The effect of hydraulic jump on the aeration efficiency

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Abstract

One of the most important parameters to determine the quality of water is the amount of the dissolved oxygen (DO) in water body. Microorganisms as bacteria need high concentration of oxygen in water to the able to continue their lives healthfully. In this case, the concentration of the dissolved oxygen in water body should be greater than 5 mg/L. The hydraulic jump is used as an effective natural mechanic mixer for the oxygen transfer from air to water body.

This study is aimed to investigate the aeration efficiency created by the water jet vertically on the turbulence shear layer in hydraulic jump. The experiments have been realized in an open channel having a width of 0.4 meters, a height of 0.65 meters and a length of 12 meters. The dissolved oxygen has been measured using by a DO200 hand type oxygen meter. Experiments are taken account five different jet flow rates and Froude numbers with in the range of Fr_1 = 3.55-6.07 in the study.

Introduction

Natural resources are being depleted quickly due to the rapid growth of urbanization and industrialization. Environmental pollution and consequent degradation are also increasing rapidly every day. Contamination of natural water resources are of great importance on the lives of living organisms from the viewpoint of the environmental pollution. One of the most important parameters in determining the quality of the water on Earth is the amount of oxygen dissolved in water (DO). For living organisms, the concentration of dissolved oxygen in the water must be greater than 5 mg/L to sustain their lives in a healthy way.

The water is called contaminated if the level of pollutants in a water system affects the ecological life. In particular, the depletion of the level of oxygen in a water system is mainly due to organic pollutants. Such substances are discharged into the water as a result of anthropogenic activities (i.e. household waste, animal waste, food factory waste, etc.). The sediments which is a mixture of organic and inorganic substances provide a good growth environment for bacteria and other organisms. In such an environment, microorganisms break down the organic matter in the sediment by using the dissolved oxygen in the water. In this way, the degradation of the organic matter in sediments by microorganisms using the dissolved oxygen in the water is called aerobic degradation. Since the dissolved oxygen is used in the aerobic degradation process, the concentration of dissolved oxygen in the water decreases with time. This decrease is compensated by absorbing the oxygen from the air [15].

The entrance of air takes place in any part of the flow in which the free surface turbulence began to grow, and this is the best place for the oxygen transfer. The natural aeration can be provided by areation with air bubbles, aeration with hydraulic jump, aeration of the water flowing through a spillway, oxygen transfer in stepped structures, and oxygen transfer with a free-fall water jet in a shaft system.

Hydraulic jump and oxygen recovery

In open channels, the transition from the flood regime (supercritical flows) to the the river regime (subcritical flows) occurs by the hydraulic jump phenomenon. The flow during the hydraulic jump is characterized by the large amount of air entrainment, energy loss, surface waves, and development of a large-scale turbulent structure. The large-scale turbulence region occurred during the hydraulic jump is called the vorticity region.

The high turbulent vortices occurred during the hydraulic jump are mainly created in the vorticity region (Fig. 1). These vortices are in continuous interaction with the free surface of the water. A significant kinetic enery loss in the flow occurs from the point where the hydraulic jump starts. Considering this fact, the hydraulic jump can be used in stream rehabilitation and low-impact hydraulic arrangements. Moreover, the current flood risk can be reduced by increasing the total energy loss during the hydraulic jump [14]

According to [7], the air passes into the turbulent shear region from the point where the vortiity of hydraulic jump hits the flow. A high turbulent flow occurs in this shear region. In this region, the air is divided into small air bubbles due to the high turbulence. Maximum air concentration is reached. The horizontally moving air bubbles travel from the region of high shear stress to the region of low shear stress. With the reduction of shear stress, air bubbles move towards each other and then combined to form larger bubbles. Thereafter, these large air bubbles move towards boiling and foam regions within the influence of buoyancy forces (Fig. 1).

