Experimental Study of the Influence of Different Weir Types on the Rate of Air Entrainment

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Aeration is used in water treatment to alter the concentration of dissolved gases, to strip volatile organics, and to reduce tastes and odours. This can be obtained by creating turbulence in the water. One method of producing such turbulence is via the overflow jets downstream of weir structures. This paper investigates the effect of varying weir types on the air entrainment rate. Empirical correlations predicting the maximum penetration depth and air entrainment rate were developed for different weir types. It is demonstrated that the air entrainment rate of the broad-crested weirs is generally much better than for the sharp-crested weir and the labyrinth weirs. The air entrainment rate increased as the weir longitudinal slope of the broad-crested weirs and the weir sill slope of the labyrinth weirs became larger.

Key words: air entrainment, aeration, weir, penetration depth, water jet expansion

Introduction

The flow over a weir could be classified as a free jet, as shown in Fig. 1. The free jet plunging into a downstream water pool causes entrainment of the air bubbles if the free jet velocity exceeds a certain critical value and hence aeration occurs. Aeration has a large number of uses in water treatment. Listing the more usual, these are:

- to increase the dissolved oxygen content of the water;
- to reduce tastes and odours caused by dissolved gases in the water, such as hydrogen sulphide, which are then released; and also to oxidize and remove organic matter;
- to decrease carbon dioxide content of a water and thereby reduce its corrosiveness and raise its pH value;
- to oxidize iron and manganese from their soluble states to their insoluble states and thereby cause them to precipitate so that they may be removed by clarification and filtration processes; and
- to remove certain volatile organic compounds (Twort et al. 1994).

A substantial number of research workers have studied the increase of dissolved oxygen in weirs and cascades. Gameson (1957) was the first to report on the aeration potential of weirs in rivers. Since then a number of laboratory investigations into weir aeration have been carried out,
notably Van der Kroon (1969a,b), Apted and Novak (1973), Avery and Novak (1978), and Nakasone (1987). Investigations also have been reported on the aeration performance of existing hydraulic structures and these are reviewed by Wilhelms et al. (1992), Chanson (1995), Ervine (1998), and Gulliver et al. (1998). Wormleaton and Soufiani (1998) and Wormleaton and Tsang (2000) studied aeration performance of triangular and rectangular labyrinth weirs and showed that these weirs do have improved aeration characteristics over straight weirs. All of these works have dealt with the increase of dissolved oxygen by means of hydraulic structures and have not specifically discussed the air entrainment rate, $Q_A$, of different weir types.

Baylar and Emiroglu (2002) investigated sharp-crested weirs having different cross-sectional geometry (rectangular sharp-crested weirs, triangular sharp-crested weirs, trapezoidal [Cipolletti] sharp-crested weir, and semi-circular sharp-crested weir) and their effect on the air entrainment rate. They demonstrated that the air entrainment rate of the triangular sharp-crested weir is better than for the other sharp-crested weir shapes.

This paper describes an experimental investigation into air entrainment rate of:

(a) $90^\circ$ triangular sharp-crested weir (Fig. 2a);
(b) $90^\circ$ triangular broad-crested weirs with the weir longitudinal slope varying from $0^\circ$ to $6^\circ$ in $3^\circ$ steps (Fig. 2b); and
(c) 90° triangular labyrinth weirs with the weir sill slope varying from 22.5° to 45° in 22.5° steps (Fig. 2c).

Weirs constructed from a sheet of metal or other material so that the jet, or nappe, springs free as it leaves the upstream face are called sharp-crested weirs (Streeter and Wylie 1983). A broad-crested weir is by definition a structure with a horizontal crest above which the fluid pressure may be considered hydrostatic (French 1986). Labyrinth weirs are those for which the weir crest is not straight in planform (Wormleaton and Soufiani 1998).

**Air Entrainment Mechanisms—Classification**

Ervine et al. (1980) stated that plunging jet flows entrain air into the receiving pool when the impact velocity of the jet exceeds a critical value. The inception velocity for a turbulent water jet is commonly observed to be about 1 m/s, but is affected by the size of disturbances on the surface of the jet. Ervine et al. (1980) suggested four mechanisms for air entrainment depending on circular water jet turbulence. Tsang (1987) adapted these to the current observations of overfall jets from normal and parallel weirs. Tsang (1987) classified mechanisms of air entrainment as: A—

![Fig. 2. Definition sketches of weirs: (a) triangular sharp-crested weir, (b) triangular broad-crested weir, and (c) triangular labyrinth weir.](image-url)
smooth, B—rough, C—oscillating, and D—disintegrated. A description of these stages is given in the following sections.

