Ain Shams Engineering Journal 11 (2020) 933–938

Contents lists available at ScienceDirect

Ain Shams Engineering Journal

journal homepage: www.sciencedirect.com

Civil Engineering

Critical submergence for a horizontal pipe intake

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ARTICLE INFO

Article history:
Received 2 December 2019
Revised 21 January 2020
Accepted 4 February 2020
Available online 12 March 2020

Keywords:
Air-entraining vortex
Critical submergence
Dead-end wall
Horizontal intake

ABSTRACT

Incipient air entrainment due to a free-surface vortex at a horizontal pipe intake passing through a dead-end wall located in a channel is investigated. Available potential flow based methods fail to predict the critical submergence due to friction effects introduced by the dead-end wall. In this study, velocity at the critical spherical sink surface, which is an imaginary spherical surface having identical center and the discharge as the intake, is associated with the average approach flow velocity instead of assuming it as a constant as in the previous studies. This simpler method for determination of critical submergence is tested with available experimental data and the agreement is found to be good. Scale effects are also discussed. It is shown that for the similarity between the model and prototype horizontal intakes in terms of air-entrainment, there is no need to consider Froude, Reynolds, and Weber numbers similarities.
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1. Introduction

Water is withdrawn from reservoirs, channels, lakes, and rivers via intake structures for various purposes (e.g., irrigation, drinking water requirements, energy production etc.). There are several types of intake structures [(frontal intake, bottom intake, lateral intake, and small scale intake structures (pipes or ducts) etc.]. One of the main concerns for hydraulic engineers is the entrainment of air by means of a free surface vortex. These vortices may lead to a reduction in efficiency of intakes and cavitation or vibration problems at the elements of water conveying system. The simplest way to avoid this problem is to keep the submergence of the intake (S) larger than the critical submergence (S_c) at all times. For a vertically downward flowing intake, critical submergence is defined as the vertical distance between the intake center and water surface level when air just enters the intake by a free-surface vortex. However, for a horizontally flowing intake air enters the intake at the summit point of the intake. As it will be presented later, for a more appropriate comparison between the theoretical and experimental results, experimental critical submergence (S_c^*) for a horizontal intake is modified by adding the half of the intake diameter ($S_c = S_c^* + 0.5D$, herein D is the diameter of the intake pipe, Fig. 1).

Determination of parameters affecting the critical submergence is important in the design of intakes. Therefore this phenomenon is investigated in several studies in the literature. Yıldırım and Kocabaş [1] found the critical submergence of a vertical pipe intake subjected to cross-flow by potential flow assumption. Yıldırım et al. [2,3] investigated the effect of flow boundaries on critical submergence of horizontal and vertical pipe intakes. They showed that potential flow solution based computation method reasonably predicts the critical submergence for a vertical intake located in a channel with no dead-end wall. However, their method over predicted the critical submergence for horizontal intakes passing through a dead-end wall up to 80% compared to the experimental results. Taştan [4] studied the scale and flow boundary effects on critical submergence of a pipe intake. It was proposed a correction factor to include the boundary-friction effects. Most of the previous studies (Gordon [5], Reddy and Pickford [6], Gulliver and Rindels [7], and Jimming et al. [8]) presented the critical submergence as a function of Froude number of the intake as given below.

$$\frac{S_c}{D} = m + nF^a \tag{1}$$

where; m, n and a are coefficients depending on experimental conditions at which they were obtained, and F is the Froude number of the intake [$F = V/(gD)^{0.5}$; V = average intake velocity, g = gravitational acceleration]. Following equations of Gordon [5] and Gulliver and Rindels [7] from previous studies may be given as examples, respec-

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Peer review under responsibility of Ain Shams University.