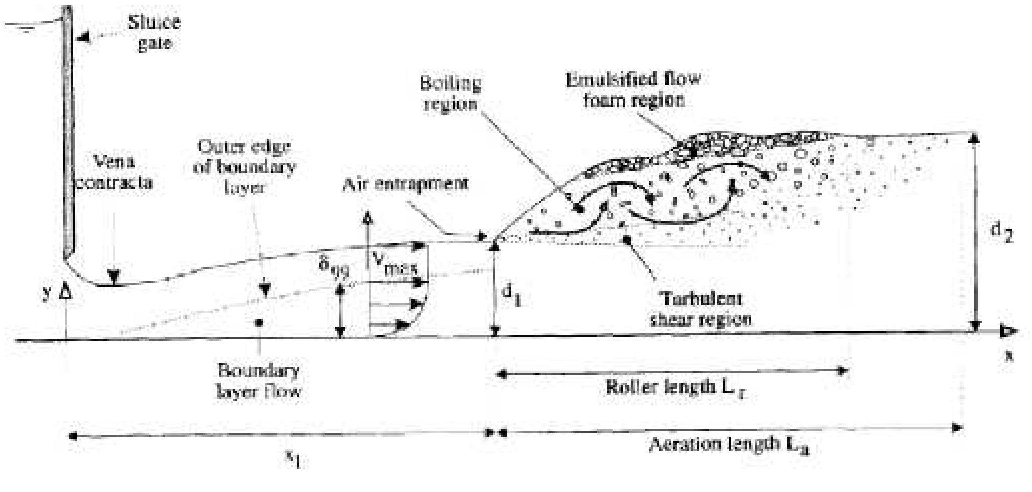


Figure 1 Aeration region in the hydraulic jump (adapted from [4]).

The macro-scale rollers in the opposite direction of the flow occurred during the hydraulic jump cause undulations in the surface of the water, resulting the absorption of air into the water from top to bottom. Additionally, the growth of macro-scale vortices in the hydraulic jump region causes an increase in the value of the turbulence diffusion coefficient and also provides a more effective physical mixture from water surface toward the bottom [17], [3].

The studies reveal that the value of the aeration length increase with the Fr_1 number during the hydraulic jump, and the mass transfer from air to water increases based on this relationship.

In addition, the amount of oxygen enters the water with air also increase with the rate of turbulence.

Natural aeratıon by hydraulıc jump

The studies of natural aeration have been generally performed on the high-slope (Jo > 0.002 m/m) hydraulic stuctures such as embankments, gates and stepped spillways. [6] [10], [5] and [4] were conducted studies on the aeration performance of the hydraulic structures.

[6] was the first researcher who studied on the oxygen transfer in hydraulic stuctures such as embankments, cascading channels and weirs. [6] who performed various measurements of dissolved oxygen concentration in the upstream and downstream, reported that the aeration performance of cascading channels and embankments were better than the others. Moreover, [6] who developed two formulations for the aeration performance, indicated that the oxygen transfer was directly related to the head loss.

[16] showed the point distribution of the amount of water in the air for different Fr_1 numbers in the hydraulic jump region. In this study, it was reported that the maximum air entrance was occurred at the beginning of the the hydraulic jump.

[12] and [2] found that the maximum air concentration and the maximum number of air bubbles were at the beginning of the the hydraulic jump. Moreover, [12] indicated that the flow conditions had a significant effect on determination of the aeration efficiency. The flow conditions reported herein were related to the status of the boundary layer thickness (δ) (Küçükali, 2006).

[11] conducted experimental studies to determine the amount of air entering to the water. The experimental results showed that the amount of entering air increased with the developing hydraulic jump, and the maximum air entrance was occurred at the beginning of the the hydraulic jump.

[4] conducted experimental studies and reviewed others on the hydraulic jump. In his own experimental study, he reported that the air-water flow in the hydraulic jump consisted of three regions such as a turbulent shear region containing small-sized air bubbles, a boiling region of large-sized air bubbles and intertwined vortices, and a foam region on the free surface.

In recent years, [13] developed a visual flow allowing the prediction of flow type (i.e. surface vortices) and the amount of entering air. Although this study provided several empirical correlations for the prediction of oxygen transfer, however, the results did not give enough idea about hydraulic jump-based air bubbles.

[1] conducted experimental studies on the oxygen transfer in the hydraulic jump and embankments. They reported that the oxygen transfer rate was related to the function of Reynolds and Froude numbers.

