The Role of Weir Types in Entrainment of Air Bubbles

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Abstract: The dominant aeration mechanism in free overfall jet from a weir is that of air bubbles being carried into the biphasic zone when the jet plunges into the receiving pool. The degree of aeration will depend upon the amount of air entrained. This paper investigates effect of the free overfall jets from sharp-crested weirs, broad-crested weirs, labyrinth weirs, and venturi weirs on the air entrainment. Results pointed that the air entrainment of the weirs changed depending on weir types. At low drop heights, triangular broad-crested weir had the higher values of the air entrainment rate than the other weir types tested and this advantage becomes more pronounced as the angle in triangular broad-crested weir was decreased. However, at high drop heights, the venturi weir was observed to have the greater values of air entrainment rate than the other weir types tested. The air entrainment rate increased as the throat width of the venturi weir was decreased.

Keywords: Air entrainment; Aeration; Dissolved oxygen; Water quality; Weirs.

Hava Kabarcıklarının Akım İçerisine Sokulmasında Savak Tiplerinin Rolü


Anahtar Kelimeler: Hava girişi; Havalandırma; Çözünmüş oksijen; Su Kalitesi; Savaklar.

1. Introduction

Aeration means adding air to water. The aeration of water downstream of weirs is caused by air being carried by the free overfall jets into the receiving pool. Air contains 21% oxygen and aeration adds oxygen vital to the sustained health of ponds and lakes, reversing lake degradation. Oxygen is a natural cleanser. The level of dissolved oxygen is one of the best indicators of overall water quality. Oxygen is a necessary element to all forms of life. Adequate oxygen levels are necessary to provide for aerobic life forms which carry on natural stream purification processes. As dissolved oxygen levels in water drop below 5 mg/L, aquatic life is put under stress. The lower the concentration, the greater the stress. Oxygen levels that remain below 1-2 mg/L for a few hours can result in large fish kills. Total dissolved oxygen concentrations in water should not exceed 110 percent. Concentrations above this level can be harmful to aquatic life.

2. Mechanisms of Entrainment of Air Bubbles

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- smooth; B-rough; C- oscillating; and D- disintegrated. A description of these stages is given in the following.

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.

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.

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.

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. Disintegrated jets have the advantage over solid jets of greater surface area; however, air entrainment rate \( Q_A \) and bubble penetration are significantly reduced because of energy loss to the surrounding atmosphere during fall (Wormleaton and Tsang 2000).

3. Literature Review

Air entrainment and oxygen content downstream of hydraulic structures were studied experimentally by a number of investigators. These studies were reviewed by Wilhelms et al. (1992), Chanson (1995), Ervine (1998), and Gulliver et al. (1998). Much of weir aeration works dealt with the increase of dissolved oxygen in straight weirs and free overfalls, among other structures, and none concentrated specifically on the air entrainment rate \( Q_A \) of differently shaped weirs. Recently, Baylar and Bagatur (2000 and 2006), Baylar et al. (2001a and 2001b), Baylar and Bagatur (2001a and 2001b), Baylar and Emiroglu (2002), Emiroglu and Baylar (2003a and 2003b), and Emiroglu and Baylar (2005) investigated the air entrainment downstream of the sharp-crested weirs, the broad-crested weirs, and the labyrinth weirs and demonstrated that the air entrainment changed depending on weir types. Baylar (2003) studied free overfall jets from venturi weirs and their effect on the air entrainment rate. A venturi weir was placed at the upstream channel end in order to increase the flow velocity of the free overfall jet and hence to increase the air entrainment. It was demonstrated that the air entrainment rate of the venturi weir was significantly better than for its equivalent-length linear weir and that this advantage became more pronounced as the throat width of the venturi weir was decreased. Predictive equations were derived in order to express the air entrainment rate of sharp-crested weirs, broad-crested weirs, labyrinth weirs, and venturi weirs (Table 1).
## Table 1. Predictive Equations for Air Entrainment Rate at Weirs