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https://doi.org/10.1016/j.asej.2020.02.010
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Nomenclature

A_c	surface area of CSSS after subtracting the boundary blockages	R	Reynolds number of the pipe intake
b_1 and b_2	distances of channel side walls to the intake center	S	submergence
c	distance between intake center and channel bottom	S_c^*	experimental critical submergence for a horizontal intake
D	pipe intake diameter	S_c	critical submergence
F	Froude number of the pipe intake	U_∞	cross-sectional average velocity of incoming flow
g	gravitational acceleration	V	average intake velocity
x	a coefficient	V_c	velocity at the CSSS
l	distance between the intake center and the dead-end wall	W	intake Weber number
m, n, a	coefficients	ρ	density of the fluid
Q	intake discharge	ν	kinematic viscosity
		σ	surface tension

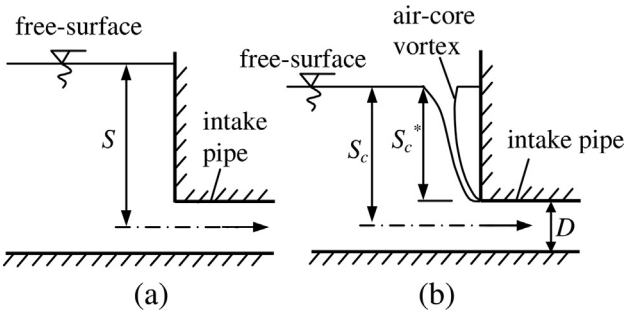


Fig. 1. Horizontal intake at dead-end wall; (a) Submergence, (b) Critical submergence.

tively. Note that these equations are valid for the cases of symmetrical and no imposed circulation flow conditions.

$$\frac{S_c}{D} = 1.72F \tag{2}$$

$$\frac{S_c}{D} = 2.5 + \frac{4}{3}F^{2/3} \tag{3}$$

Borghei and Kabiri-Samani [9], Naderi et al. [10], and Trivellato [11] studied several anti-vortex devices preventing or delaying the occurrence of air-entraining vortices. Hecker [12], Padmanabhan and Hecker [13] investigated the scale effects on the critical submergence at the prototype intakes. Daggett and Keulegan [14], Jain et al. [15], and Anwar and Amphlett [16] discussed the limit values of intake Reynolds and Weber numbers beyond which their effects may be neglected on the occurrence of air-entraining vortices. Taştan and Yıldırım [17], Yang et al. [18], Yıldırım [19], Eroğlu and Bahadırlı [20], and Taştan [21] studied the effects of different intake entrance geometries on the critical submergence of intakes.

Previous methods are mostly used intake Froude number (or intake Reynolds and Weber numbers) to find the critical submergence. This approach restricts the solutions to be valid for only the conditions for which they are obtained. Besides, intake Froude number based solutions introduce scale effects. On the other hand potential flow based solutions, although they are more reliable in terms of scale effects since kinematic similarity is sufficient for them as previous studies indicate [4], they fail to predict the critical submergence due to ignoring friction effects.

In the present study, a more realistic method which considers the friction and retarding effects of dead-end wall on the formation of air-entraining vortex at horizontal intakes is proposed. Proposed method is also based on potential flow assumption. Therefore, it does not require solving complete Navier-Stokes equations and it is easy to use in practice. Moreover, scale effects are also investigated and it is showed that there is no need to consider Froude, Reynolds, and Weber numbers similarities. The only similarity condition that should be met is the equality between ratios of intake velocity to radial velocity at critical spherical sink surface for both model and prototype intakes.

2. The proposed method

Yıldırım and Kocabaş [1] showed that an imaginary critical spherical sink surface (CSSS) occurs in the flow field which can be considered as the combination of intake flow (point sink) and approach flow (uniform flow) at the critical condition of a pipe intake located in a cross-flow. CSSS has identical center and discharge as the intake and radius of CSSS is equal to S_c (Fig. 2). Details related to derivation of CSSS can be found in [1].

