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Study of Aeration Performance of Open Channel Chutes Equipped with a Flip Bucket

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Abstract

An adequate supply of dissolved oxygen (DO) is essential for the survival of aquatic organisms. Hydraulic structures can increase DO levels by creating turbulent conditions where small air bubbles are carried into the bulk of the flow. The flip bucket on open channel chutes with mild slopes is a particular instance of this, although the aeration performance of such structures has not been studied in the laboratory and field. This paper considers flip bucket chutes with different inclination angles and lip angles and how they affect aeration performance. It is demonstrated that the aeration efficiency of chutes with flip buckets is better than for those without.

Key words: Aeration efficiency, Chute, Dissolved oxygen, Flip bucket, Open channel, Oxygen transfer

Introduction

Oxygen is vital to the life cycle common to water. It is essential for keeping organisms alive, for sustaining species reproduction and for the development of populations. Oxygen is soluble in water in direct proportion to the partial pressure in the gas phase, and solubility decreases as temperature increases. Salt water holds less oxygen than fresh water. Oxygen enters the water by direct absorption from the atmosphere or by plant photosynthesis. It is removed by respiration of organisms and by organic decomposition. During respiration and decomposition, animals and plants consume dissolved oxygen (DO) and give off carbon dioxide. Organic waste from municipal, agricultural and industrial sources may overload the natural system, causing a serious depletion of the oxygen supply in the water. Water rich in nutrients produces algae in quantities which upon decomposition deplete the oxygen supply. Fish kills are often associated with this process of eutrophication. Standards for DO vary. Habitats for warm water fish populations should contain DO concentrations of not less than 4.0 mg/L. Habitats for cold water fish populations should not be less than 5.0 mg/L.

Hydraulic structures have an impact on the amount of DO in a river system, even though the water is in contact with the structure for only a short time. The same quantity of oxygen transfer that would normally occur over several kilometres in a river can occur at a single hydraulic structure, since the flow over a structure is typically highly turbulent, resulting in increased interfacial renewal. Hydraulic structures are typically associated with rivers and reservoirs and may be categorised as (1) a gated or ungated spillway; (2) a gated sill or sluice gate; (3) a gated conduit; and (4) a fixed or adjustable crest weir (Gulliver *et al.*, 1997; Gulliver *et al.*, 1998).

The aeration performance of hydraulic structures has been studied experimentally by a number of investigators, including Avery and Novak (1978), Markofsky and Kobus (1978), Nakasone (1987), Thene (1988), Tang *et al.* (1995), Labocha *et al.* (1996), Watson *et al.* (1998), Wormleaton and Soufiani (1998), Wormleaton and Tsang (2000), Baylar and Bagatur (2000), and Baylar *et al.* (2001), who investigated the aeration performance of weirs. Preul and Holler (1969), Wilhelms (1988) and Urban *et al.* (2001) conducted a series of laboratory experiments to determine the oxygenation potential of gated sill structures. Tainter gates, gated conduits, and ogee crests were studied by Holler (1970), Wilhelms and Smith (1981), and Rindels and Gulliver (1991), respectively. The literature search did not identify any published analytical or physical studies of the DO levels produced in the plunge pools of chutes equipped with flip buckets.

This paper describes an experimental investigation into the aeration efficiency of flip buckets on open channel chutes with mild slopes (Figure 1), and in particular the effect of varying the chute inclination angle (α) and lip angle of the flip bucket (θ).

Background

Oxygen is a highly volatile compound with a gas-water transfer rate controlled entirely by the liquid phase. Thus, the change in oxygen concentration over time in a parcel of water as the parcel travels through a hydraulic structure can be expressed as

$$\frac{dC}{dt} = K_L \frac{A}{V}(Cs - C) \tag{1}$$

where C = DO concentration, K_L = liquid film coefficient for oxygen, A = surface area associated with the volume V, over which transfer occurs, C_s = saturation concentration and t = time.

The term A/V is often called the specific surface area, a, or surface area per unit volume. Equation (1) does not consider sources and sinks of oxygen in the water body because their rates are relatively slow compared to the oxygen transfer which occurs at most hydraulic structures due to the increase in free-surface turbulence and the large quantity of air normally entrained into the flow.

The predictive relations described herein all assume that C_s is constant and determined by the water-atmosphere partitioning. If that assumption is made, C_s is constant with respect to time, and the oxygen transfer efficiency (aeration efficiency), E, may be defined as (Gulliver *et al.,* 1990):

$$E = \frac{Cd - Cu}{Cs - Cu} = 1 - \frac{1}{r} \tag{2}$$

where u and d = subscripts indicating upstream and downstream locations, respectively and r = oxygen deficit ratio $[(C_s - C_u)/(C_s - C_d)]$.

A transfer efficiency value of 1.0 means that the full transfer up to the saturation value has occurred at the structure. No transfer would correspond to E = 0.0. The saturation concentration in distilled, deionised water may be obtained from charts or equations. This is an approximation because the saturation DO concentration for natural waters is often different from that of distilled, deionised water due to the salinity effects. In this study, the saturation concentrations were determined by the chart of McGhee (1991) (Table 1). The salinity effect was minimised by using tap water with a low salt concentration.

