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THE EFFECT OF MEAN AIR CONCENTRATION ON THE AERATION EFFICIENCY IN SKIMMING FLOW

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ABSTRACT:

The flow over stepped chutes can be classified into skimming flow regime, transition flow regime, and nappe flow regime. The aeration efficiencies of the three flow regimes differ significantly due to the different air entrainment mechanisms in the nappe, transition, and skimming flow regimes. It is well known that aeration efficiency increases in the stepped chutes due to earlier self-aeration and slower flow velocities compared to the smooth chutes. This paper investigates the aeration efficiency of stepped chutes, particularly the effect of mean air concentration. The results showed that mean air concentration had a significant effect on aeration efficiency. They also showed that the aeration efficiency increased as the mean air concentration increased. A design equation was also developed to predict the aeration efficiency in the stepped chutes as a function of mean air concentration and roughness Froude number.

1. INTRODUCTION

In a stepped chute, the chute face is provided with a series of steps, from near the crest to the toe. The provision of steps can result in significant energy dissipation. Stepped chutes are commonly used for gabion weirs, river training, irrigation channels, storm waterways, and RCC dams. Stepped chutes are also used for in-stream aeration and in-water treatment plants to improve the air-water transfer of atmospheric gases (e.g., oxygen, nitrogen) and volatile organic compounds (VOCs).

Stepped chute flows are characterized by strong turbulent mixing, long residence time, and significant air bubble entrainment. Stepped flows can be classified as skimming flow, transition flow, and nappe flow. For narrow steps or larger discharges such as the design discharge, the water skims over the step corners and recirculation zones develop in triangular niches formed by the step faces and the pseudo-bottom, as shown in Figure 1.

Skimming flow is a condition where water flows down the stepped surface in a reasonably coherent stream above a line connecting the step tips. The zones within the triangular spaces below this virtual or pseudo-bottom contain recirculating eddies which are kept stable by the exchange of energy with the skimming flow in an intense shear layer just above the step tips. The steps behave as macro-roughness elements and are important for the dissipation of energy along the slope as well as being responsible for increasing the self-aeration of the flow relative to that of a smooth chute with a similar slope and specific discharge (USBR, 2015).

Four regions can be observed in a skimming flow regime: (1) the unaerated region near the crest, (2) the partially developed aerated flow region beginning at the inception point, (3) the fully developed aerated flow region, and (4) the uniform flow region where the depth, velocity, and air concentration are in equilibrium. Near the crest, the water has a smooth appearance described by the drawdown curve and the flow is not aerated. Above the bottom of the chute, turbulence is created, and the boundary layer grows until it reaches the surface. At the point where the outer edge of the boundary layer reaches the surface, the turbulence has become large enough to initiate natural free surface aeration, and the location of the start of air entrainment is called the inception point. In the partially developed aerated flow region, the air is entrained near the water surface but does not reach the bottom of the chute. In the fully aerated uniform flow region, an important feature is the evaluation of the clear water depth. Both the aerated depth measured through the chute sidewalls and the characteristic depth Y_{90} show a wave pattern of decreasing amplitude along the chute, but this is not observed in the equivalent clear water depth. The equivalent clear water depth is much smaller than Y_{90} because of both entrained and entrapped air at the depth where the air concentration is equal to 90 percent (USBR, 2015). After the fully developed aerated flow region, a mixture of water and air prevails (white water), and the flow only reaches uniform equilibrium if the chute is long enough. Once the equilibrium is reached, the velocity distribution, air concentration, and flow depth will not vary downstream of the structure (Llano, 2003).

The air concentration distribution in the skimming flow on stepped chutes is like that in the self-aerated flow on smooth chutes. The amount of air entrained in the flow is usually defined in terms of the mean air concentration (the mean void fraction). Uniform or equilibrium flow conditions are important in predicting the mean air concentration in skimming flow down a stepped chute. Uniform flow is achieved at the point on the spillway chute where the incremental flow depth, velocity, and air concentration are essentially constant. Several researchers have shown in model and prototype chute studies that the mean air concentration of a stepped chute is very similar to that of a smooth chute once uniform flow is achieved. They found that the equilibrium mean air concentration is only a function of the slope (USBR, 2015).