<table>
<thead>
<tr>
<th>Equation Source</th>
<th>Predictive Relationship</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baylar and Bagatur (2006)</td>
<td>[ Q_A = 0.171 \ h^{-0.293} \ Q^{-0.158} (\cos \alpha/2)^{-0.172} ] [ 4.598 ]</td>
<td>Triangular sharp-crested weirs</td>
</tr>
<tr>
<td>Emiroglu and Baylar (2003a)</td>
<td>[ Q_A = 2.160 \cos(\alpha/2) \ h^{1.030} ] [ 0.782 ]</td>
<td>Triangular broad-crested weirs</td>
</tr>
<tr>
<td>Emiroglu and Baylar (2005)</td>
<td>[ Q_A = 1.128 \ Q^{0.096} \ h^{1.074} ] [ 0.095 \cos(\phi) ] [ 1.154 \sin(\theta) ]</td>
<td>Triangular labyrinth weirs for [ 22.5^\circ \leq \phi \leq 45^\circ ]</td>
</tr>
<tr>
<td>Emiroglu and Baylar (2005)</td>
<td>[ Q_A = 0.0033 \ Q^{0.166} \ h^{1.955} ] [ 1.193 \cos(\theta/2) ]</td>
<td>Triangular labyrinth weirs for [ \phi = 0^\circ ]</td>
</tr>
<tr>
<td>Baylar (2003)</td>
<td>[ Q_A = 0.055 \ q^{1.097} \left( \frac{L}{h} \right)^{-1.025} ] [ \left( \frac{B}{L} \right)^{-0.605} ]</td>
<td>Venturi weirs</td>
</tr>
</tbody>
</table>

where the air entrainment rate \( Q_A \) is in cubic meters per second, the drop height \( h \) is in meters, the discharge \( Q \) is in cubic meters per second, the angle in triangular sharp-crested and broad-crested weirs \( \alpha \) is in degrees, the weir sill slope \( \phi \) and the weir included angle \( \theta \) in triangular labyrinth weir are in degrees, the unit discharge \( q \) is in \( m^3/s \), the crest width of the venturi weir \( L \) is in meters, and the throat width of the venturi weir \( B \) is in meters.

### 4. The Present Work

The aims of this paper may be summarized as follows:

- To review studies conducted by Baylar and Emiroglu (2002), Baylar (2003), Emiroglu and Baylar (2003a), and Emiroglu and Baylar (2005).
- To compare the air entrainment rate of sharp-crested weirs, broad-crested weirs, labyrinth weirs, and venturi weirs with each other.
- To determine the most suitable weir type which will be used as highly effective aerators in streams, rivers, constructed channels, fish hatcheries, water treatment plants, etc.

### 5. Experimental Setup and Procedures

#### 5.1. Experimental Installation

The data used in this study were taken from studies conducted by Baylar and Emiroglu (2002), Baylar (2003), Emiroglu and Baylar (2003a), and Emiroglu and Baylar (2005). A schematic representation of the experimental set-up used in these studies is shown on Fig. 1. The experimental set-up consisted of a water pump, a water flow meter, a flow control valve, a stilling tank, a grid baffle, a downstream channel, an exchangeable weir, a receiving pool, an adjustable weir, a release valve, a bubble trap, an air flow meter, and a return flow system.

The upstream channel used in these studies was 3.4 m long, 0.6 m wide, and 0.5 m deep with a maximum discharge of 4 L/s (Fig. 1). 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 re-circulated by a water pump. The water depth in the downstream pool was controlled by an adjustable weir. The plan-view dimensions of the downstream water pool were 1.2 x 1.2 m.

Seven sharp-crested weirs and seven broad-crested weirs investigated in this research were in shapes of rectangular, \( 30^\circ \) triangular, \( 45^\circ \) triangular, \( 90^\circ \) triangular, \( 135^\circ \) triangular, trapezoidal (Cipolletti), and semi-circular. Moreover, nine exchangeable triangular labyrinth weirs and three venturi weirs were studied in this research. The triangular labyrinth weirs had a weir included angle \( \theta \) varying from \( 45^\circ \) to \( 180^\circ \) in \( 45^\circ \) steps and a weir sill slope \( \phi \) varying from \( 0^\circ \) to \( 45^\circ \) in \( 22.5^\circ \) steps. The venturi weirs had a converging level inlet section with vertical sidewalls and a diverging level outlet.
section also with vertical sidewalls. There was the sharp connection between the converging section and the diverging section. The venturi weirs didn’t have any parallel walls forming a straight throat. The throat width of the venturi weir $B$ was varied from 5 to 15 cm in 5 cm steps. The lengths of the converging section $L_1$ and the diverging section $L_2$ were 25 and 30 cm, respectively. The venturi weirs had a vertical sidewall height $L_3$ of 15 cm. The crest width of the venturi weir $L$ was kept constant at 20 cm in all experiments. The dimensions of all weir types tested are given Tables 2 and 3.