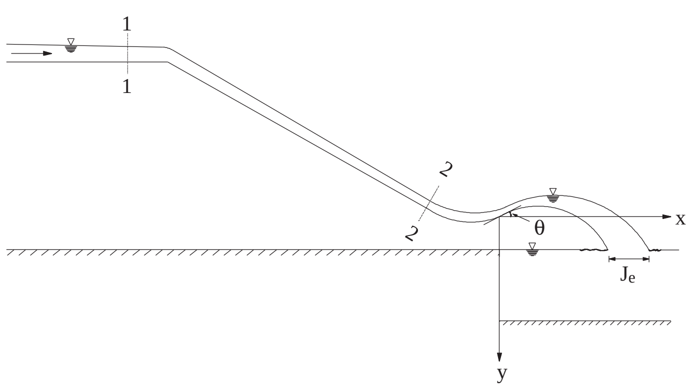

Figure 1. Flip bucket chute.

Table 1. Saturation values of dissolved oxygen in fresh and seawater exposed to an atmosphere containing 20.9% oxygen under a pressure of 760 mm of mercury.

Temperature	DO (mg/L) for stated concentrations of chloride, mg/L					Difference per
(°C)	0	5.000	10.000	15.000	20.000	100 mg/L chloride
0	14.62	13.79	12.97	12.14	11.32	0.0165
5	12.80	12.09	11.39	10.70	10.01	0.0140
10	11.33	10.73	10.13	9.55	8.98	0.0118
15	10.15	9.65	9.14	8.63	8.14	0.0100
20	9.17	8.73	8.30	7.86	7.42	0.0088
25	8.38	7.96	7.56	7.15	6.74	0.0082
30	7.63	7.25	6.86	6.49	6.13	0.0075

Factors Affecting Aeration Efficiency

The oxygen transfer which occurs at a given structure is sensitive to water temperature, water quality and DO deficit.

Water temperature

Oxygen transfer efficiency is sensitive to water temperature, and investigators have typically employed a temperature correction factor. For hydraulic structures, the most frequently used temperature correction factor has been that of Gameson *et al.* (1958), although some investigators have chosen to use an Arrhenius-type water temperature correction (Holler, 1970). Gulliver *et al.* (1990) applied the theories of Levich (1962), Hinze (1955) and Azbel (1981) to mass transfer similitude and developed the relationship

$$1 - E_{20} = (1 - E)^{1/f} \tag{3}$$

where E = transfer efficiency at the water temperature of measurement, E_{20} = transfer efficiency at 20 °C and f = the exponent described by

$$f = 1.0 + 0.02103(T - 20) + 8.261x10^{-5}(T - 20)^2 \tag{4}$$

Water quality

The presence of surface active agents, organic substances and suspended solids in water has been observed to affect the aeration process. Surface active agents in particular appear to modify the process by reducing surface tension, forming diffusion-inhibiting films at the air-water interface and affecting the hydrodynamic characteristics of the flow. The effect of water quality is often generalised by the use of a "water quality factor" in equations for the deficit ratio, as in Gameson (1957) and Markofsky and Kobus (1978). Avery and Novak (1978) used a similar constant to allow for the effects of different concentrations of sodium nitrate in their water.

The salt content of tap water used for all of the experiments reported in this paper was low and it was monitored constantly during the experiments to ensure there was no build-up of residues caused by the deoxygenation chemicals added to the water. Therefore, the results were not affected by the presence of any chemicals or pollutants.

Dissolved oxygen deficit

From Equation (2) it can be seen that the measurement of transfer efficiency becomes quite sensitive to measurement errors with a low upstream DO deficit. Gulliver and Wilhelms (1992) have stated that an upstream DO deficit of greater than 2.5 mg/L is normally required for accuracy in oxygen-transfer efficiency measurement. The primary source of measurement uncertainty was found to be uncertainty in the oxygen-saturation concentration. In the summer time, when the average saturation concentration is about 7 mg/L in most areas, this specification results in an upstream DO of less than 4.5 mg/L. Wilhelms *et al.* (1992) found that a substantial part of the oxygen-transfer measurements at hydraulic structures given in the literature suffered from the low upstream deficit problem. They were dropped from the data base because of the unacceptably high uncertainty in these measurements.

Wormleaton and Soufiani (1998) investigated the independence of oxygen transfer efficiency and upstream DO level. A set of readings was taken of the deficit ratio for a model rectangular weir without end contractions, with a 320 mm sill width under constant drop height, discharge, tailwater depth and temperature conditions. The upstream DO concentration C_u was varied over a range from 0 to 80% of its saturation value, and the variation in the downstream DO value C_d was noted. The results showed a linear relationship between C_u and C_d. The DO deficit ratio and hence oxygen transfer efficiency, E, are independent of the upstream DO value C_u.

A relationship between C_u and C_d was derived from Equation (2) as

$$C_d = (1 - E)C_u + EC_s \tag{5}$$

A regression analysis indicated that the best-fit line between C_u and C_d was

$$C_d(\%) = 0.289C_u(\%) + 69.53 \tag{6}$$

which implies that the oxygen transfer efficiency E is 0.711 and C_s is 97.8%, thus confirming that the oxygen transfer efficiency is sensibly independent of the upstream DO deficit. It also reinforces the use of oxygen transfer efficiency as a useful indicator of the aeration behaviour of structures.

In this study, sodium sulphite (Na_2SO_3) was added to the water to ensure a minimum upstream DO deficit of 2.5 mg/L. Cobalt chloride ($CoCl_2$) was used as the catalyst.