Water quality and its improvement are closely linked to the presence of dissolved oxygen. The concentration of oxygen in surface waters is a key indicator of the water quality for human use and for aquatic biota. The physical process of transferring or absorbing oxygen from the atmosphere serves to replenish the oxygen used. This process is known as re-aeration or aeration. The use of macro-roughness to enhance aeration is well-known in water treatment and one form is the stepped chute. Stepped chutes are used in water treatment for re-oxygenation, denitrification, or removal of volatile organic compounds. In drinking water treatment, stepped chute aeration can be used to remove chlorine and to eliminate or reduce unpleasant taste and odor. In summary, stepped chutes are a very efficient means of aeration due to the high turbulent mixing, long residence time, and substantial air bubble entrainment (Toombes and Chanson, 2000).

The hydraulic design of stepped chutes, and in particular, the characteristics of nappe flow, transition flow, and skimming flow over stepped chutes has been studied experimentally by a few researchers. Recently, Toombes and Chanson (2000, 2005), Chanson and Toombes (2002), Baylar and Emiroglu (2003, 2004, 2005), Emiroglu and Baylar (2003a, 2003b, 2006), Baylar et al. (2006, 2007a, 2007b, 2009, 2011a, 2011b), Felder and Chanson (2015), Erpicum et al. (2016), Zhang and Chanson (2017), Abas et al. (2017), Bung and Valero (2018), Salmasi et al. (2021), Nina et al. (2022) and Puri et al. (2023) have carried out some detailed studies on the stepped chute aeration.

It is important to predict the aeration efficiency in stepped chutes as they are used for re-oxygenation in most water treatment applications. A comprehensive review of the literature reveals that no study has investigated the effect of mean air concentration on aeration efficiency in stepped chutes for the skimming flow regime. The purpose of this paper is to investigate the effect of mean air concentration on aeration efficiency in stepped chutes for a skimming flow regime.

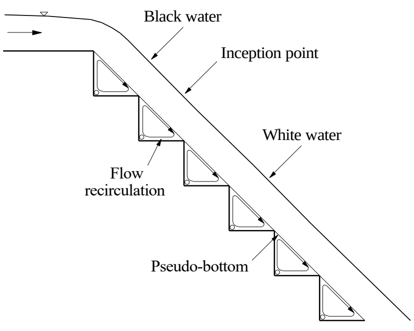


Figure 1. Skimming flow regime

2. BACKGROUND

In the skimming flow regime, self-aeration begins at the free surface when turbulent forces overcome the surface tension and the bubble's rising velocity. The local air concentration C is defined as the time-averaged value of the volume of air per unit volume of air and water. In the stepped chute, the local air concentration, the longitudinal velocity of the air-water flow, and the size of the air bubbles are measured with a double-fiber optical probe at various cross-sections in partially and fully developed aerated zones. The mean air concentration (the mean void fraction) is defined as:

$$C_{mean} = \frac{1}{Y_{90}} \int_0^{Y_{90}} C\, dy \quad (1)$$

Where: y is measured perpendicular to the pseudo-bottom formed by the step edges and Y_{90} is the depth at which the mean air concentration is 90 %.

Hager (1991) showed that mean air concentration is only a function of the chute slope angle and presented a simplified equation for predicting the mean air concentration in uniform flow:

$$C_{mean} = 0.75\,(\sin\alpha)^{0.75} \quad (2)$$

Chanson (1997) also developed an equation to predict the mean air concentration in uniform flow:

$$C_{mean} = 0.90 \sin\alpha \quad (3)$$

In stepped chutes, the oxygen transfer is enhanced by the aeration of the flow, the strong turbulent mixing, and increased residence time. The latter results from a lower flow velocity than in smooth chutes for the same flow rate. Many entrained air bubbles increase the air-water interface area due to the cumulative bubble surface area. For example, if the mean bubble diameter is 1 mm and the air content is 10 %, the specific interface area is 600 m^2 per cubic meter of air and water (Chanson, 2002).

For a hydraulic structure, the overall oxygen transfer can be measured by the deficit ratio defined as:

$$r = \frac{C_s - C_u}{C_s - C_d} \quad (4)$$

Where: r is deficit ratio, C_s is saturation concentration, C_u is dissolved oxygen concentration upstream of stepped chute and C_d is dissolved oxygen concentration downstream of stepped chute. Another measure of aeration is the aeration efficiency as defined by Gulliver et al. (1990):

$$E = \frac{C_d - C_u}{C_s - C_u} = 1 - \frac{1}{r} \quad (5)$$

Where: E is aeration efficiency at actual water temperature.

A transfer efficiency value of 1 means that the full transfer up to the saturation value has occurred at the structure. No transfer would correspond to E=0. The saturation concentration in distilled, deionized water can be obtained from charts or equations. This is an approximation as the saturation DO concentration for natural water is often different from that of distilled, deionized water due to salinity effects.