Critical submergence of such intake can be found from the integral continuity equation presented below.

$$Q = A_c V_c$$

In which, Q = intake discharge, A_c = net surface area of the critical spherical sink surface (surface area that is left after subtracting the area intersected by solid boundaries: dead-end walls, side walls, channel bottom and intake pipe itself), and V_c = uniformly distributed (an average) radial velocity at the CSSS. Note that in reality V_c can not be uniform over the entire surface of CSSS. Sections of CSSS close to the solid boundaries should have smaller V_c

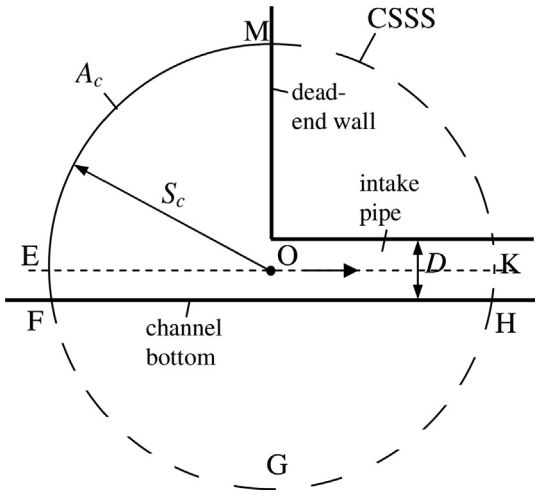


Fig. 2. CSSS for a horizontal intake.

compared to that of sections away from the solid boundaries due to no slip boundary condition at the solid surfaces. However, it is difficult to find an analytical expression for the variation of V_c over CSSS. Therefore, in the present study and previous studies as well, an average V_c ($V_c = Q/A_c$) has been used. In case of a uniform flow, Yıldırım and Kocabaş [1] calculated $V_c = U_\infty/2$ in which U_∞ = average cross-section velocity of uniform cross-flow. The agreement between this method and available experimental results for the critical submergence of a vertically downward flowing intake located in channel with no dead-end wall is good (the error is ± 10–15%) [1]. However, the same theory overpredicts the critical submergence of a horizontal intake entraining water from a dead-end wall up to 80% [2]. The reason is as follows. Potential flow assumption requires irrotational flow. However, because of the no-slip boundary condition on the dead-end wall, which is a boundary that disturbs flow at the water surface, introduces vorticity and retards the air-entrainment. Hence, potential flow solution based method overpredicts the critical submergence since V_c is taken identical as that of the case for vertically downward flowing intake with no dead-end wall ($V_c = U_\infty/2$). In fact, V_c should be much larger than $0.5U_\infty$ for these cases to satisfy the continuity equation given in Eq. (4). Due to friction effects introduced by dead-end wall on free-surface vortex, S_c and hence, A_c decreases. Therefore, to satisfy the continuity V_c should increase. In this study a coefficient obtained from the available experimental data for horizontal pipe intakes with dead-end wall is presented to find V_c in terms of U_∞ for various flow and geometrical conditions to represent the physical situation much better in the theory.

A general parameters relating to a horizontal intake and its position in a rectangular channel is given in Fig. 3.

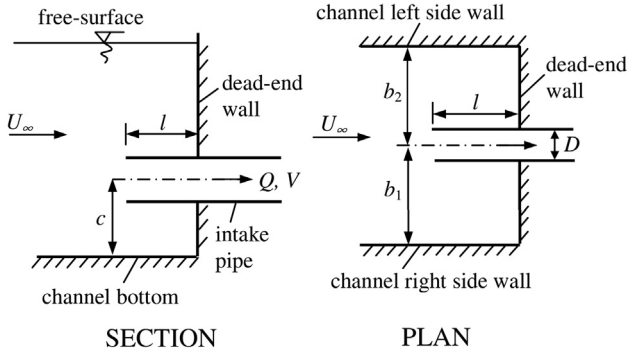


Fig. 3. Parameters related to a horizontal intake and its position in a rectangular channel.

In Fig. 3; c = distance between intake center and channel bottom, l = distance between the intake center and the dead-end wall (in this study $l = 0$), D = inside diameter of the intake, b_1 and b_2 = distances of channel side walls to the intake center, and V = average intake velocity [22]. Herein, it is considered a horizontal intake at the bottom of the channel with no clearance between the intake center and the dead-end wall as shown in Fig. 3. The available studies related to critical submergence of a horizontal intake is summarized in Table 1. Note that for all of the studies there is no imposed or induced circulation on the approach flow. Details of the experimental procedure can be found in [1–2].