Experimental Study

All experiments were conducted in a prismatic rectangular chute channel of width b = 0.30 m and wall height h = 0.50 m (Figure 2). Water was pumped from the storage tank to the stilling tank, from which water entered the chute through an approach channel, with its bed 0.75 m above the laboratory floor. The downstream channel used in this study was 3.0 m long, 0.60 m wide and 0.60 m deep. An ogee crest was installed at the entrance to the chute channel so that water was guided into the chute channel. The discharge was measured by means of a flow meter installed in the supply line. The slope of the chute channel was varied as 8.40°, 10.82°, and 12.94°. All experimental runs were carried out with discharges ranging between 5 (F_1 = 1.06) and 50 (F_1 = 1.95) L/s. A flip bucket was placed at the downstream end of the chute channel. The lip angle of the flip bucket varied from 30° to 60° in 15° steps.

Free-falling jets from the flip bucket chute plunged through the atmosphere, impinged on the downstream channel below and entrained air bubbles into the downstream channel, thus increasing oxygen transfer. Each experiment was started by filling the storage tank and adding Na_2SO_3 and $CoCl_2$ to ensure a minimum upstream DO deficit of 2.5 mg/L. During the experiments, DO measurements upstream and downstream of the flip bucket chute were taken using calibrated portable HANNA Model HI 9142 oxygen meters at the locations identified in Figure 2. Measurements were obtained by submersing the probe to a depth of approximately 0.20 m at sampling points. The DO meters were calibrated daily according to local atmospheric pressure, prior to use, by the air calibration method. Calibration procedures followed those recommended by the manufacturer. The calibration was performed in humid air under ambient conditions. The saturation concentrations given in Table 1 were adjusted for local atmospheric pressure.

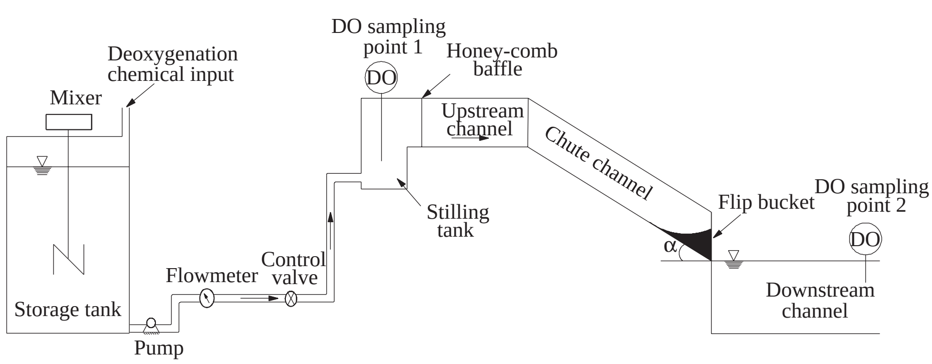

Figure 2. Experimental setup.

Experimental Results

In this study, the values of the aeration efficiency of open channel chutes with and without a flip bucket were obtained depending on the chute inclination angle (α), the lip angle of the flip bucket (θ) and the Froude number (F_1). The following sections present and discuss the aeration efficiency results (E_{20}).

The change in jet expansion (J_e) was measured as a function of chute inclination angle, lip angle of flip bucket and discharge, as illustrated in Tables 2-5. At the lowest discharge, 5 L/s, the flip bucket chute acted like a stilling basin with water flowing over the lip and downstream face. Jet expansions in the flip bucket chutes at the lowest discharge were, therefore, lower than for the other discharges. As the discharge increased, the flip bucket chute started to operate properly with a jet. It was observed from Tables 2-5 that jet expansions of chutes with flip buckets had greater values than for chutes without flip buckets.

Chutes with a flip bucket had greater values of aeration efficiency than chutes without flip buckets, as illustrated in Figures 3(a-c). The primary reason for this lies in the variation in free-falling jet expansion. For chute inclination angles of 8.40° and 10.82° at high discharges, 40 ($F_1 = 1.78$) and 50 ($F_1 = 1.95$) L/s, the flip bucket chute with lip angle of 45° was observed to have greater values of aeration efficiency than the flip bucket chutes with lip angles of 30° and 60°. However, at low discharges, 5 ($F_1 = 1.06$), 10 ($F_1 = 1.17$) and 15 ($F_1 = 1.28$) L/s, the flip bucket chute with a lip angle of 30° had greater values of aeration efficiency than the flip bucket chutes with a lip angles of 45° and 60° (Figures 3a-b). At a chute inclination angle of 12.94°, the flip bucket chute with lip angle of 60° showed greater values of aeration efficiency than the flip bucket chutes with lip angles of 30° and 45°. For the flip bucket chutes with a lip angle of 30° at a chute inclination angle of 12.94°, the values of aeration efficiency were in general agreement with the values of the flip bucket chutes with a lip angle of 45° (Figure 3c).

Table 2. Flip bucket chute data for $\theta = 30°$.