Comparative assessment of oxygen uptake by hydraulic structures requires the aeration efficiency to be corrected to a reference temperature. To provide a uniform basis for comparing measurement results, the aeration efficiency is often normalized to a 20 °C standard. Gulliver et al. (1990) proposed the following equation to describe the effect of temperature:

$$1 - E_{20} = (1 - E)^{1/f} \quad (6)$$

Where: E_{20} is aeration efficiency for 20 °C; and f is exponent described by:

$$f = 1.0 + 2.1 \times 10^{-2}\,(T - 20) + 8.26 \times 10^{-5}\,(T - 20)^2 \quad (7)$$

In this study, the aeration efficiency was normalized to 20 °C using Equation (6).

3. METHODOLOGY

Aeration enhancement by macro-roughness is well-known in water treatment, and one form is the stepped chute. The macro-roughness of the steps significantly reduces flow velocities and results in flow aeration along the stepped chute. Baylar and Emiroglu (2003) and Baylar et al. (2006) investigated the aeration efficiency of stepped chutes, in particular the effect of varying chute slope angle and step height. The aeration efficiency data used in this study were taken from studies by Baylar and Emiroglu (2003) and Baylar et al. (2006) on a large model of a stepped chute.

The aeration experiments were carried out using an experimental apparatus at the Hydraulic Laboratory of the Faculty of Engineering, Firat University, Elazig, Turkey. A schematic representation of the experimental set-up is shown in Figure 2 which shows a prismatic rectangular chute channel, 0.30 m wide and 0.50 m deep, in which the steps were installed. The side walls were made of transparent methacrylate to follow the flow regime.

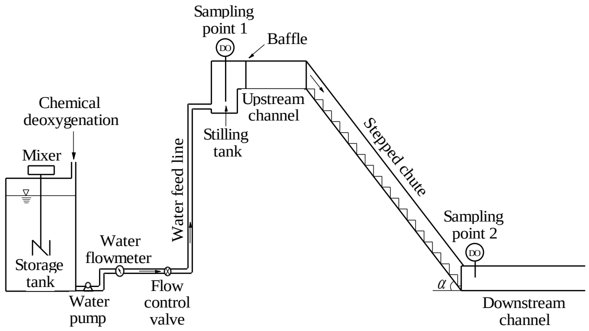


Figure 2. Laboratory stepped chute apparatus

Water was pumped from the storage tank to the stilling tank, from where it entered the chute through an approach channel. The downstream channel used in this study was 3.0 m long, 0.35 m wide, and 0.45 m deep. The experiments were conducted with unit discharges ranging from 33.33×10^{-3} m^2/s to 166.67×10^{-3} m^2/s. Discharge was measured by a flowmeter installed in the supply line. The chute slope angles were equal to 14.48°, 18.74°, 22.55°, 30°, 40° and, 50° and for all slopes tested, steps of 5, 10, and 15 cm were used (Table 1).

Parameters	Minimum	Maximum
α (°)	14.48	50.00
h (m)	0.05	0.15
q (m^2/s)	33.33×10^{-3}	166.67×10^{-3}
Fr* (-)	0.837	9.518

Table 1. Stepped chute geometry and hydraulic conditions

Tap water was used for all experiments reported in this paper. The salt content was therefore low and was constantly monitored during the experiments to prevent any build-up of residues from the deoxidizing chemicals added to the water. Therefore, the presence of chemicals or contaminants did not affect the results. Each experiment was started by filling the storage tank with water and adding Na_2SO_3 and $CoCl_2$ for chemical deoxygenation. During the experiments, DO measurements were taken upstream and downstream of the stepped chute using calibrated HANNA model HI 9142 portable oxygen meters at the locations shown in Figure 2. The probes were submerged to a depth of approximately 0.20 m at the sampling points to ensure that the measurements were not affected by any disturbance. The DO meters were calibrated daily at local atmospheric pressure prior to use using the air calibration method. Calibration procedures followed those recommended by the manufacturer. Calibration was performed in humid air under ambient conditions. Trace contaminants and salinity effects were minimized by using tap water in the experiments. Therefore, air calibration of the DO meters was used to eliminate the influence of these saturation uncertainties on the experimental results.