Physical and chemical characteristics of the water change at different temperatures. This affects the dynamics of air, gas and water. Aeration formulas are given for the standard temperatures. The formula given in [9] is used for aeration efficiency at the standard temperature. [10] revealed the gas transfer calculation in the embankments very well by using the equations given in [1].

Experimental set-up

In order to examine the oxygen transfer in open channels, the experiments were carried out in Hydraulic and Coastal Harbor Engineering Practice Laboratory Yildiz Technical University in Istanbul, Turkey. Measurements for dissolved oxygen concentration and water surface were performed by creating various hydraulic jumps along a channel with the help of vertical gates.

The experiments were conducted in a horizontal-based channel with the dimensions of 0.4 m × 12 m × 0.65 m (width, length, height, respectively). The side walls of the channel was made of glass and the channel had a rectangular cross-section.

Figure 2 A photograph of the open channel used in the experiments.

The flow was generated by providing a closed-loop water recirculation in the channel. The water was stored in a 2.8-m^3 reservoir located at the bottom of the channel, and then transferred to a 8-m^3 tank located above the channel by using a 7.5-kW pump. Thus, the circulation of water in the closed-loop system was provided (Fig. 3).

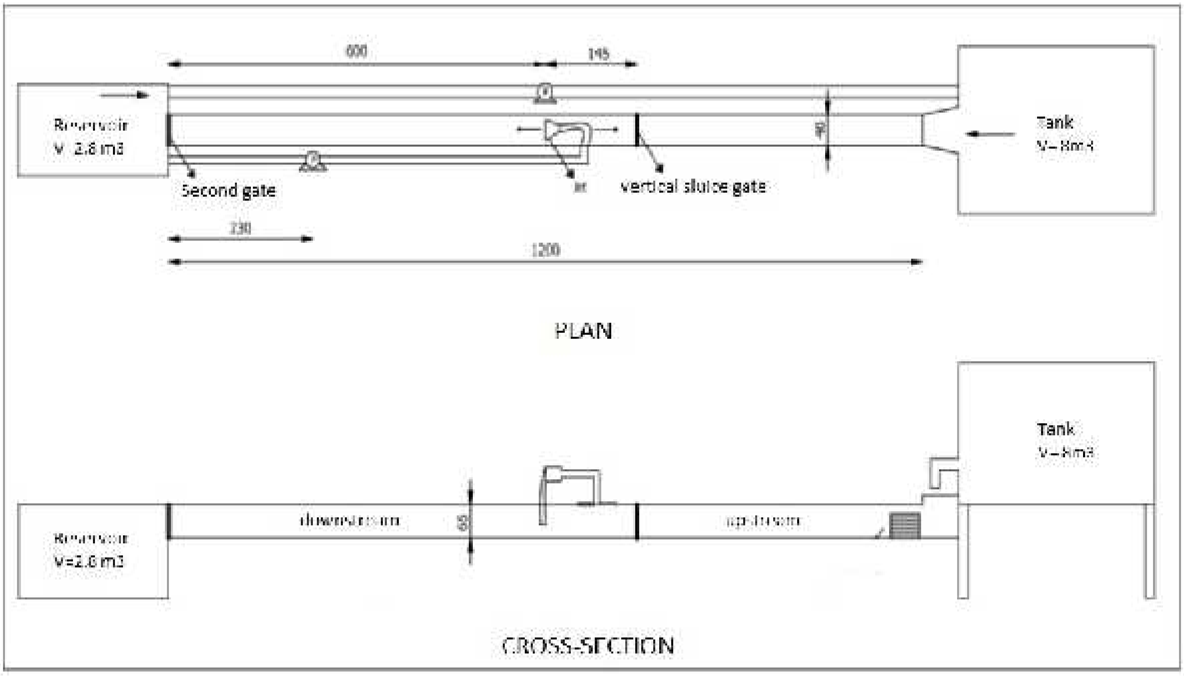


Fig. 3. A schematic of the open channel used in the experiments.

In order to create a hydraulic jump in the channel, a vertical sluice gate (0.65 × 0.40 m) made of sheet metal was placed at 4.55 m downstream side of the beginning of the channel, and a second gate was also placed at the output of the channel as a control unit.