![Figure 1. Schematic of testing flume (side view)](image1.png)

![Figure 2. Notation diagram for (a) sharp-crested weir; (b) broad-crested weir](image2.png)
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Table 2. Sharp-Crested and Broad-Crested Weir Geometries

<table>
<thead>
<tr>
<th></th>
<th>$L_c$ (cm)</th>
<th>$L_w$ (cm)</th>
<th>$b$ (cm)</th>
<th>$s$ (cm)</th>
<th>$h_w$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>60.0</td>
<td>40.0</td>
<td>20.0</td>
<td>15.0</td>
<td>35.0</td>
</tr>
<tr>
<td>30° Triangular</td>
<td>60.0</td>
<td>40.0</td>
<td>13.4</td>
<td>25.0</td>
<td>25.0</td>
</tr>
<tr>
<td>45° Triangular</td>
<td>60.0</td>
<td>40.0</td>
<td>16.6</td>
<td>20.0</td>
<td>30.0</td>
</tr>
<tr>
<td>90° Triangular</td>
<td>60.0</td>
<td>40.0</td>
<td>30.0</td>
<td>15.0</td>
<td>35.0</td>
</tr>
<tr>
<td>135° Triangular</td>
<td>60.0</td>
<td>40.0</td>
<td>48.3</td>
<td>10.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Trapezoidal</td>
<td>60.0</td>
<td>40.0</td>
<td>27.5</td>
<td>15.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Semi-circular</td>
<td>60.0</td>
<td>40.0</td>
<td>20.0</td>
<td>10.0</td>
<td>40.0</td>
</tr>
</tbody>
</table>

Table 3. Labyrinth Weir Geometries

<table>
<thead>
<tr>
<th>$\theta$ (°)</th>
<th>$\phi$ (°)</th>
<th>$b_1$ (cm)</th>
<th>$w$ (cm)</th>
</tr>
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<tbody>
<tr>
<td>45</td>
<td>0</td>
<td>15.00</td>
<td>11.48</td>
</tr>
<tr>
<td>45</td>
<td>22.5</td>
<td>15.00</td>
<td>11.48</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
<td>15.00</td>
<td>11.48</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
<td>15.00</td>
<td>21.21</td>
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<tr>
<td>90</td>
<td>22.5</td>
<td>15.00</td>
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</tr>
<tr>
<td>135</td>
<td>45</td>
<td>15.00</td>
<td>27.72</td>
</tr>
</tbody>
</table>

5.2 Range of Experiments

Each weir configuration was tested under discharges $Q$ varying from 1 to 4 L/s in 1 L/s steps. The drop height $h$ was varied between 0.2 to 1.0 m in 0.2 m steps. To ensure suitable aeration experiment conditions, the water depth in the downstream pool was maintained throughout greater than penetration depth of the bubbles produced by the overfall jet, which was defined as the vertical distance from the water surface to the lower end of the submerged biphasic region in the water.

6. Technique for Measurement of Air Entrainment

Plunging overfall jet from weirs impinges on the downstream water pool and entrains air bubbles. Since air entrainment by plunging overfall jets occurs as a local phenomenon at the plunging point, air can be trapped after it has been entrained into the downstream water pool. An air-hood was used to trap the air 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 does not greatly affect the amount of entrained air. In this study, the dimensions of the air hood were 0.75 m x 0.60 m. Experimental values of $Q_A$ were measured by using an air flow meter installed on the air hood.

7. Experimental Results and Discussion

The aeration of water downstream of weirs is caused by air being carried by the free overfall jets into the receiving pool. The precise mechanism by which the air is entrained into the receiving pool is extremely complex and varies with free overfall jet geometry, drop height, and discharge. The following sections discuss the effects of drop height and discharge on the air entrainment rate $Q_A$ of the sharp-crested weirs, the broad-crested weirs, the labyrinth weirs, and the venturi weirs.

The results indicate that drop height and discharge are important parameters influencing the air entrainment rate $Q_A$ of the sharp-crested weirs, the broad-crested weirs, the labyrinth weirs, and the venturi weirs. $Q_A$ increased with increasing drop height and discharge in all weir types. The increase in $Q_A$ with increases in drop height and discharge can be explained with the increased momentum and surface roughness of free overfall jet flow from weir, as shown in Figs. 5-8.

Air entrainment that occurred at weirs was sensitive to drop height across the structure. Initially, a nappe with a relatively smooth surface issued from the weir and air entrainment took place mainly at the surface of the receiving pool. As the drop height increased, the surface of the nappe first became roughened, entraining air as described by rough jet mechanism. This resulted in larger air flow into the receiving pool. For 30° triangular sharp-crested weir, the values of the air entrainment rate $Q_A$ increased with drop height up to a certain point and then the tendency of $Q_A$ decreased with a further increase of drop height, except in the case of discharge of 1 L/s, as illustrated in Figs. 5-8. The primary reason of this was that oscillating jet mechanism occurred in this weir type for high drop heights. Moreover, it should be noted that disintegrated jet mechanism did not occur in weir types tested.