The experimental results of aeration efficiency in stepped chutes for the skimming flow regime obtained by Baylar and Emiroglu (2003) and Baylar et al. (2006) are given in Table 2.

q ($m^2/s\times10^{-3}$)	h (m)	α (°)	Fr* (-)	C_{mean} (-)	E_{20} (-)
50.00	0.05	14.48	2.855	0.265	0.55
66.67	0.05	14.48	3.807	0.265	0.45
100.00	0.05	14.48	5.711	0.265	0.30
133.33	0.05	14.48	7.614	0.265	0.26
166.67	0.05	14.48	9.518	0.265	0.23
50.00	0.05	18.74	2.519	0.320	0.52
66.67	0.05	18.74	3.359	0.320	0.44
100.00	0.05	18.74	5.038	0.320	0.28
133.33	0.05	18.74	6.717	0.320	0.22
166.67	0.05	18.74	8.397	0.320	0.16
50.00	0.05	22.55	2.306	0.365	0.53
66.67	0.05	22.55	3.074	0.365	0.42
100.00	0.05	22.55	4.611	0.365	0.32
133.33	0.05	22.55	6.148	0.365	0.29
166.67	0.05	22.55	7.686	0.365	0.24
33.33	0.05	30.00	1.346	0.446	0.82
50.00	0.05	30.00	2.019	0.446	0.74
66.67	0.05	30.00	2.693	0.446	0.70
100.00	0.05	30.00	4.039	0.446	0.62
133.33	0.05	30.00	5.385	0.446	0.59
166.67	0.05	30.00	6.731	0.446	0.57
33.33	0.05	40.00	1.187	0.538	0.75
50.00	0.05	40.00	1.781	0.538	0.72
66.67	0.05	40.00	2.375	0.538	0.70
100.00	0.05	40.00	3.562	0.538	0.63
133.33	0.05	40.00	4.749	0.538	0.59
166.67	0.05	40.00	5.937	0.538	0.56
33.33	0.05	50.00	1.087	0.614	0.77
50.00	0.05	50.00	1.631	0.614	0.75
66.67	0.05	50.00	2.175	0.614	0.74
100.00	0.05	50.00	3.263	0.614	0.72
133.33	0.05	50.00	4.350	0.614	0.66
166.67	0.05	50.00	5.438	0.614	0.64
133.33	0.10	14.48	2.692	0.265	0.41
166.67	0.10	14.48	3.365	0.265	0.34
133.33	0.10	18.74	2.375	0.320	0.41
166.67	0.10	18.74	2.969	0.320	0.37

100.00	0.10	22.55	1.630	0.365	0.46
133.33	0.10	22.55	2.174	0.365	0.39
166.67	0.10	22.55	2.717	0.365	0.30
100.00	0.10	30.00	1.428	0.446	0.72
133.33	0.10	30.00	1.904	0.446	0.67
166.67	0.10	30.00	2.380	0.446	0.60
100.00	0.10	40.00	1.259	0.538	0.70
133.33	0.10	40.00	1.679	0.538	0.66
166.67	0.10	40.00	2.099	0.538	0.63
100.00	0.10	50.00	1.154	0.614	0.71
133.33	0.10	50.00	1.538	0.614	0.68
166.67	0.10	50.00	1.923	0.614	0.65
166.67	0.15	30.00	1.295	0.446	0.71
166.67	0.15	40.00	1.142	0.538	0.68
133.33	0.15	50.00	0.837	0.614	0.70

Table 2. Stepped chute data for skimming flow regime

The mean air concentration (the mean void fraction) for the skimming flow regime is calculated by using Equation 2 developed by Hager (1991).

The aeration efficiency is a function of the following variables:

$$E_{20}=f_1\ (q,\ g,\ \alpha,\ h,\ C_{mean}) \quad (8)$$

Using dimensional analysis, the most effective parameters for aeration efficiency on stepped chutes are derived as:

$$E_{20}=f_2\ (q/\sqrt{g\ \sin(\alpha)\ h^3},\ C_{mean}) \quad (9)$$

$$E_{20}=f_3\ (Fr_*,\ C_{mean}) \quad (10)$$

Where: E_{20} is aeration efficiency at 20 °C, q is water discharge per unit width, g is gravitational acceleration, sin(α) is slope, α is chute slope angle, h is step height, Fr_* is roughness Froude number, and C_{mean} is mean (depth-averaged) air concentration.

4. ANALYSIS OF RESULTS

Stepped chutes are effective in transporting air bubbles into the water. The stepped chutes create strong turbulent mixing, long residence time, and significant entrainment of air bubbles. The aim of the study was to understand the role of the mean air concentration (the mean void fraction) on the aeration efficiency in stepped chutes for the skimming flow regime.

