G.U. Journal of Science
22(4): 325-332 (2009)

www.gujs.org

Influence of Chute Slope on Oxygen Content in Stepped Waterways

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Received: 26.06.2007 Revised: 28.07.2007 Accepted: 10.09.2009

ABSTRACT

Water quality and its enhancement have a close connection with the presence of dissolved oxygen. In fact, the oxygen concentration in surface waters is a prime indicator of the water quality for human use as well as for the aquatic biota. The physical process of oxygen transfer or oxygen absorption from the atmosphere acts to replenish the used oxygen. This process is termed re−aeration or aeration. Aeration enhancement by macro−roughness is well−known in water treatment, and one form is the aeration cascade. The macro−roughness of the steps significantly reduces flow velocities and leads to flow aeration along the stepped cascade. This paper seeks influence of channel slope on oxygen content in stepped cascade aerators. It is demonstrated that the aeration efficiency of the stepped cascade aerators increases with increasing channel slope.

Key Words: *Aeration efficiency, Oxygen transfer, Stepped waterway, Chute slope*.

1. INTRODUCTION

Stepped waterways (cascades) are commonly used as river training, debris dam structures, storm water systems and aeration cascades. Stepped cascade flows are characterized by the strong turbulent mixing, the large residence time and the substantial air bubble entrainment. Air bubble entrainment is caused by turbulence fluctuations acting next to the air−water free surface. Through this interface, air is continuously tapped and released. Air entrainment occurs when the turbulent kinetic energy is large enough to overcome both surface tension and gravity effects. The turbulent velocity normal to the free surface must overcome the surface tension pressure, and be greater than the bubble rise velocity component for the bubbles to be carried away [1].

Stepped flows can be classified into 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 recirculating zones develop in triangular niches formed by the step faces and the pseudo−bottom, as shown in Figure 1a. In skimming flow the water flows as a coherent stream over the pseudo−bottom formed by the step corners. For a range of intermediate discharges, a transition flow regime takes place. The dominant feature is stagnation on the horizontal step face associated with significant splashing and a chaotic appearance (Figure 1b). For nappe flow the steps act as a series of overfalls with the water plunging from one step to another (Figure 1c). Generally speaking nappe flow is found for low discharges and wide steps [1].

Self−aeration on stepped cascades is now recognized for its substantial contribution to the air−water transfer of atmospheric gases such as oxygen and nitrogen. Stepped cascades are very efficient means of aeration because of the strong turbulent mixing, the large residence time and the substantial air bubble entrainment. Stepped cascades are used in water treatment for re−oxygenation, denitrification or VOC removals. In the treatment of drinking water, cascade aeration may be used to remove chlorine and to eliminate or reduce offensive taste and odor [2].

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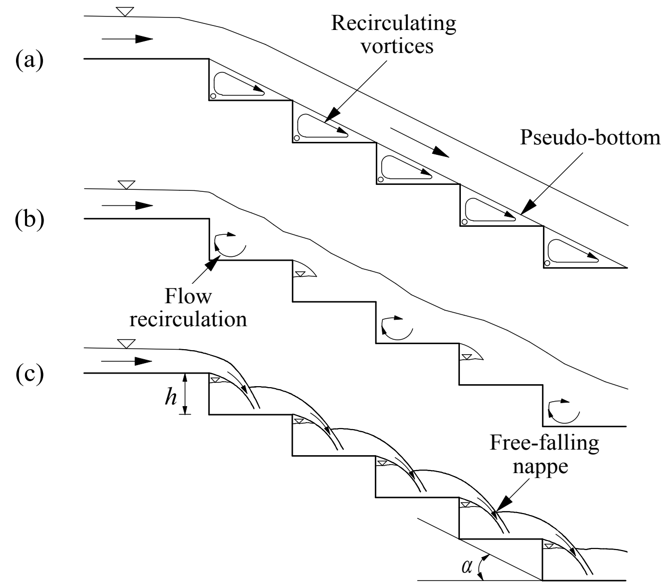

Figure 1. Flow regimes above stepped cascades: a) skimming flow, b) transition flow, c) nappe flow [13].