In Table 1, $R = VD/\nu$ (intake Reynolds number); $W = \rho DV^2/\sigma$ (intake Weber number), where ν = kinematic viscosity of water, ρ = density of the water, and σ = surface tension.

The ranges of F, R, and W considered in this study are within the limit values of previous studies as presented in Table 2.

Hecker [12] reviewed the several prototype pump, hydropower turbine, and cooling system intakes that are in operation around the world and showed that the ranges of model scales of these prototype intakes is 1:12–1:122. The values given in Table 1 and 2 showed that the results of this study can be used for the models of prototype intakes. For example if D = 5 cm is considered as model, and D = 297 cm is considered as prototype; model scale is found as (5/297) ≅ 1/60. This value is within the limits that Hecker [12] indicated.

In Fig. 4, variation of intake discharge, Q, and A_c is shown for intakes having different diameters with $l/D = 0$ and $c/D = 0.5$. The data used in this graph contains the cases which side wall clearances (b_1/D and b_2/D) are larger than S_c/D so that CSSS is not intersected by side walls of the channel (the situations of presence of side wall boundary blockage effects will be explained little later). Net surface area of CSSS (A_c or area of spherical sector MEF) can be computed by adding quarter of a complete surface area of a CSSS with radius S_c and the spherical sector area of (EF) (Fig. 2).

Area of spherical sector (EF) can be obtained from following equations.

$$Area\ (EF) = 0.5[Area\ (EFGHK) - Area\ (FGH)] \tag{5a}$$

$$Area\ (EFGHK) = 2\pi S_c^2 \text{ and } Area\ (FGH) = 2\pi S_c(S_c - 0.5D) \tag{5b}$$

$$Area\ (EF) = \frac{1}{2}\left(2\pi S_c^2 - 2\pi S_c(S_c - 0.5D)\right) = \pi S_c 0.5D \tag{5c}$$

Then A_c is found as;

$$A_c = \frac{1}{4}4\pi S_c^2 + \pi S_c 0.5D = \pi S_c^2 + \pi S_c 0.5D = \pi S_c(S_c + 0.5D) \tag{5d}$$

Table 1
Summary of the experimental parameters related to horizontal intakes in previous studies.

Study	D (cm)	Q (lt/s)	F	R	W	b_1/D (or b_2/D)	c/D
Gürbüzdal [23]	6.12–19.72	1.43–38.85	0.51–4.03	2.96×10^4 –2.89×10^5	198–1070	1.597–5.147	0.5
Göğüş et al. [24]	5–30	6.66–62.55	0.3–10.68	1.42×10^5–6.55×10^5	842–29,102	0.67–8	0.5
Arslan [25]	5.32	0.6–8.13	0.39–5.15	1.46×10^4–1.91×10^5	58–9897	2.7–6.7	1
Yıldırım et al. [2]	5.32	1.33–10.13	0.83–6.31	3.12×10^4–2.38×10^5	264–15,335	4.7	1–2

Table 2
Parameters related to prototype intakes reported in various studies.

Study	Intake Type	D (m)	Q (m^3/s)	F	R	W
Gulliver and Rindels [7]	Prototype hydropower turbine intake	2.97	17.53	0.47	7.4×10^6	2.64×10^5
Iversen [26]	Prototype pump intake	0.46	0.164	0.46	4.5×10^4	6.26×10^3
Sweeney et al. [27]	Prototype cooling system intake	2.95	12.5	0.34	5.3×10^6	1.37×10^5

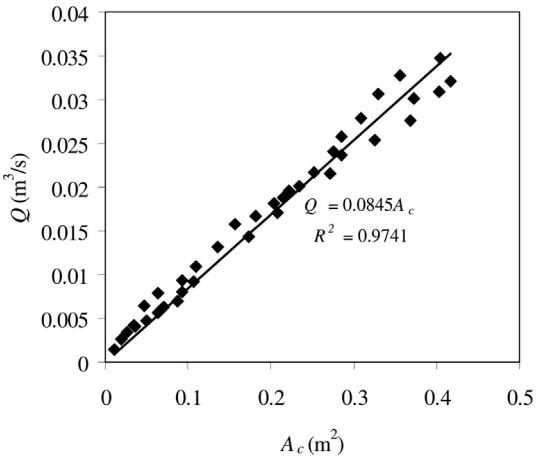


Fig. 4. Variation of Q with A_c for different intake diameters ($S_c/D < b_1/D$ and $S_c/D < b_2/D$) (Test data is taken from Gürbüzdal [23]).