A) Smooth, Solid Jets

The major source of air supply is visualized as a thin layer surrounding the jet and carried into the water upon impact, and therefore air entrainment capacity is limited. The water surface in the receiving pool is relatively undisturbed (see Fig. 3a).

B) Rough, Solid Jets

The air supply can be considered as coming largely from small air pockets entrapped between the jet surface roughness and the receiving water. At impact, the jet produces ripples on the pool surface. Compared to the type A mechanism under similar conditions, this results in shallower bubble penetration depth but increased entrainment rate, because the bubbles are more densely packed in the biphasic zone (see Fig. 3b).

C) Oscillating Jets and those Approaching Disintegration

The primary air source originates from large air pockets entrapped between the undulating jet and the pool surface. The pool surface is considerably agitated, and air may also be entrained by surface roller and splashing. Large air pockets are transported from the surface into the water and broken down due to turbulence (see Fig. 3c).

Fig. 3. Bubble generation mechanisms by overfall jet from weir.
D) Disintegrated Jets

The pool surface is intensely agitated, and air is entrained by the action of surface rollers and by engulfing air pockets as jet fragments hit the pool surface. The bubbles are generally only transported to relatively shallow depths (see Fig. 3d). Disintegrated jets have the advantage over solid jets of greater surface area; however, $Q_A$ and bubble penetration are significantly reduced because of energy loss to the surrounding atmosphere during fall (Wormleaton and Tsang 2000).

Factors Affecting Air Entrainment Rate

The variation in air entrainment rate, $Q_A$, of weirs is sensitive to weir type, drop height, weir discharge, and tailwater depth.

Weir Type

The aeration of water downstream of weirs is caused by air being carried by the overfall jet into the downstream receiving pool. The precise mechanism by which the air is entrained into the pool is extremely complex and varies with jet velocity and geometry. The shape of weir dictates the behaviour of the jet. This in turn is believed to alter the air entrainment and contact time in both the jet itself and the downstream receiving pool, and hence, aeration performance of the weir as a whole.

Drop Height

Air entrainment that occurs at weirs is sensitive to drop height across the structure. Initially, a nappe with a relatively smooth surface issues from the weir and air entrainment takes place mainly at the surface of the downstream water pool. As the drop height increases, the surface of the nappe first becomes roughened and then begins to oscillate during fall, entraining air. This results in greater air flow into the downstream water pool. With increasing drop height, the nappe eventually breaks up into discrete droplets. The breakup of the nappe reduces air entrainment.

Weir Discharge

The air entrainment for weirs varies with discharge. At low discharges, breakup of the jet is observed as drop height increases. This leads to reduced air entrainment into the downstream water pool. At high discharges, air entrainment increases with drop height up to a certain point and then decreases with a further increase of drop height because the jet breaks up into discrete droplets.

Tailwater Depth

Tailwater depth can affect aeration efficiency of a falling jet, because oxygen mass transfer is to some degree dependent upon the residence
time of the oxygen bubbles in the water. If the downstream water pool is less than the bubble penetration depth, the bubbles’ flow path through the water will be curtailed by the bed of the pool and residence time, and hence aeration efficiency will be limited. However, there is a limit in tail-water depth because the penetrating air bubbles will not go to infinite depths. For each combination of discharge and fall height, there is an approximate maximum depth to which the bubbles penetrate.

**Experimental Investigation**

**Apparatus**

Laboratory experiments were carried out with: (a) a triangular sharp-crested weir ($\alpha = 90^\circ$), (b) triangular broad-crested weirs ($\alpha = 90^\circ$) with the weir longitudinal slope $\beta$ varying from 0° to 6° in 3° steps, and (c) triangular labyrinth weirs ($\theta = 90^\circ$) all having the same total sill length of 0.30 m and with the weir sill slope $\phi$ varying from 22.5° to 45° in 22.5° steps.

The dimensions of these weirs tested are given Table 1. Each weir configuration was tested under flow rates $Q$ varying from 1.0 to 4.0 L/s in 1-L/s steps. The drop height, $H$, defined as the difference between the water levels upstream and downstream of the weir, was varied between 0.20 to 1.00 m in 0.20-m steps.