Essery et al. [3] studied nappe flow in pooled stepped−channel chutes. Toombes and Chanson [2] considered aeration in small−slope stepped−channel chutes. Chanson and Toombes [4] conducted gas−liquid interface measurements in stepped cascade. Local void fractions, bubble count rates, bubble size distributions and gas−liquid interface areas were measured simultaneously in the air−water flow region using resistivity probes. However, they stated that future work is needed to compare aeration efficiencies estimated with detailed interfacial area data and based upon dissolved gas measurements. Recently, Emiroglu and Baylar [5], Baylar and Emiroglu [6], Baylar et al. [7, 8, 9, 10] and Hanbay et al. [11, 12] did some detailed studies on the aeration efficiency of stepped cascades. Baylar and Emiroglu [6] for flat stepped cascades and Baylar et al. [7] for steep stepped cascades studied aeration efficiency. It was found that water can trap a lot of air when passing through steps and then increasing oxygen content in water body, so stepped cascades can be used as highly effective aerators in streams, rivers, constructed channels, fish hatcheries, water treatment plants, etc. The aim of this paper is to seek influence of channel slope on aeration efficiency in stepped cascades.

2. MATERIALS AND METHODS

2.1. Oxygen Transfer Process

The rate of oxygen mass transfer, i.e. from the gas (air bubbles) to the liquid phase (water) is governed by the terms described below.

$$\frac{dC}{dt} = K_L \frac{A}{V}(C_s - C) \tag{2.1}$$

where C = Dissolved oxygen (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 that occurs at most hydraulic structures due to the increase in free−surface turbulence and the large quantity of air that is normally entrained into the flow.

The predictive relations 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 [14]:

$$E = \frac{C_d - C_u}{C_s - C_u} = 1 - \frac{1}{r} \tag{2.2}$$

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, deionized 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, deionized water due to the salinity affects.

Comparative evaluations of oxygen uptake at hydraulic structures require that aeration efficiency is corrected to a reference temperature. To provide a uniform basis for comparison of measurement results, the aeration efficiency is often normalized to a 20°C standard. Gulliver et al. [14] proposed the following equation to describe the influence of temperature

$$1-E_{20}=(1-E)^{1/f} \quad (2.3)$$

where E = transfer efficiency at actual water temperature; E_{20} = transfer efficiency for 20°C; and f = exponent described by

$$f=1.0+2.1x10^{-2}(T-20)+8.26x10^{-5}(T-20)^2 \quad (2.4)$$

where T = water temperature. In this study, the aeration efficiency was normalized to 20°C using Eq. (2.3).

2.2. Experimental Arrangement

The data used in this study were taken from studies conducted by Baylar and Emiroglu [6] and Baylar et al. [7] on a large model of a stepped cascade. Schematic representation of the experimental setup is given on Figure 2. All experiments were conducted in a prismatic rectangular channel with 0.30 m wide and 0.50 m deep. The side walls were made of transparent methacrylate to follow flow regime. Water was pumped from the storage tank to stilling tank, from which water entered the stepped channel through an approach channel. The discharge was measured by means of a flow meter installed in the supply line. All experimental runs were carried out in unit discharges ranging between 16.67 and 166.67 L/s.m. For stepped channel, downstream channel was 3.0 m long, 0.35 m wide and 0.45 m deep. The slopes of stepped channel were varied as 14.48°, 18.74°, 22.55°, 30°, 40°, and 50°. For all slopes tested, steps with h equal to 5, 10, and 15 cm were used.

Tap water was used throughout the present experiments. The water was changed for each experiment. The water in the tank was deoxygenated by sodium sulfite method. Theoretically, 7.9 g/m^3 of sodium sulfite is required to remove 1 g/m^3 of DO. Based on the DO of the test tap water, the approximate sodium sulfite requirements are estimated (a 10−20% excess is used). Usually, addition of cobalt II chloride is required at a dosage of 3.3 g/m^3 as a catalyst for the deoxygenation reaction. In this study, 70 g/m^3 of sodium sulfite and 3.3 g/m^3 of cobalt II chloride were added. The salt content of tap water used for all of the experiments reported in this paper was low and monitored constantly during the experiments to ensure no significant buildup of residues caused by the deoxygenation chemicals added to the water. Therefore, it is unlikely that the results were measurably affected by the presence of chemicals or pollutants.

Each experiment was started by filling the storage tank with water by adding Na_2SO_3 and $CoCl_2$ for chemical de−oxygenation. During the experiments, DO measurements upstream and downstream of the stepped cascade were taken using calibrated portable HANNA Model HI 9142 oxygen meters at the locations identified in Figure 2. Measurements were made 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. In this study, the saturation concentrations were determined by the chart of McGhee [15].

3. RESULTS

The results highlight that the aeration efficiencies are strongly affected by the type of flow regime which in turn is a function of the step height, channel slope and flow rate. Three different flow regimes, namely the nappe, the transition and the skimming flow regimes occur in stepped cascades. A tendency towards the nappe flow regime is observed with increasing step height and decreasing unit discharge and channel slope. However, the results show a tendency towards the transition and the skimming flow regimes as unit discharge and channel slope increase and as step height decreases (Table 1).