As it is seen from Fig. 4, no matter what the diameter of the intake pipe is, the relationship between intake discharge and net area of CSSS can be considered as linear which means slope of this line, V_c, is a constant (correlation coefficient R^2 = 0.97 and V_c = 0.0845 m/s). Data of Fig. 4 is taken from the experiments given in Gürbüzdal [23].

Since V_c is a radial velocity at an imaginary critical spherical sink surface, it is not easy to measure in experiments or in practice. Therefore, in this study, it is looked for a relationship between V_c and more easily computable or measurable U_∞ as presented in Eq. (6). In this way, it will also be easier to compare the present study and the study of Yıldırım et al. [2].

$$V_c = xU_\infty$$

In which, x is a dimensionless coefficient and it can be obtained from experiments as indicated in Fig. 5.

In Fig. 5, relationship between x and Q is found to be as follows.

$$x = 0.1518Q^{-0.4614} \quad \left(R^2 = 0.9823\right) \tag{7}$$

The value of x approaches to 0.5 as Q increases, which is the value when no dead-end wall is existed as previous studies indicate (Yıldırım [1], Yıldırım et al. [2]; $V_c = 0.5U_\infty$ and x = 0.5). This supports the findings of this study. The reason is, as the intake discharge increases inertial forces applied by intake flow on the fluid

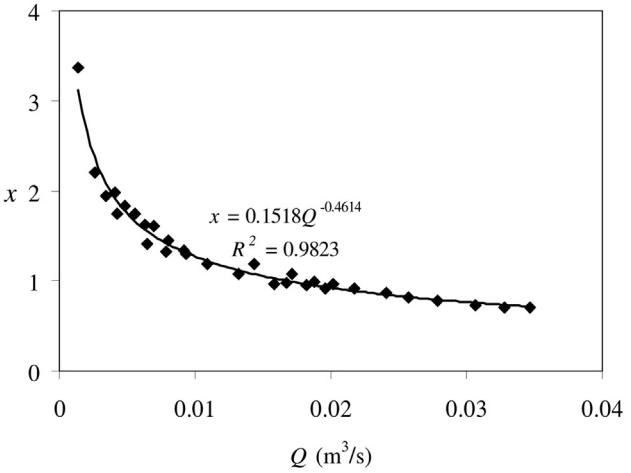


Fig. 5. Variation of x with Q for the data presented in Fig. 4.

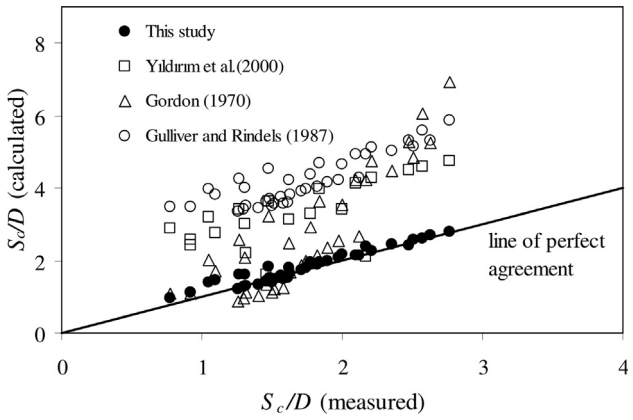


Fig. 6. Comparison of experimental and theoretical results.

particles close to the dead-end wall starts to dominate the friction forces introduced by the dead-end wall, that is why the agreement between results of the method of Yıldırım et al. [2] and experimental results becomes little better as Q increases (Fig. 6). However, for smaller intake discharges since the friction effects is still larger compared to inertial forces due to intake flow, Yıldırım et al. [2] method overpredicts the critical submergence significantly.