Experiments were carried out using an experimental apparatus in the Hydraulic Laboratory at the Engineering of Firat University, Elazig, Turkey. The experimental channel used in this study was 3.40 m long,

**Table 1. Weir geometries**

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<th>90° Triangular sharp-crested weir</th>
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<th>90° Triangular broad-crested weirs</th>
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<td>$\beta$ (°)</td>
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<th>90° Triangular labyrinth weirs</th>
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<td>$\theta$ (°)</td>
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The water jet from the test weir plunged into a downstream water pool, whose height could be adjusted using a pulley arrangement. The water in the experimental channel was recirculated by a pump. The water depth in the downstream water pool was controlled by an adjustable weir. The plan-view dimensions of the downstream water pool were 1.20 × 1.20 m.

Penetration depth, \( D_p \), of the bubbles produced by the jet, which was defined as the vertical distance from the water surface to the lower end of the submerged biphasic region in the water, was measured by a scale fitted to the downstream water pool wall. In all of the experiments for all weir types, the tailwater depth was selected greater than the maximum bubble penetration depth so that bubbles cannot reach the floor of the downstream water pool.

Since air entrainment by plunging overfall jets occurs as a localized phenomenon at the plunging point, air can be caught after it has been entrained into the downstream water pool. An air hood can be used to catch the air which is entrained into the downstream water pool. The air hood may interfere with the fluid flow in the pool. However, since the air entrainment phenomenon depends mainly on the flow in the direct neighborhood of the plunging point, an appropriate submergence and geometry of the air hood should not greatly affect the amount of entrained air. In this study, an air hood for which the plan-view dimensions were 0.75 m × 0.60 m, was used to obtain the values of \( Q_A \) using an air flow meter installed on its surface.

**Results**

The air entrainment rates, \( Q_A \), of different weir types were obtained in relation to weir discharge, \( Q \), drop height, \( H \), the weir longitudinal slope, \( \beta \), in triangular broad-crested weirs, and the weir sill slope, \( \phi \), in triangular labyrinth weirs. The following sections discuss the experimental results.

![Fig. 4. Laboratory weir aeration apparatus.](image-url)
The residence time of entrained air bubbles in a water body directly affects the oxygen mass transfer. This residence time is related to the bubble flow path and hence the bubble penetration depth into the receiving water. In this study, the effect of weir type on the penetration depth of bubbles was investigated in relation to drop height, discharge, water jet expansion at impact point, and the weir longitudinal slope, $\beta$, in broad-crested weirs and the weir sill slope, $\phi$, in labyrinth weirs. It was observed from experimental results that penetration depth is closely related to the jet shape that is unique to each weir type. Generally, water jet expansion and penetration depth increased with increase of discharge and decreased with increase of drop height, as illustrated in Fig. 5 and 6. Empirical correlations predicting maximum depth of bubble penetration were developed for each weir type. The resulting correlations are given in equations 1 to 3:

**90° Sharp-Crested Weir**

$$D_p = \exp(-0.011Q^{-0.8}H^{0.815}J_e^{0.269})$$; Correlation coefficient = 0.96  (1)

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**Fig. 5.** Variation in water jet expansion of different weir types with drop height for (a) $Q = 1 \text{ L/s}$, (b) $Q = 2 \text{ L/s}$, (c) $Q = 3 \text{ L/s}$, and (d) $Q = 4 \text{ L/s}$. 

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Fig. 6. Variation in penetration depth of different weir types with drop height for (a) $Q = 1$ L/s, (b) $Q = 2$ L/s, (c) $Q = 3$ L/s, and (d) $Q = 4$ L/s.

90° Broad-Crested Weir

$$D_p = 0.440 \left[ \frac{0.610^\beta + 2.722H^{-0.188}Je^{-0.283}}{1.594Q^{-0.251}} \right] ; \text{Correlation coefficient} = 0.85 \ (2)$$

90° Labyrinth Weir

$$D_p = \frac{3.740\cos\phi\ Q^{0.275}\ H^{0.019}}{[1.874 + 0.580 Je^{0.626}]^H} ; \text{Correlation coefficient} = 0.94 \ (3)$$

where the penetration depth, $D_p$, is in metres, the drop height $H$ is in metres, the water jet expansion at impact point, $Je$, is in metres, the discharge, $Q$, is in cubic metres per second, and the weir longitudinal slope, $\beta$, in broad-crested weirs and the weir sill slope, $\phi$, in labyrinth weirs are in degrees.