The air entrainment rate $Q_A$ increased as the angle in triangular sharp-crested and broad-crested weirs and the throat width of the venturi weirs were decreased. For labyrinth weirs, $Q_A$ increased as the weir included angle $\theta$ and the weir sill slope $\phi$ became larger. Thus, 30° triangular sharp-crested weir, 30° triangular broad-crested weir, the triangular labyrinth weir with the weir included angle of 135° and the weir sill slope of 45°, and the venturi weir with the throat width of 5 cm were found to have the higher values of $Q_A$ than the other types tested, as illustrated in Figs. 5-8. The primary reason for these differences in $Q_A$ can be found by variation in the geometry of the jet depending on weir type.

At low drop heights, 30° broad-crested weir had the higher values of the air entrainment rate $Q_A$ than the other weir types tested, as shown in Fig. 9. However, at high drop heights, the venturi weir with the throat width of 5 cm was observed to have the greater values of $Q_A$ than the other weir types tested (Fig. 9). Moreover, the results indicated that for high discharge situations, the venturi weir with the throat width of 5 cm had the better values of $Q_A$ than the other weir types tested. The reason for this increase in $Q_A$ of the venturi weir can be found by the increased flow velocity over the venturi weir and the increased jet surface roughness of free overfall jet flow from the venturi weir.

In a practical situation, economic considerations will establish the appropriate compromise involving the crest width and the throat width of the venturi weir, drop height, and discharge, which will lead to optimum air entrainment rate $Q_A$. At wide channels, multiple weirs can be used instead of single weir. When drop height becomes greater than a certain value, the jet eventually would break up into discrete droplets. The breakup lengths would be shorter for lower discharges. The breakup of the jet would reduce its penetration depth into the receiving pool and hence also the depth of the biphasic zone. This effectively would reduce contact time between the bubbles and the surrounding water and hence also aeration efficiency. In this case, cascades would be advised instead of single fall weirs.

The 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...
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generally similar to prototype scale. The results indicated that the air entrainment rate $Q_A$ in the sharp-crested weirs, the broad-crested weirs, the labyrinth weirs, and the venturi weirs 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.

Figure 5. Variation in air entrainment rate of all weir types with drop height for $Q=1$ L/s (a) sharp-crested weirs; (b) broad-crested weirs; (c) labyrinth weirs; (d) venturi weirs
Figure 6. Variation in air entrainment rate of all weir types with drop height for $Q=2$ L/s
(a) sharp-crested weirs; (b) broad-crested weirs; (c) labyrinth weirs; (d) venturi weirs
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Figure 7. Variation in air entrainment rate of all weir types with drop height for $Q=3$ L/s
(a) sharp-crested weirs; (b) broad-crested weirs; (c) labyrinth weirs; (d) venturi weirs
Figure 8. Variation in air entrainment rate of all weir types with drop height for $Q=4$ L/s
(a) sharp-crested weirs; (b) broad-crested weirs; (c) labyrinth weirs; (d) venturi weirs
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8. Conclusions

Air entrainment due to a free overfall jet from a weir is a complex process, which depends on the geometry and hydraulics of the jet itself. The geometry of the jet is in turn dependent on that of the weir. It was observed from the results that weir type was the most important factor influencing the air entrainment rate. It was concluded that for low drop heights, broad-crested weirs had the higher values of the air entrainment rate than the other weir types tested. The air entrainment rate increased as the angle in triangular broad-crested weir was decreased. However, for high drop heights, the venturi weirs were observed to have the greater values of air entrainment rate than the other weir types tested. Decreasing throat width of the venturi weir led to higher air entrainment rate. Moreover, it was noted that the air entrainment advantage of the venturi weirs became greater at larger discharges.
Notation
B = throat width of venturi weir;
b = crest width of weir;
bL = half-crest length in labyrinth weir;
h = drop height;
h_t = tailwater depth;
h_w = difference between base and crest of weir;
L = crest width in venturi weir;
L_1 = converging length of venturi weir;
L_2 = diverging length of venturi weir;
L_3 = vertical sidewall height of venturi weir;
L_e = experimental channel width;
L_w = weir length in broad-crested weir;
Q = discharge;
Q_A = air entrainment rate;
q = unit discharge;
s = difference between crest and top of weir;
w = weir width in labyrinth weir;
α = angle in triangular sharp-crested and broad-crested weirs;
θ = weir included angle in labyrinth weir;
ϕ = weir sill slope in labyrinth weir.

References