Q (L/s)	F_1 (-)	F_2 (-)	θ (deg.)	α (deg.)	T (°)	J_e (cm)	C_u (mg/L)	C_d (mg/L)	C_s (mg/L)	r (-)	E (-)	E_{20} (-)
5	1.06	4.51	30	8.40	22.0	2.5	4.6	5.8	7.95	1.56	0.36	0.35
10	1.17	4.44	30	8.40	21.5	40.5	3.8	5.6	8.02	1.74	0.43	0.42
15	1.28	4.48	30	8.40	21.0	50.5	3.9	5.9	8.09	1.91	0.48	0.47
20	1.40	4.47	30	8.40	21.0	58.5	4.6	6.1	8.09	1.75	0.43	0.42
30	1.61	4.47	30	8.40	21.0	64.0	5.2	6.4	8.09	1.71	0.42	0.41
40	1.78	4.42	30	8.40	21.0	62.5	5.4	6.6	8.09	1.81	0.45	0.44
50	1.95	4.33	30	8.40	21.0	60.5	5.6	6.7	8.09	1.79	0.44	0.43
5	1.06	4.97	30	10.82	21.0	16.0	5.2	6.4	8.09	1.71	0.42	0.41
10	1.17	4.90	30	10.82	21.0	46.0	4.3	6.1	8.09	1.90	0.47	0.47
15	1.28	4.91	30	10.82	21.0	56.0	4.5	6.1	8.09	1.80	0.45	0.44
20	1.40	4.98	30	10.82	21.0	68.5	4.1	5.7	8.09	1.67	0.40	0.39
30	1.61	4.93	30	10.82	21.0	63.5	4.3	5.8	8.09	1.66	0.40	0.39
40	1.78	4.80	30	10.82	21.0	53.5	5.4	6.6	8.09	1.81	0.45	0.44
50	1.95	4.65	30	10.82	21.0	51.0	5.5	6.6	8.09	1.74	0.42	0.42
5	1.06	5.32	30	12.94	20.5	4.0	5.4	6.4	8.17	1.56	0.36	0.36
10	1.17	5.29	30	12.94	20.5	42.5	4.6	5.9	8.17	1.57	0.36	0.36
15	1.28	5.28	30	12.94	20.5	48.0	4.3	5.9	8.17	1.70	0.41	0.41
20	1.40	5.34	30	12.94	20.5	51.5	4.0	5.5	8.17	1.56	0.36	0.36
30	1.61	5.27	30	12.94	20.5	49.5	4.1	5.7	8.17	1.65	0.39	0.39
40	1.78	5.08	30	12.94	20.5	48.5	4.7	6.2	8.17	1.76	0.43	0.43
50	1.95	4.90	30	12.94	20.5	47.5	4.7	6.1	8.17	1.68	0.40	0.40

Table 3. Flip bucket chute data for $\theta = 45°$.

Q (L/s)	F_1 (-)	F_2 (-)	θ (deg.)	α (deg.)	T (°)	J_e (cm)	C_u (mg/L)	C_d (mg/L)	C_s (mg/L)	r (-)	E (-)	E_{20} (-)
5	1.06	4.51	45	8.40	21.0	4.0	5.0	6.1	8.09	1.55	0.36	0.35
10	1.17	4.44	45	8.40	21.0	42.5	4.4	5.9	8.09	1.68	0.41	0.40
15	1.28	4.48	45	8.40	21.0	46.0	4.6	6.0	8.09	1.67	0.40	0.39
20	1.40	4.47	45	8.40	21.0	55.0	4.7	6.1	8.09	1.70	0.41	0.41
30	1.61	4.47	45	8.40	21.0	61.5	5.1	6.4	8.09	1.77	0.43	0.43
40	1.78	4.42	45	8.40	21.0	56.0	5.6	6.8	8.09	1.93	0.48	0.47
50	1.95	4.33	45	8.40	21.0	55.0	5.5	6.7	8.09	1.86	0.46	0.46
5	1.06	4.97	45	10.82	21.0	4.5	5.0	6.2	8.09	1.63	0.39	0.38
10	1.17	4.90	45	10.82	21.0	39.0	3.9	5.5	8.09	1.62	0.38	0.38
15	1.28	4.91	45	10.82	21.0	47.0	4.2	5.9	8.09	1.78	0.44	0.43
20	1.40	4.98	45	10.82	21.0	53.0	3.7	5.3	8.09	1.57	0.36	0.36
30	1.61	4.93	45	10.82	21.0	57.5	4.1	5.7	8.09	1.67	0.40	0.39
40	1.78	4.80	45	10.82	21.0	55.0	4.7	6.2	8.09	1.79	0.44	0.44
50	1.95	4.65	45	10.82	21.0	54.0	5.5	6.6	8.09	1.74	0.42	0.42
5	1.06	5.32	45	12.94	20.5	4.5	4.9	6.0	8.17	1.51	0.34	0.33
10	1.17	5.29	45	12.94	20.5	46.5	4.0	5.6	8.17	1.62	0.38	0.38
15	1.28	5.28	45	12.94	20.5	47.5	4.4	5.9	8.17	1.66	0.40	0.39
20	1.40	5.34	45	12.94	20.5	50.5	4.6	6.0	8.17	1.65	0.39	0.39
30	1.61	5.27	45	12.94	20.5	47.0	4.8	6.1	8.17	1.63	0.39	0.38
40	1.78	5.08	45	12.94	20.5	45.5	5.4	6.6	8.17	1.76	0.43	0.43
50	1.95	4.90	45	12.94	20.5	43.0	5.5	6.6	8.17	1.70	0.41	0.41

Table 4. Flip bucket chute data for $\theta = 60°$.