The measured penetration depths were compared with those predicted with equations 1 to 3. Good agreement between the measured penetration depth and the values computed from the predictive equations was obtained. Further confidence in the correlations is seen in Fig. 7.
Fig. 8 shows air entrainment rate, $Q_A$, of each weir type as a function of drop height, discharge, the weir longitudinal slope, $\beta$, in triangular broad-crested weirs, and the weir sill slope, $\phi$, in triangular labyrinth weirs. Fig. 9 also shows variation in $Q_A$ of weirs with drop height while the discharge is constant. Experiments with weirs indicate that the drop height is an important factor influencing $Q_A$. All of these graphs show an increase in $Q_A$ with drop height. A bigger drop height leads to greater air entrainment which increases $Q_A$.

Fig. 8 shows that weir discharge influencing air entrainment rate, $Q_A$, is closely related to weir type. The results of experiments involving differing weir discharges were far less explicit than those involving drop height. $Q_A$ increased as the discharge increased over the whole range of the weirs tested.

It was demonstrated that $90^\circ$ triangular sharp-crested weirs generally had lower values of air entrainment rate $Q_A$ than $90^\circ$ triangular broad-crested weirs and the $90^\circ$ triangular labyrinth weir with the weir sill slope of $45^\circ$. The $90^\circ$ triangular sharp-crested weir was generally shown to have greater values of $Q_A$ than $90^\circ$ triangular labyrinth weirs having the weir sill slope of $22.5^\circ$, as shown in Fig. 9. All weirs except for the $90^\circ$ triangular labyrinth weir with the weir sill slope of $45^\circ$ showed approximately similar values of $Q_A$ to each other at the lowest discharge, 1 L/s, as illustrated in Fig. 9a.

It was apparent from Fig. 9 that $90^\circ$ triangular broad-crested weirs had the highest values of air entrainment rate, $Q_A$, among all weirs tested, except for discharge of 1 L/s. The values of $Q_A$ of $90^\circ$ triangular broad-crested weirs with the weir longitudinal slope of $0^\circ$, $3^\circ$, and $6^\circ$ were in general agreement with each other at the lowest discharge, 1 L/s. $Q_A$ increased as the weir longitudinal slope became larger for $90^\circ$ triangular broad-crested weirs.

It was clear from the results in Fig. 9 that the $90^\circ$ triangular labyrinth weir with the weir sill slope of $45^\circ$ was observed to have better values of air...
entainment rate, $Q_A$, than the other weirs at the lowest discharge, 1 L/s. It was observed that the values of $Q_A$ of 90° triangular labyrinth weir with the weir sill slope of 22.5° were the lowest among all weirs tested. $Q_A$ increased as the weir sill slope became larger for 90° triangular labyrinth weirs.

![Diagrams showing variations in air entrainment rate](image-url)

**Fig. 8.** Variation in air entrainment rate with drop height and discharge for triangular weirs: (a) sharp-crested, (b) broad-crested, $\beta = 0^\circ$, (c) broad-crested, $\beta = 3^\circ$, (d) broad-crested, $\beta = 6^\circ$, (e) labyrinth, $\phi = 22.5^\circ$, and (f) labyrinth, $\phi = 45^\circ$. 
Empirical correlations predicting the air entrainment rate, $Q_A$, were developed for each weir type. The resulting correlations are given in equations 4 to 6:

**90° Sharp-Crested Weir**

$$Q_A = 0.352Q^{0.774}H^{1.235}; \text{ Correlation coefficient = 0.99} \quad (4)$$

**90° Broad-Crested Weir**

$$Q_A = 1.025\beta Q^{0.941}H^{0.709}; \text{ Correlation coefficient = 0.99} \quad (5)$$

**90° Labyrinth Weir**

$$Q_A = 0.145\cos\phi Q^{0.709}H^{1.004}; \text{ Correlation coefficient = 0.97} \quad (6)$$

where $Q_A$ is in cubic metres per second, the drop height, $H$, is in metres, the discharge, $Q$, is in cubic metres per second, and the weir longitudinal slope, $\beta$, in broad-crested weirs and the weir sill slope, $\phi$, in labyrinth weirs are in degrees.