The place of the hydraulic jump varies depending on the opening of the outlet gate. Because the outlet gate adjucts the place of the hydraulic jump and determines the value of the upsetream (Fr_1) number.

The Fr_1 number ranges within 3.55-6.07 during the hydraulic jump. The experiments were conducted in partially developed hydraulic jump conditions.

The measurements of dissolved oxygen and water temperatures was performed behind the sluice gate (SG) and after the hydraulic jump (HJ) by using oxygen meters (Fig. 4). The oxygen meters were calibrated before each experiment. The measurement ranges of oxygen meter were 0-20 mg/L for DO with an accuracy of ±2 %, and -6-46 ºC for temperature with an accuracy of ±0.3 ºC.

Fig. 4. A photograph of DO200 oxygen meter and dissolved oxygen measurement.

In order to determine the aeration efficiency during the hydraulic jump, the DO concentration of the water flow must be less than its saturation value in the water. To achieve this, sodium sulfide (Na_2SO_3) and cobalt chloride ($CoCl_2$) were added into the reservoir located at the bottom of the channel.

$$Na_2SO_3 + 1/2\ O_2 \xrightarrow{CoCl_2} Na_2SO_4 \tag{1}$$

As a result of this chemical reaction, dissolved oxygen in the water forms a new compound by reacting with sodium sulfide and this results in a decrease in the DO level of the water flow (Küçükali, 2006).

In order to find the aeration efficiency during the hydraulic jump, the DO values behind the gate and after the hydraulic jump were manually read and recorded by oxygen meter for a half-minute intervals.

The required aeration efficiency based on the arithmetic mean of temporal increase of the measured DO values is calculated by the following expression [6]:

$$E = (C_D - C_U)/(C_S - C_U) \tag{2}$$

where C_s is the oxygen concentration in the air, C_u is the oxygen concentration in the upstream, and C_u is the oxygen concentration in the downstream.

The E values calculated at different temperatures are converted to the efficiency of aeration at 20°C reference temperature by using the following equation [8]:

$$1 - E_{20} = (1 - E_T)^{1/f_T} \tag{3}$$

If E = 0, the flow does not recover oxygen. The value of E = 1 means that oxygen recovery reached its maximum value.

Experimental study

In the experimental study, the effect of different Froude numbers on the oxygen transfer was investigated in the channel flow in which the hydraulic jump is created. During the hydraulic jump, the most important parameter affecting the efficiency of aeration is the upstream Froude (Fr_1) number. In this study, partially developed hydraulic jump was created for 6 different Fr_1 numbers. Flow conditions considered in the experiments and the experimental results are given in Table 1.

Table 1 Test matrix of the experiments

Experiment No	Fr_1	H (mm)	*a* (mm)	d_1 (mm)	d_2 (mm)	E_{20}	U_1 (m/s)	T_{su} (ºC)	L_r (mm)	Q (m³/s)
1	3.55	174	19	24	92	0.044	1.72	25.5	610	$13.07.10^{-3}$
2	3.92	190	19	22	104	0.050	1.82	28.9	640	$13.83.10^{-3}$
3	4.24	270	19	24	138	0.052	2.05	25.4	770	$15.58.10^{-3}$
4	4.67	261	19	22	156	0.055	2.17	29.5	800	$16.49.10^{-3}$
5	5.16	301	19	21	183	0.060	2.34	28	865	$17.78.10^{-3}$
6	6.07	368	19	19	194	0.073	2.62	30.4	945	$19.91.10^{-3}$