Q (L/s)	F_1 (-)	F_2 (-)	θ (deg.)	α (deg.)	T (°)	J_e (cm)	C_u (mg/L)	C_d (mg/L)	C_s (mg/L)	r (-)	E (-)	E_{20} (-)
5	1.06	4.51	60	8.40	21.5	3.0	5.5	6.3	8.02	1.47	0.32	0.31
10	1.17	4.44	60	8.40	21.5	41.5	4.4	5.9	8.02	1.71	0.41	0.40
15	1.28	4.48	60	8.40	21.0	50.5	3.9	5.7	8.09	1.75	0.43	0.42
20	1.40	4.47	60	8.40	21.0	53.0	4.7	6.2	8.09	1.79	0.44	0.44
30	1.61	4.47	60	8.40	21.0	58.0	4.9	6.2	8.09	1.69	0.41	0.40
40	1.78	4.42	60	8.40	21.0	62.0	5.4	6.5	8.09	1.69	0.41	0.40
50	1.95	4.33	60	8.40	21.0	55.0	5.6	6.7	8.09	1.79	0.44	0.43
5	1.06	4.97	60	10.82	21.0	3.5	5.3	6.2	8.09	1.48	0.32	0.32
10	1.17	4.90	60	10.82	21.0	35.5	4.0	5.6	8.09	1.64	0.39	0.38
15	1.28	4.91	60	10.82	21.0	42.5	3.8	5.6	8.09	1.72	0.42	0.41
20	1.40	4.98	60	10.82	21.0	47.5	4.2	5.9	8.09	1.78	0.44	0.43
30	1.61	4.93	60	10.82	21.0	58.0	5.0	6.4	8.09	1.83	0.45	0.45
40	1.78	4.80	60	10.82	21.0	57.0	5.1	6.4	8.09	1.77	0.43	0.43
50	1.95	4.65	60	10.82	21.0	56.0	5.6	6.6	8.09	1.67	0.40	0.40
5	1.06	5.32	60	12.94	22.0	5.5	4.5	5.6	7.95	1.47	0.32	0.31
10	1.17	5.29	60	12.94	22.0	45.0	4.2	5.7	7.95	1.67	0.40	0.39
15	1.28	5.28	60	12.94	21.0	46.5	4.3	6.0	8.09	1.81	0.45	0.44
20	1.40	5.34	60	12.94	21.0	47.5	4.2	6.0	8.09	1.86	0.46	0.46
30	1.61	5.27	60	12.94	21.0	51.0	4.5	6.1	8.09	1.80	0.45	0.44
40	1.78	5.08	60	12.94	21.0	52.0	4.8	6.2	8.09	1.74	0.43	0.42
50	1.95	4.90	60	12.94	21.0	53.0	5.5	6.7	8.09	1.86	0.46	0.46

Table 5. Chute without flip bucket data.

Q (L/s)	F_1 (-)	F_2 (-)	α (deg.)	T (°)	J_e (cm)	C_u (mg/L)	C_d (mg/L)	C_s (mg/L)	r (-)	E (-)	E_{20} (-)
5	1.06	4.51	8.40	21.0	14.0	5.3	6.1	8.09	1.40	0.29	0.28
10	1.17	4.44	8.40	21.0	18.0	3.2	4.8	8.09	1.49	0.33	0.32
15	1.28	4.48	8.40	21.0	24.0	3.5	5.1	8.09	1.54	0.35	0.34
20	1.40	4.47	8.40	21.0	26.0	3.9	5.4	8.09	1.56	0.36	0.35
30	1.61	4.47	8.40	21.0	27.5	4.5	5.9	8.09	1.64	0.39	0.38
40	1.78	4.42	8.40	21.0	23.5	5.2	6.3	8.09	1.61	0.38	0.37
50	1.95	4.33	8.40	21.0	22.5	5.4	6.4	8.09	1.59	0.37	0.37
5	1.06	4.97	10.82	21.0	5.0	5.0	5.8	8.09	1.35	0.26	0.25
10	1.17	4.90	10.82	21.0	13.0	4.8	5.7	8.09	1.38	0.27	0.27
15	1.28	4.91	10.82	21.0	19.0	3.5	5.0	8.09	1.49	0.33	0.32
20	1.40	4.98	10.82	21.0	25.5	3.4	5.0	8.09	1.52	0.34	0.34
30	1.61	4.93	10.82	21.0	28.5	3.5	5.0	8.09	1.49	0.33	0.32
40	1.78	4.80	10.82	21.0	23.0	4.6	5.8	8.09	1.52	0.34	0.34
50	1.95	4.65	10.82	21.0	22.5	4.7	5.8	8.09	1.48	0.32	0.32
5	1.06	5.32	12.94	21.0	13.5	5.3	6.1	8.09	1.40	0.29	0.28
10	1.17	5.29	12.94	21.0	30.0	4.8	5.8	8.09	1.44	0.30	0.30
15	1.28	5.28	12.94	21.0	34.0	3.8	5.2	8.09	1.48	0.33	0.32
20	1.40	5.34	12.94	21.0	35.0	4.3	5.6	8.09	1.52	0.34	0.34
30	1.61	5.27	12.94	21.0	29.0	5.0	6.1	8.09	1.58	0.36	0.35
40	1.78	5.08	12.94	21.0	27.5	5.4	6.3	8.09	1.50	0.33	0.33
50	1.95	4.90	12.94	21.0	27.0	5.4	6.2	8.09	1.42	0.30	0.29