Fig. 9. Variation in air entrainment rate of different weir types with drop height for (a) $Q = 1$ L/s, (b) $Q = 2$ L/s, (c) $Q = 3$ L/s, and (d) $Q = 4$ L/s.
The measured air entrainment rates were compared with those predicted with equations 4 to 6. The high correlation coefficient values of all weirs suggest excellent correlation. Further confidence in the correlations is seen in Fig. 10.

**Conclusions**

A series of laboratory experiments was carried out to measure the air entrainment rate of different weir types. Correlations were developed that predict the maximum bubble penetration depth, \( D_p \), and air entrainment rate, \( Q_A \), for different weir types. The following conclusions can be drawn from the experimental study:

- Experimental results indicated that water jet expansion, \( J_e \), and bubble penetration depth, \( D_p \), became different in each of the weir types. In general, water jet expansion and penetration depth increased with increasing discharge and decreased with increasing drop height.
- Weir types were found to be an important factor influencing \( Q_A \). The weir type defines jet shapes that are unique to each weir, and \( Q_A \) seems to strongly depend on these jet shapes.
- Increasing drop height and weir discharge led to higher \( Q_A \) in all weir types tested.
- The 90° triangular sharp-crested weir was generally observed to have lower values of \( Q_A \) than 90° triangular broad-crested weirs and the 90° triangular labyrinth weir with the weir sill slope of 45°.
- Values of \( Q_A \) of all weirs except for the 90° triangular labyrinth weir with the weir sill slope of 45° were in general agreement with each other at the lowest discharge, 1 L/s.
- It was observed that the values of \( Q_A \) of the 90° triangular labyrinth weir with the weir sill slope of 22.5° were the lowest among the other weir types tested.

![Fig. 10. Comparison of measured air entrainment rate values with those predicted from equations 4 to 6.](image-url)
weir types. Thus, the 90° triangular labyrinth weir with the weir sill slope of 22.5° would not be recommended for aeration processes.

- The 90° triangular labyrinth weir with the weir sill slope of 45° was observed to have better values of $Q_A$ than the other weirs at the lowest discharge, 1 L/s. The 90° triangular labyrinth weir with the weir sill slope of 45° can therefore aerate significantly better than the other weir types at low discharges. $Q_A$ increased as the weir sill slope became larger in the triangular labyrinth weirs.

- 90° triangular broad-crested weirs were shown to have substantially better values of $Q_A$ than other weir types tested except for the lowest discharge, 1 L/s. $Q_A$ increased as the weir longitudinal slope became larger in 90° triangular broad-crested weirs. Therefore, this weir type would be recommended for the purpose of aeration.

- Scaling of aeration data to prototype size is virtually impossible, largely due to the relative invariance of bubble size. The experiments described in this paper can cover discharges that are smaller than some prototype applications, although the drop heights are generally similar to prototype scale. The results indicated that the air entrainment rate in all weir types increased at all drop heights tested as the discharge increased. Clearly, tests at higher discharges should be carried out to see if this trend extrapolates.

Acknowledgements

Funding for this work was provided by Firat University Scientific Research Projects (FUBAP).

References


Received: March 11, 2003; accepted: July 8, 2003.

**Notation**

- \( b \): Crest width in triangular sharp and broad-crested weir.
- \( b_L \): Half-crest length in triangular labyrinth weir.
- \( d \): Breadth in triangular labyrinth weir.
- \( D_p \): Penetration depth.
- \( H \): Drop height.
- \( H_t \): Tailwater depth.
- \( H_w \): Difference between base and crest in triangular sharp and broad-crested weir.
- \( J_e \): Water jet expansion at impact point.
- \( L \): Experimental channel width.
- \( L_W \): Length in triangular broad-crested weir.
- \( Q \): Weir discharge.
- \( Q_A \): Air entrainment rate.
- \( s \): Difference between crest and top in triangular sharp and broad-crested weir.
- \( w \): Width in triangular labyrinth weir.
- \( \alpha \): Angle in triangular sharp and broad-crested weir.
- \( \beta \): Longitudinal slope in triangular broad-crested weir.
- \( \theta \): Included angle in triangular labyrinth weir.
- \( \phi \): Sill slope in triangular labyrinth weir.