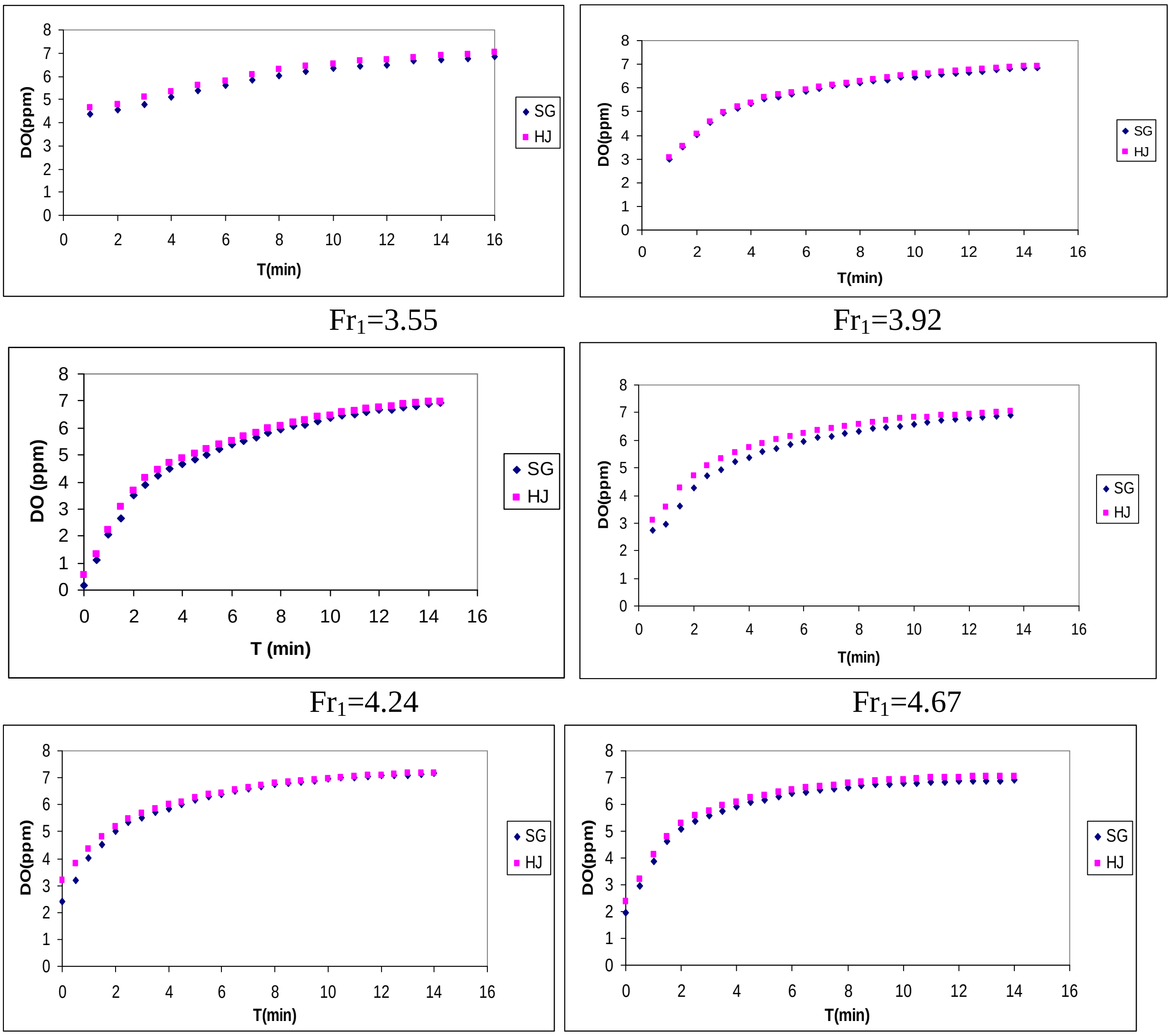
The effective dimensionless parameters obtained after the dimensional analysis can be given as follows:

$$E'_{20(1)} = f\left[(d_1/H),(d_2/H),(L_r/H),Q/(U_1H^2),Fr_1\right] \qquad (4)$$

In the experimental studies, the system was operated by adding sodium sulfide (Na_2SO_3) and cobalt chloride ($CoCl_2$) into the water in suitable amounts corresponding to volume of available water, and the amount of dissolved oxygen in the whole system was reduced to the lowest level. For both mixing of these substances thoroughly and reduction of the dissolved oxygen in the water, the system was operated for a certain period of time.

While the dissolved oxygen was consumed during this process, however, concentration of the dissolved oxygen in the initial water could not be reduced to zero due to the recovery of oxygen during the water flow through the channel and waiting in the water tank, during the transition of circulation water through the closed pipe, and during the discharge of pumped water from the pipe. For this reason, the measured values begin with a certain dissolved oxygen concentration value. The amount of dissolved oxygen in the water reaches to 90-95% of its saturation value in about 15 minutes (Figure 5).