For the flip bucket chute with a lip angle of 30°, the aeration efficiency of a chute inclination angle of 8.40° was greater than for chute inclination angles of 10.82° and 12.94°, except for discharges of 5 (F_1 = 1.06) and 10 (F_1 = 1.17) L/s. The flip bucket chute with a lip angle of 30° and inclination angle of 12.94 showed lower values of aeration efficiency than the flip bucket chutes with a lip angle of 30° and inclination angles of 8.40° and 10.82°, as illustrated in Figure 4a. At the flip bucket chute with a lip angle of 45°, the aeration efficiency of a chute inclination angle of 8.40° had a greater value than for chute inclination angles of 10.82° and 12.94°, except for discharges of 5 (F_1 = 1.06), 10 (F_1 = 1.17) and 15 (F_1 = 1.28) L/s. Generally, for the flip bucket chute with a lip angle of 45° and inclination angle of 10.82°, the values of aeration efficiency were in general agreement with a the values of the flip bucket chute with a lip angle of 45° and inclination angle of 12.94° (Figure 4b). For the flip bucket chute with lip angle of 60°, the values of aeration efficiency of a chute inclination angle of 8.40° were generally similar to the values of aeration efficiency of chute inclination angles of 10.82° and 12.94° (Figure 4c). For the chutes without a flip bucket, the aeration efficiency values of a chute inclination angle of 8.40° were greater than for chute inclination angles of 10.82° and 12.94° (Figure 4d).

For the flip bucket chute with a lip angle of 30° at low discharges, 5 (F_1 = 1.06) and 10 (F_1 = 1.17) L/s, the aeration efficiency values of a chute inclination angle of 10.82° were greater than for chute inclination angles of 8.40° and 12.94°, as illustrated in Figures 5a-b. At the chutes without a flip bucket, the aeration efficiency of a chute inclination angle of 10.82° showed lower values than for chute inclination angles of 8.40° and 12.94°, except for discharges of 40 (F_1 = 1.78) and 50 (F_1 = 1.95) L/s (Figures 5a-g). For the flip bucket chute with a lip angle of 45° at high discharges, 40 (F_1 = 1.78) and 50 (F_1 = 1.95) L/s, the aeration efficiency values of a chute inclination angle of 8.40° were greater than for chute inclination angles of 10.82° and 12.94°, as shown in Figures 5f-g.

Conclusions

Based on the findings of this study, the following conclusions can be drawn:

- Free-falling jet expansion for chutes with a flip bucket was greater than for chutes without a flip bucket. Increasing free-falling jet expansion led to higher aeration efficiency.

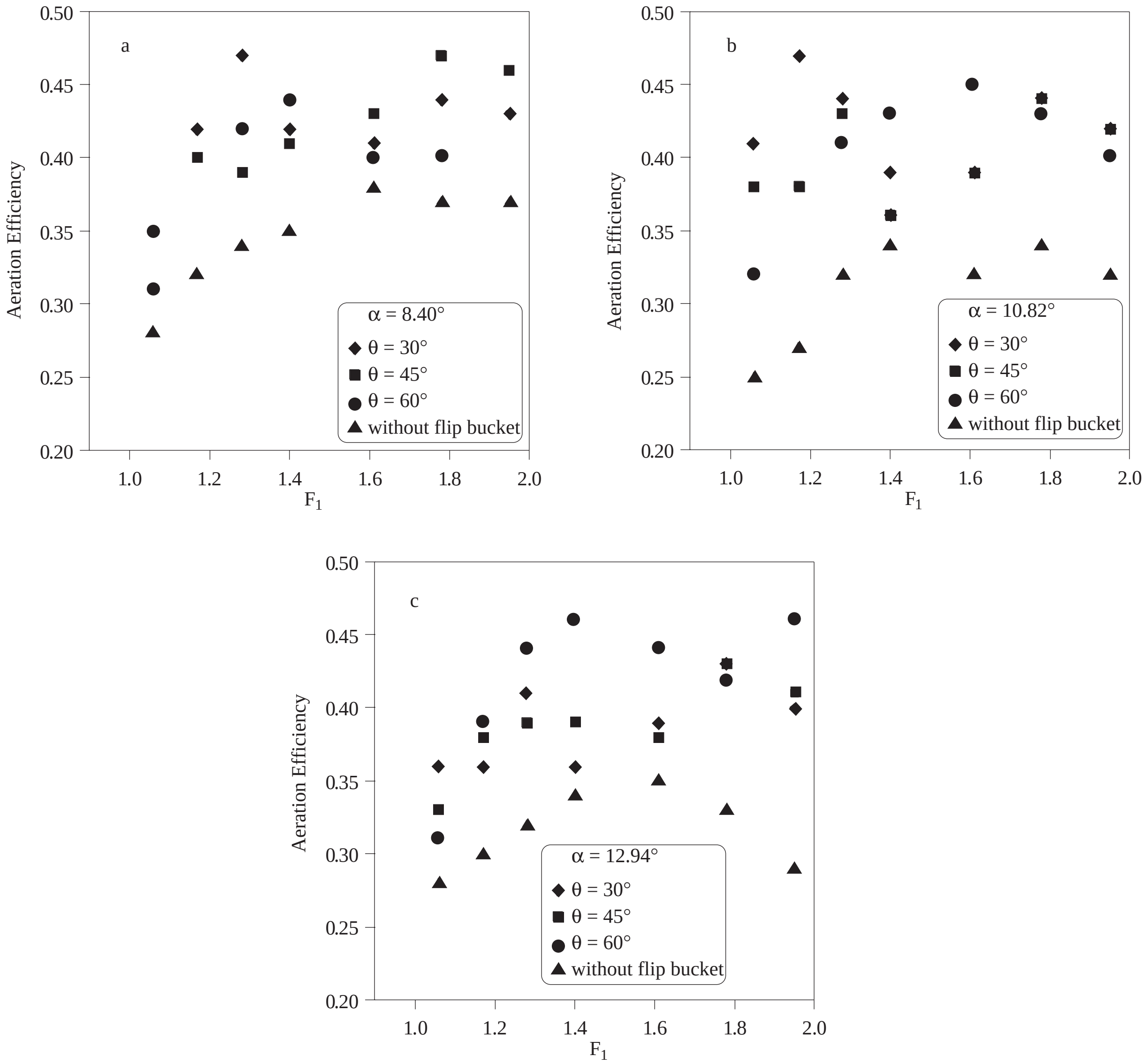

Figure 3. Variation in aeration efficiency with Froude number for chutes with and without a flip bucket: (a) $\alpha = 8.40°$; (b) $\alpha = 10.82°$; (c) $\alpha = 12.94°$.