In Fig. 6 comparison of available experimental results with several theoretical studies are made. As it can be seen from this figure the method presented in this study agrees well with available experimental results of [2,23–25]. The error which is defined as the deviation between the results of the suggested method and the available experimental results (or deviation from the line of perfect agreement) is found as approximately ±10%.

The solution steps for determining the critical submergence requires a trial–error procedure, that is as follows.

- Select a value for S_c.
- From scaled drawings or, if it is possible, from geometrical calculations find A_c.
- Compute U_∞ from continuity equation (U_∞ = intake discharge/channel cross section area).
- Read x from Fig. 5.
- Check whether Eq. (4) is satisfied or not.
- If Eq. (4) is not satisfied repeat the whole procedure by selecting a new S_c.

Note that if A_c can be found explicitly from geometrical calculations as in Eq. (5), there is no need to perform a trial–error procedure, S_c may be readily found from Eq. (4).

3. Effects of side wall clearances

Previous discussion is related to the cases b_1/D and b_2/D are larger than S_c/D. Therefore, CSSS is not intersected by the side walls of the channel. It is known that formation of an air-core vortex is very sensitive to disturbances present within the surface flow. Side walls, similar to dead-end walls, are the boundaries that create no-slip boundary condition at the free-surface. However, for most of the cases (excluding the cases where clearances of the side walls to the intake is very small, i.e, b_1/D or $b_2/D \approx 1$) since the path of the vortex is away from the side walls, their friction effect is not significant as that of dead-end wall with l = 0. Therefore suggested method should also give acceptable results. To prove this, data of the cases for $b_1/D < S_c/D$ or $b_2/D < S_c/D$ is presented in the variation of Q and A_c as shown in Fig. 7. For this situation A_c is not easily computable as in Eq. (5), however it can be calculated by scaled drawings or equations presented in Yıldırım et al. [2].

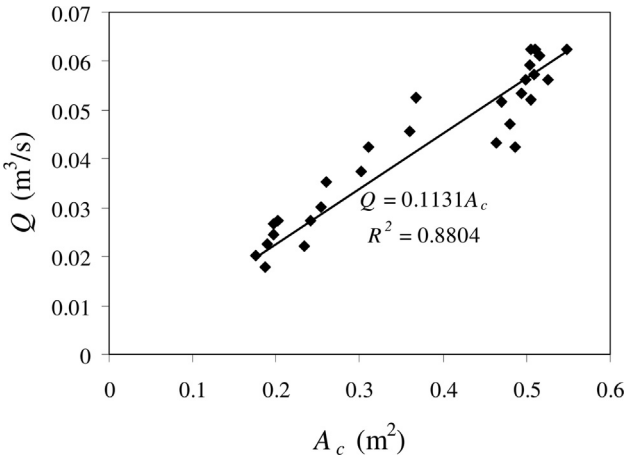


Fig. 7. Variation of Q with A_c for different intake diameters ($b_1/D < S_c/D$ and $b_2/D < S_c/D$) (Test data is taken from Göğüş et al. [24], and Zaloğlu [28]).

As it can be seen from Fig. 7 the variation of Q and A_c can still be considered as linear ($R^2 = 0.8804$ and $V_c = 0.1131$) but the slope of this linear line, V_c, is equal to a different value. From the experimental data it can be said that value of V_c is very close to the case where no side wall effect is present until b_1/D or $b_2/D < 0.5(S_c/D)$. Reasons that the relationship between Q and A_c moves away from the linearity when it is compared to case with no side wall effects are as follows. First of all, as side wall clearance decreases friction effects due to side walls on the formation of the air-entraining vortex increases. Total friction effects of both dead-end wall and side walls become complex and this linear relationship starts to spoil. Second of all, as the side wall clearance decreases and the pipe diameter increases, intake flow may not be considered as point sink anymore. Since the theory presented in this study is based on the assumption of point sink flow for intake flow, theoretical results may not perfectly agree with experimental results.