The type of flow regime is a function of the step height, chute slope angle, and flow rate. A tendency towards the skimming flow regime was observed with decreasing step height and increasing unit discharge and chute slope angle (Table 2).

The variation of the aeration efficiency (E_{20}) with the roughness Froude number (Fr*) for all step heights (h) is shown in Figure 3a-c. As can be seen, E_{20} increased with a decrease in Fr* in all experiments. This is because, at low roughness Froude numbers, the total air-water interface increases significantly under the influence of surface waves.

The variation of the aeration efficiency (E_{20}) with the roughness Froude number (Fr*) at different mean air concentrations (C_{mean}) for all step heights (h) is shown in Figure 4a-c. As can be seen, E_{20} increased with increasing C_{mean} in all experiments. In other words, there is a direct relationship between C_{mean} and E_{20}. The higher aeration efficiency with increasing mean air concentration can be explained by the increased entrainment of air bubbles.

In skimming flow, the aeration efficiency upstream of the inception point is close to zero because the upstream flow region is not aerated. The flow far downstream of the inception point remains uniform, and the flow characteristics such as equivalent clear water depth, mean water velocity, and mean air concentration for a given flow rate do not change along the stepped chute.

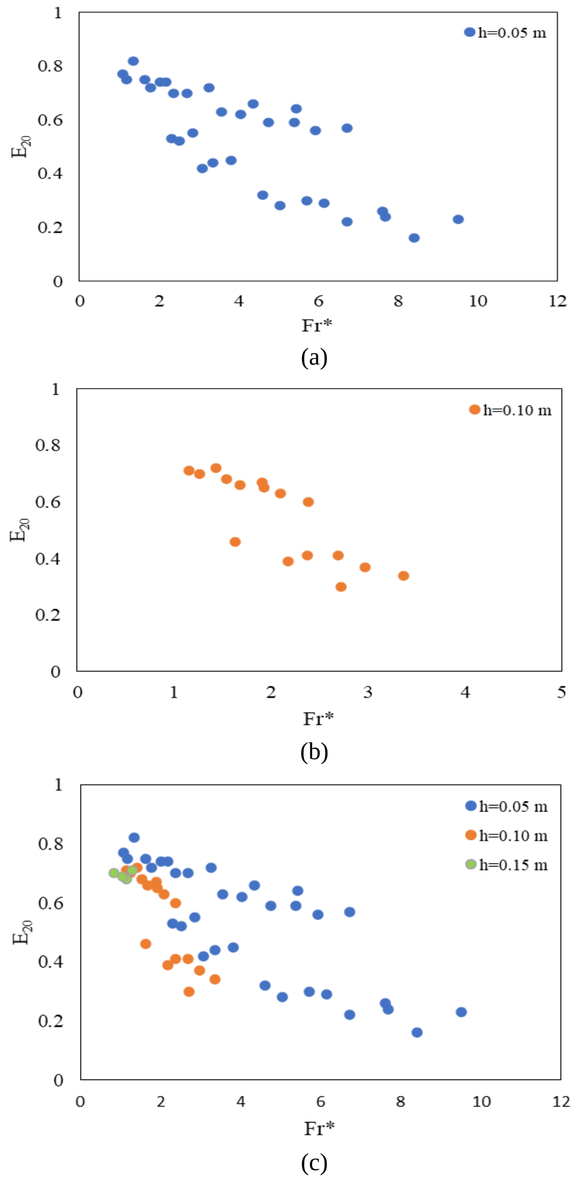
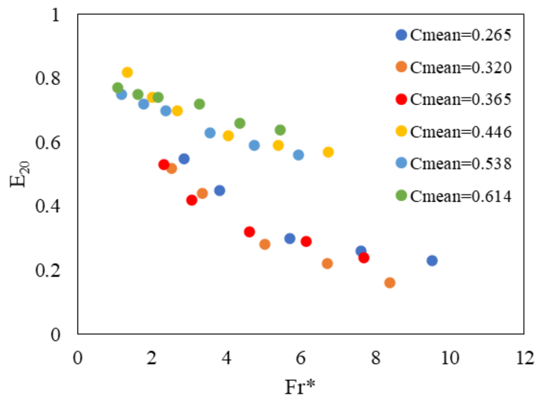
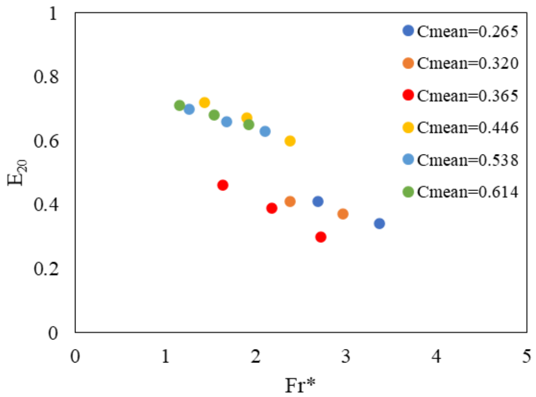