As seen from all the graphics, although the oxygen recovery was very high within the first 5 minutes, the amount of oxygen recovery showed a decreasing trend in the measurements conducted after the first 5-minute period. In other words, the recovery of oxygen was high in the conditions of high dissolved oxygen demand in the water, but low in the conditions of low dissolved oxygen demand. Despite minor differences for Froude numbers, the change in dissolved oxygen values showed the same trend behind the sluice gate. In addition, the differences between the values of dissolved oxygen indicated the amount of dissolved oxygen recovered as a result of the hydraulic jump occured after the flow through the bottom of the gate.



Fr_1=3.55 Fr_1=3.92

Fr_1=4.24 Fr_1=4.67

Fr_1=5.16 Fr_1=6.07

Figure 5 Variation of dissolved oxygen concentration for different Froude numbers and time.

The variation of aeration efficiency (E_{20}) within the range of Fr_1 = 3.55-6.07 is depicted in Fig. 6. The E_{20} value (aeration efficiency at 20°C) increased about 14% and about 20% within the range of Fr_1 = 3.5-4 and Fr_1 = 4-5, respectively. The aeration efficiency (E_{20}) increased 65% in total within the range of Fr_1 = 3.55-6.07.

In the hydraulic jump, the value of the roller length increases with the upstream Fr_1 number during the hydraulic jump. Depending on this pyhsical development, the mass of oxygen transferred from air to water also increases with the roller length (Fig. 6).

As a result of the regression analysis conducted by the help of a statistical program (SPSS software), the following equation is obtained for conditions of B = 0.40 m and Fr_1 = 3:55 to 6:07:

$$E_{20} = 0.0014.Fr_1^2 - 0.0028.Fr_1 + 0.0384 \qquad (5)$$

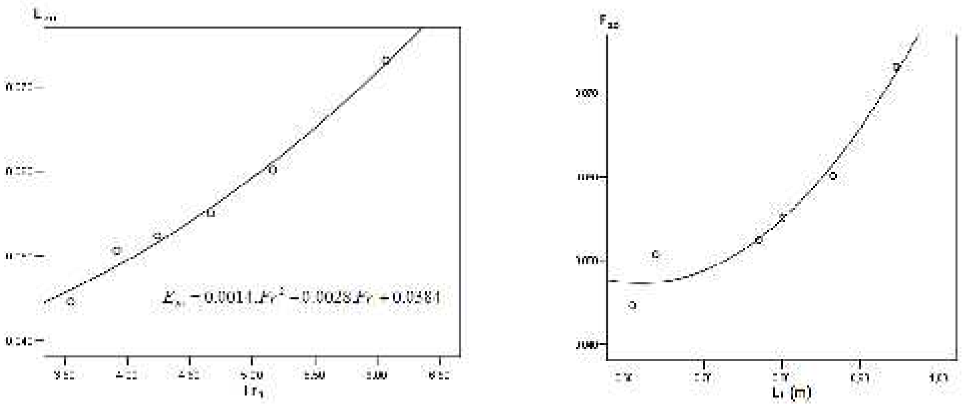


Fig. 6. Variation of aeration efficiency (E_{20}) for Froude number (Fr_1) and roller length (L_r) during the hydraulic jump.

The relative energy loss ($\Delta H / H$) increases with the increase in the value of Fr_1. This is due to the increase in surface turbulence magnitude, in addition to the formation of roller and eddies during the hydraulic jump [18]. Accordingly, the areation efficiency was also increased by the increase in the relative energy loss depending on the increase in Fr number (Figure 7).

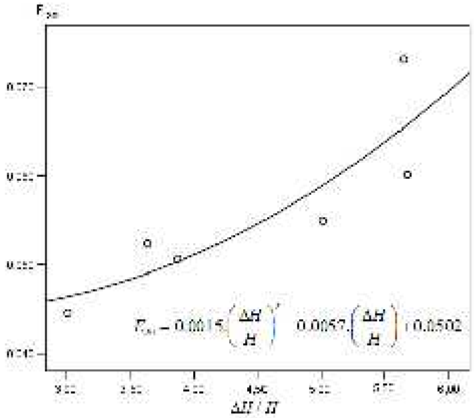


Figure 7 Variation of aeration efficiency (E_{20}) during the hydraulic jump for relative energy loss.