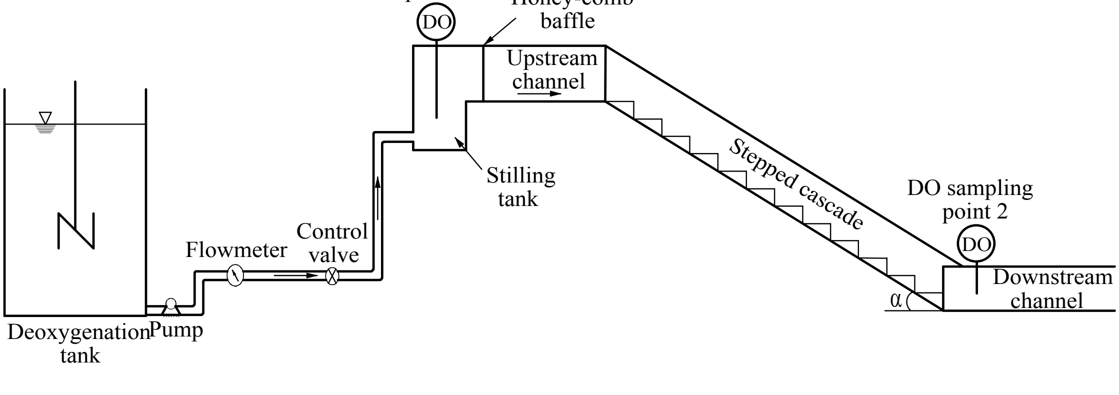

Figure 2. Experimental arrangement for stepped cascade model.

Table 1. Experimental results for stepped cascades [6, 7].

		h=0.05 m; L=5.00 m			**h=0.10 m; L=5.00 m**			**h=0.15 m; L=5.00 m**		
q ($m^2/s \times 10^{-3}$)	**α (deg.)**	**N**	**E_{20} (−)**	**Flow Regime**	**N**	**E_{20} (−)**	**Flow Regime**	**N**	**E_{20} (−)**	**Flow Regime**
16.67	14.48	25	0.60	Nappe	12	0.55	Nappe	8	0.49	Nappe
33.33	14.48	25	0.58	Transition	12	0.54	Nappe	8	0.50	Nappe
50.00	14.48	25	0.55	Skimming	12	0.54	Nappe	8	0.48	Nappe
66.67	14.48	25	0.45	Skimming	12	0.52	Transition	8	0.46	Nappe
100.00	14.48	25	0.30	Skimming	12	0.44	Transition	8	0.43	Nappe
133.33	14.48	25	0.26	Skimming	12	0.41	Skimming	8	0.40	Transition
166.67	14.48	25	0.23	Skimming	12	0.34	Skimming	8	0.40	Transition
16.67	30.00	50	0.81	Nappe	25	0.80	Nappe	16	0.78	Nappe
33.33	30.00	50	0.82	Skimming	25	0.79	Nappe	16	0.76	Nappe
50.00	30.00	50	0.74	Skimming	25	0.77	Nappe	16	0.75	Nappe
66.67	30.00	50	0.70	Skimming	25	0.75	Transition	16	0.75	Nappe
100.00	30.00	50	0.62	Skimming	25	0.72	Skimming	16	0.73	Nappe
133.33	30.00	50	0.59	Skimming	25	0.67	Skimming	16	0.72	Transition
166.67	30.00	50	0.57	Skimming	25	0.60	Skimming	16	0.71	Skimming
		h=0.05 m; L=3.89 m			**h=0.10 m; L=3.89 m**			**h=0.15 m; L=3.89 m**		
q ($m^2/s \times 10^{-3}$)	**α (deg.)**	**N**	**E_{20} (−)**	**Flow Regime**	**N**	**E_{20} (−)**	**Flow Regime**	**N**	**E_{20} (−)**	**Flow Regime**
16.67	18.74	25	0.60	Nappe	12	0.58	Nappe	8	0.57	Nappe
33.33	18.74	25	0.57	Transition	12	0.58	Nappe	8	0.58	Nappe
50.00	18.74	25	0.52	Skimming	12	0.55	Nappe	8	0.53	Nappe
66.67	18.74	25	0.44	Skimming	12	0.55	Transition	8	0.52	Nappe
100.00	18.74	25	0.28	Skimming	12	0.47	Transition	8	0.47	Nappe
133.33	18.74	25	0.22	Skimming	12	0.41	Skimming	8	0.43	Transition
166.67	18.74	25	0.16	Skimming	12	0.37	Skimming	8	0.39	Transition
16.67	40.00	50	0.74	Transition	25	0.74	Nappe	16	0.76	Nappe
33.33	40.00	50	0.75	Skimming	25	0.76	Nappe	16	0.76	Nappe
50.00	40.00	50	0.72	Skimming	25	0.77	Transition	16	0.77	Nappe
66.67	40.00	50	0.70	Skimming	25	0.76	Transition	16	0.76	Nappe
100.00	40.00	50	0.63	Skimming	25	0.70	Skimming	16	0.71	Transition
133.33	40.00	50	0.59	Skimming	25	0.66	Skimming	16	0.69	Transition
166.67	40.00	50	0.56	Skimming	25	0.63	Skimming	16	0.68	Skimming
		h=0.05 m; L=3.26 m			**h=0.10 m; L=3.26 m**			**h=0.15 m; L=3.26 m**		
q ($m^2/s \times 10^{-3}$)	**α (deg.)**	**N**	**E_{20} (−)**	**Flow Regime**	**N**	**E_{20} (−)**	**Flow Regime**	**N**	**E_{20} (−)**	**Flow Regime**
16.67	22.55	25	0.68	Nappe	12	0.62	Nappe	8	0.56	Nappe
33.33	22.55	25	0.61	Transition	12	0.59	Nappe	8	0.56	Nappe
50.00	22.55	25	0.53	Skimming	12	0.57	Nappe	8	0.53	Nappe
66.67	22.55	25	0.42	Skimming	12	0.55	Transition	8	0.52	Nappe
100.00	22.55	25	0.32	Skimming	12	0.46	Skimming	8	0.51	Nappe
133.33	22.55	25	0.29	Skimming	12	0.39	Skimming	8	0.47	Transition
166.67	22.55	25	0.24	Skimming	12	0.30	Skimming	8	0.41	Transition
16.67	50.00	50	0.79	Transition	25	0.77	Nappe	16	0.77	Nappe
33.33	50.00	50	0.77	Skimming	25	0.74	Transition	16	0.75	Nappe
50.00	50.00	50	0.75	Skimming	25	0.74	Transition	16	0.74	Nappe
66.67	50.00	50	0.74	Skimming	25	0.73	Transition	16	0.74	Transition
100.00	50.00	50	0.72	Skimming	25	0.71	Skimming	16	0.72	Transition
133.33	50.00	50	0.66	Skimming	25	0.68	Skimming	16	0.70	Skimming
166.67	50.00	50	0.64	Skimming	25	0.65	Skimming	16	0.69	Skimming