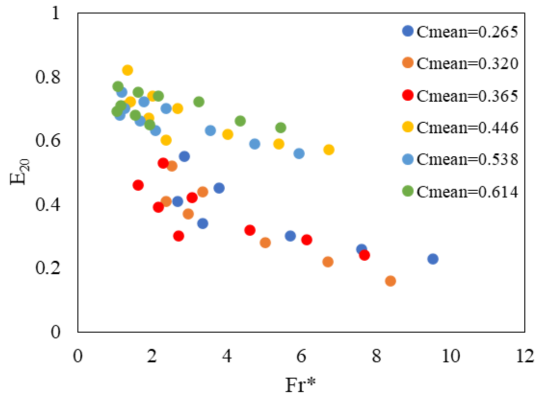
Figure 3. E_{20} vs. Fr* for (a) h=0.05 m, (b) h=0.10 m, (c) all step heights



(a)



(b)



(c)

Figure 4. E_{20} vs. Fr* at different mean air concentrations for (a) h=0.05 m, (b) h=0.10 m, (c) all step heights

Figure 5 shows the variation of the aeration efficiency (E_{20}) with the roughness Froude number (Fr*) at different chute slope angles (α) for all step heights (h). As can be seen from the figure, there is a direct relationship between α and E_{20}. In all experiments, E_{20} increases with increasing α. This can be explained by the fact that the mean air concentration increases with an increasing chute slope angle.

A design equation was developed to predict aeration efficiency by relating the aeration efficiency to the mean air concentration and the roughness Froude number. For the 53 tests, the correlation coefficient for Equation 11 is 0.80.

$$E_{20} = 1 - \exp\left(0.755 - 1.404\, Fr_*^{-0.279} - 2.122\, C_{mean}^{1.760}\right) \quad (11)$$

Where: E_{20} is aeration efficiency at 20 °C, Fr_* is roughness Froude number, and C_{mean} is mean (depth-averaged) air concentration.

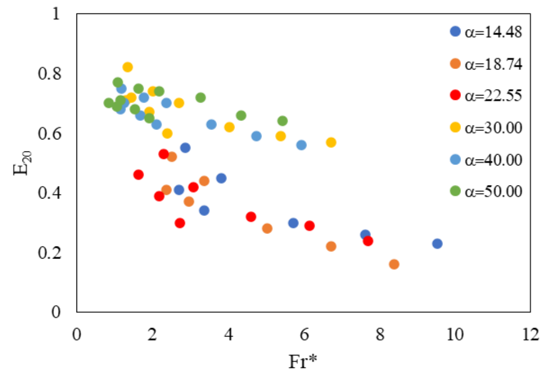


Figure 5. E_{20} vs. Fr* at different chute slope angles for all step heights

5. CONCLUSIONS

Hydraulic structures can increase dissolved oxygen levels by creating turbulent conditions where small air bubbles are carried into the bulk of the flow. Stepped chute aeration is a particular example of this. This paper investigates the aeration efficiency of stepped chutes for the skimming flow regime, particularly the effect of mean air concentration (mean void fraction). Based on the results of this study, the following conclusions can be drawn:

The results of this investigation showed that mean air concentration had a significant effect on aeration efficiency. Aeration efficiency increased with increasing mean air concentration. However, the aeration efficiency decreased as the roughness Froude number increased.

A design equation has been developed to predict aeration efficiency by relating the aeration efficiency to the mean air concentration and the roughness Froude number. This equation will be very useful in estimating the aeration efficiency in stepped chutes for the skimming flow regime. Researchers will be able to use this equation to determine the aeration efficiency at the design stage without the need for experimental studies. This gives researchers a significant time and cost advantage.

Scaling aeration data to prototype size is almost impossible, largely due to the relative invariance of bubble size. The experiments described in this paper cover much smaller discharges than most prototype applications. Additional testing is required to evaluate the effect of the discharge on the aeration efficiency in the stepped chutes.

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