• The results indicated that the aeration efficiency values of a chute inclination angle of 10.82° at low discharges were greater than for chute inclination angles of 8.40° and 12.94°. However, at high discharges, the values of aeration efficiency of a chute inclination angle of 8.40° were greater than for chute inclination angles of 10.82° and 12.94°. For the chutes without a flip bucket, the aeration efficiency of a chute inclination angle of 10.82° showed generally lower values than for chute inclination angles of 8.40° and 12.94°.

• It was apparent from the results that aeration efficiency values were greater at the flip bucket chutes with a lip angle of 30° for low discharges and at the flip bucket chutes with a lip angle of 45° for high discharges.

• Chutes with a flip bucket were shown to have significantly better aeration efficiency than chutes without a flip bucket. Therefore, using a simple flip bucket in open channel chutes could significantly increase aeration efficiency.

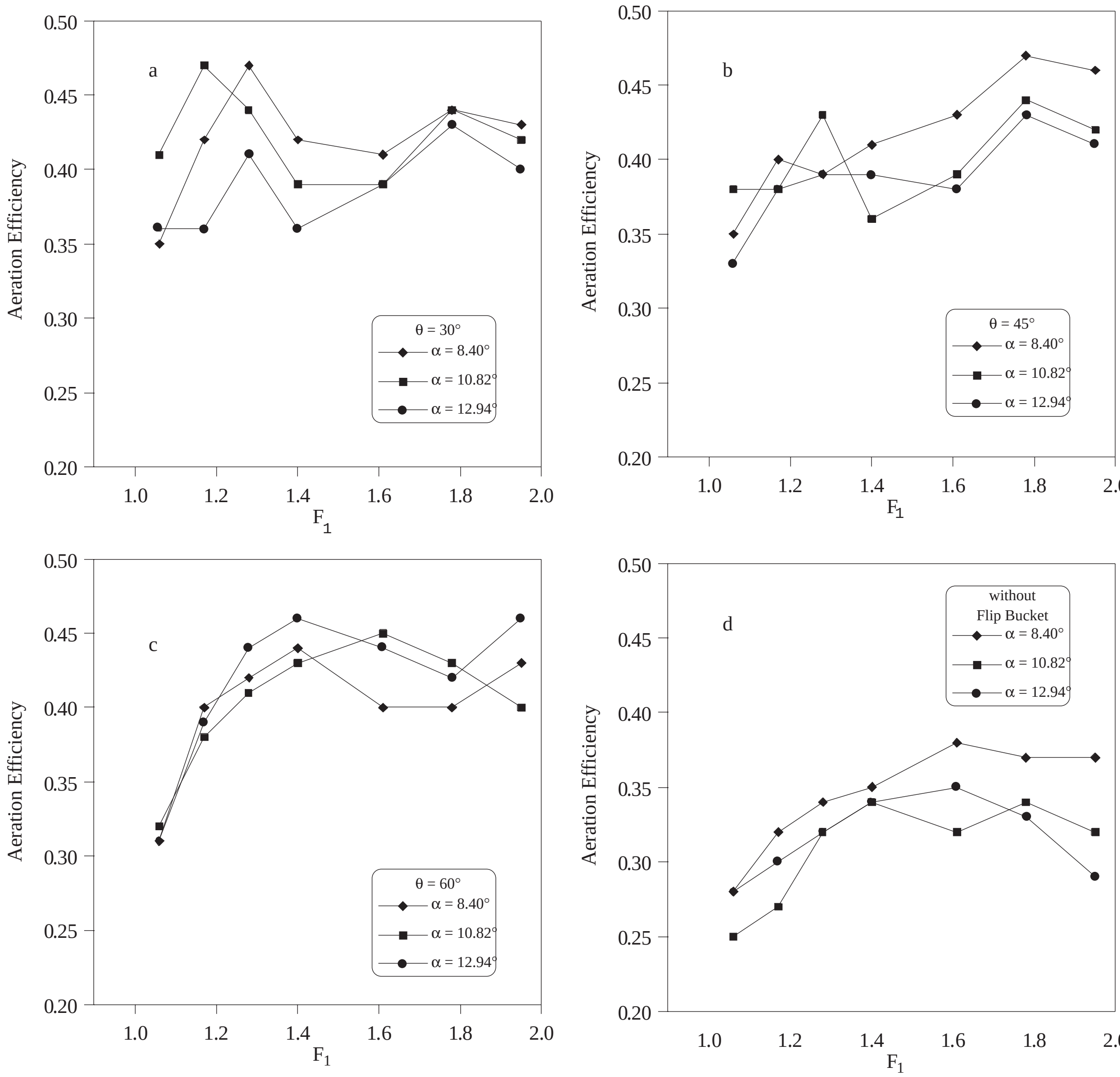

Figure 4. Variation in aeration efficiency with Froude number for chute inclination angle: (a) $\theta = 30°$; (b) $\theta = 45°$; (c) $\theta = 60°$; (d) without a flip bucket.