The aeration efficiency can be given as follows:

$$E_{20} = 0.0015.\left(\frac{\Delta H}{H}\right)^2 - 0.0057.\left(\frac{\Delta H}{H}\right) + 0.0502 \tag{6}$$

The mathematical formulation given in Eq. (6) shows that the value of aeration efficiency increases about 0.046 for per unit change in the relative energy loss.

The aeration efficiency decreases with the increase in d_1/H and L_r/H ratios (Fig. 8). This is due to the fact that the height of the water behind vertical gate (H) shows more changes than L_r and d_1 during the change in the channel current flow.

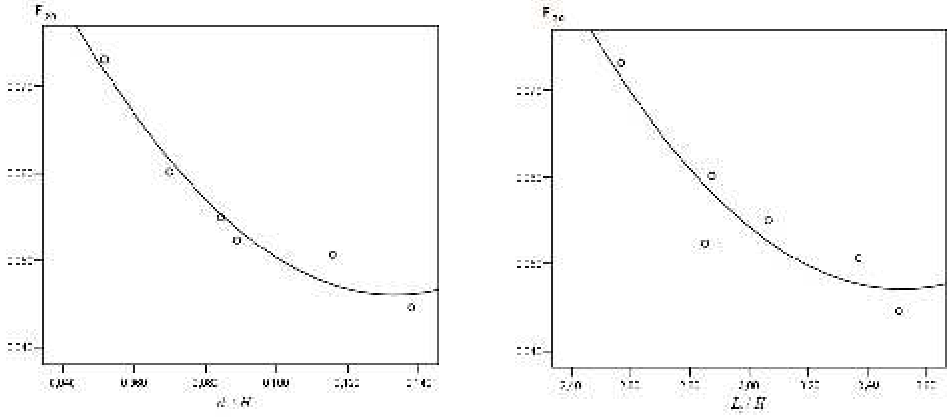


Figure 8 Variation of aeration efficiency (E_{20}) during the hydraulic jump for d_1 / H and L_r / H ratios.

As seen from all the graphics, the values of the oxygen recovery varied widely depending on the flow rates within the first 5 minutes after the measurement period of dissolved oxygen and the minimization of its relative value. This caused an oscillation in the concentration of dissolved oxygen in the water due to the oxygen consumption by the catalyst effect of sodium sulphite added to the water, as well as to the oxygen recovery during the flow of water at the same time. Irregularity of the values in the first 5 minutes may be due to this. When analysing the values of oxygen recovery after the first 5-minute period, results indicated that the amount of dissolved oxygen in water reached its saturation value in a shorter time with the increase in the Fr_1 number of flow in the main channel.

Conclusions

In this study, aeration efficiency of the hydraulic jump were investigated for six different Fr_1 numbers between 3:55 and 6:07 in an open channel having a width of 0.40 m. The results and recommendations obtained as a result of the experiments can be summarized as follows:

1. During the flow in the main channel, the concentration of dissolved oxygen measured behind the sluice gate and after the hydraulic jump increased rapidly within the first 5 minutes (increase in dissolved oxygen recovery), but showed a decrease with time after 5 minutes.
2. The dissolved oxygen deficit in the water is proportional with the dissolved oxygen recovery. In other words, dissolved oxygen recovery decreases with the increase in the amount of dissolved oxygen in water.
3. In the measurements performed with different Froude numbers, the hydraulic jump was found to be effective on the increase in the amount of dissolved oxygen in the water. The aeration efficiency (E_{20}) increased around 65% within the range of Fr_1 = 3.55-6.07.
4. With the increase in the Fr_1 number of the flow in the main channel, the amount of dissolved oxygen in water reached its saturation value in a shorter time.
5. The aeration efficiency increased with the relative energy loss. The value of this change was measured as 0.046 of increase in the aeration efficiency per unit of relative energy loss.

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