mechanics. In 2003, he also received an award for being among the top 10Education at Sharif University of Technology.

He has authored more than 40 scientific publications, including 10 papers in scientific journals, 30 conference papers and 4 technical reports. Under his guidance, six MS students have also completed their graduate degrees in hydraulic engineering.

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He is also a member of seven professional societies, including IAHR, EWRI, IHA, etc.