• 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 cover discharges which are considerably smaller than most prototype applications. Additional testing is necessary to assess the effect of aeration efficiency for open channel chutes with and without flip buckets when the discharge is higher than the largest discharge tested in this study.

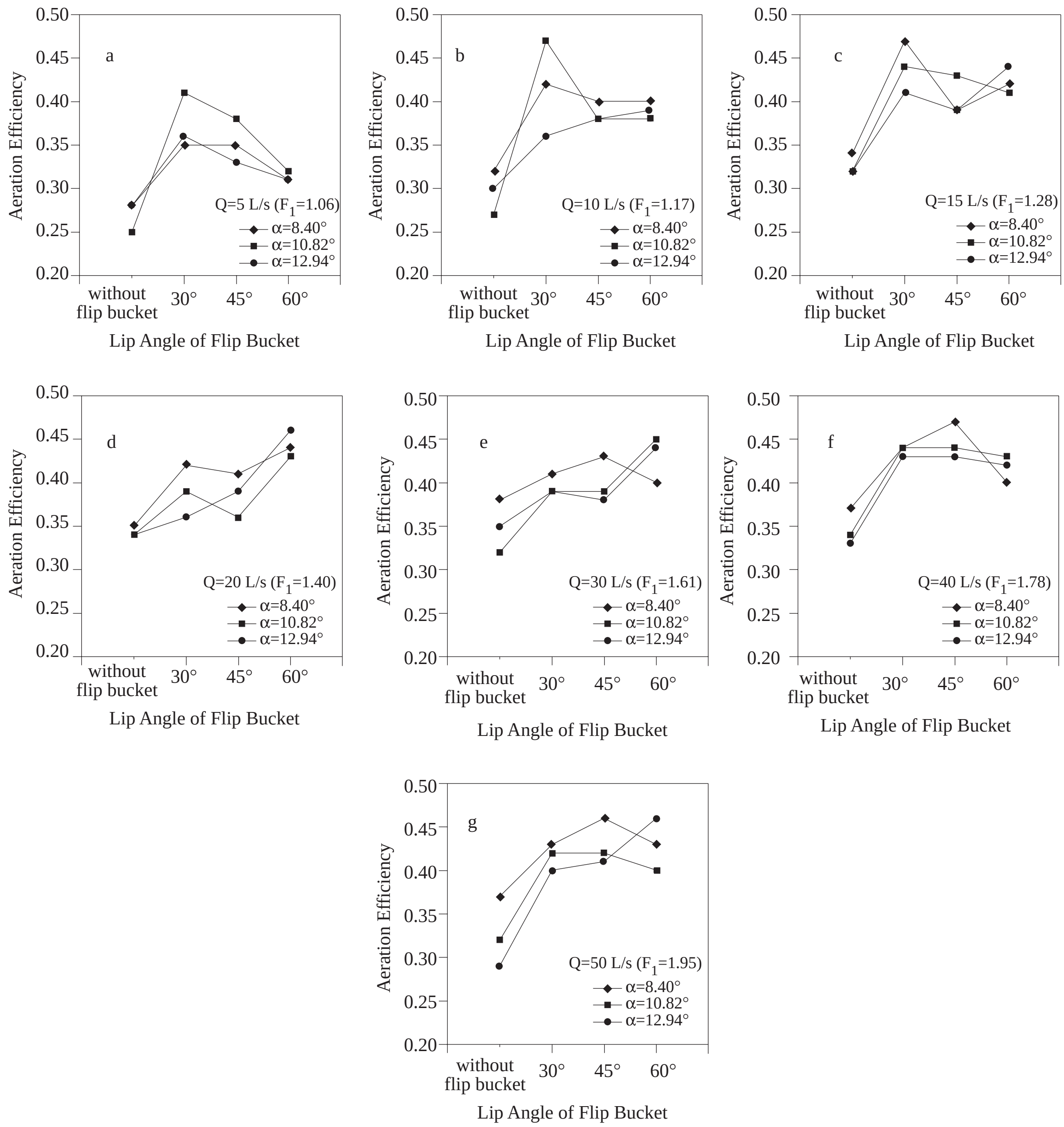

Figure 5. Variation in aeration efficiency with lip angle of flip bucket for chute inclination angle: (a) Q = 5 L/s; (b) Q = 10 L/s; (c) Q = 15 L/s; (d) Q = 20 L/s; (e) Q = 30 L/s; (f) Q = 40 L/s; (g) Q = 50 L/s.

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Nomenclature

a	the specific surface area (A/V), or surface area per unit volume
A	surface area associated with the volume V, over which transfer occurs
C	DO concentration
C_d	DO concentration downstream of a hydraulic structure

C_s saturation concentration
C_u DO concentration upstream of a hydraulic structure
DO dissolved oxygen
E transfer efficiency at the water temperature of measurement
E_{20} transfer efficiency at 20 °C
f term to adjust from 20 °C to T °C
F_1 Froude number at section 1 of open channel chute
F_2 Froude number at section 2 of open channel chute
J_e jet expansion
K_L liquid film coefficient for oxygen
Q flow discharge
r oxygen deficit ratio
t time
T water temperature
α chute inclination angle
θ lip angle of flip bucket

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