4. Scale effects

In most of the previous studies it was tried to construct a relationship involving Froude (or Reynolds and Weber numbers) of the intake to find the critical submergence. Fig. 8 shows the variation

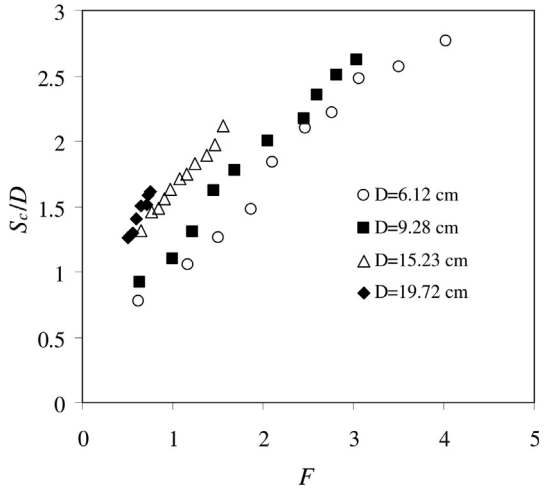


Fig. 8. Variation of F with S_c/D for different intake diameters (Test data is taken from Gürbüzdal [23]).

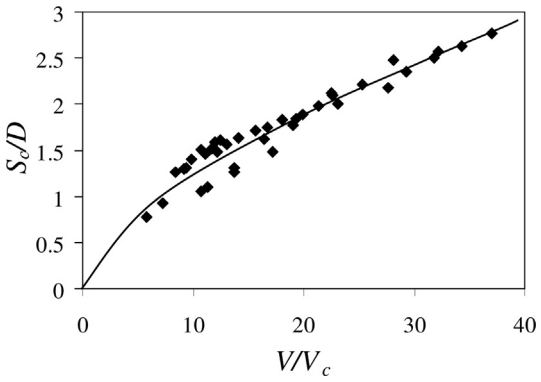


Fig. 9. Variation of S_c/D with V/V_c for different intake diameters (Test data is taken from Gürbüzdal [23]).

of critical submergence with Froude numbers for different diameter intakes. Scale effect is clearly seen in this graph. Similar graphs can also be drawn based on Reynolds and Weber numbers.

Taştan and Yıldırım [29] and Taştan [4] showed that for similarity between model and prototype intakes in terms of critical submergence, only the kinematic similarity, which is the equality of V/V_c for model and prototype, is sufficient. In Fig. 9 variation of S_c/D with V/V_c is presented for horizontal intakes having various diameters and subjected to different flow conditions. Scale effects almost diminish as the data for all the different diameter intakes approximately fall on the same curve.

5. Conclusions

In this study, a method based on the assumption of potential flow is proposed to find the submergence at which air entrainment just starts for a horizontal pipe intake. Proposed method gives better results compared the ones given in previous studies. Summary of the conclusions drawn from the present study is given as follows.

- It is shown that for a horizontal pipe intake with dead-end wall, velocity at the imaginary spherical sink surface which has the identical center and discharge as the real intake can not be taken equal to the case for a vertical intake with no dead-end wall.
- Velocity at CSSS is associated with approach flow velocity which is easier to measure or compute.
- Relationship between the intake discharge and the net area of CSSS may be thought as linear for the cases having different diameters in this study. Therefore V_c can be considered as a constant.
- Side wall effects increase as dimensionless clearances of side walls to the intake becomes less than dimensionless critical submergence. Even with the side wall effects V_c still be taken as constant (but error is higher compared to cases with no side wall effects).
- Froude (or Reynolds and Weber numbers) based similarities introduce scale effects. However, for the range of horizontal pipe intake diameters considered in this study, equality between ratios of intake velocity to radial velocity at imaginary sink surface for both model and prototype is sufficient for the similitude.
- For the future studies it is proposed that experiments should be conducted with dimensions close to the prototype values to test the method given in this study.

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