Due to the different mechanisms of air entrainment in the nappe, the transition and the skimming flow regimes, the aeration efficiencies of the three flow regimes differ significantly from each other. It is observed from the results that the nappe flow regime lead to the greater aeration efficiency than the other flow regimes (Table 1). In the nappe flow regime, the oxygen transfer on each step results from the flow aeration and mixing in the free−falling nappe, at the plunge point and possibly at the downstream hydraulic jump. In other words, the reason for the greater aeration efficiency in the nappe flow regime can be explained with the high level of turbulence, the large residence time and the substantial air bubble entrainment.

The results indicate that the aeration efficiency increases as the unit discharge decreases, as shown in Figures 3-5. Moreover, it is demonstrated that the aeration efficiency of the stepped cascade aerators increases with increasing channel slope (Figures 3-5). The primary reason for the increase in the aeration efficiency of the stepped cascade aerators with increasing channel slope can be found by the increase in the total number of steps.

In summary, the paper demonstrates that stepped cascades are one of the ideal forms to increase oxygen content in water body for hydraulic and environmental engineering. Stepped cascades are very efficient means of aeration because of the strong turbulent mixing, the large residence time and the substantial air bubble entrainment, and that this advantage becomes more pronounced as channel slope is increased.

Figure 6 compares nappe flow data of Toombes and Chanson [2], Essery et al. [3] and present study, transition flow data of present study and skimming flow data of Essery et al. [3] and present study. The results indicated that the aeration efficiency on stepped−channel chutes differ significantly in the nappe, the transition and the skimming flow regimes. This may be explained by the different mechanisms of air entrainment and air−water gas transfer between the three flow regimes.

4. CONCLUSIONS

Hydraulic structures can increase dissolved oxygen levels by creating turbulent conditions where small air bubbles are carried into the bulk of the flow. Chute aeration is a particular instance of this. A chute is characterized by a steep bed slope associated with torrential flow. This chute flow may be either smooth or stepped. The present paper investigates influence of channel slope on aeration efficiency in stepped cascade aerators. The results indicate that stepped cascade aerators are very efficient at oxygen transfer because of the strong turbulent mixing associated with substantial air bubble entrainment and that this advantage becomes more pronounced in nappe flow regime and with increasing channel slope

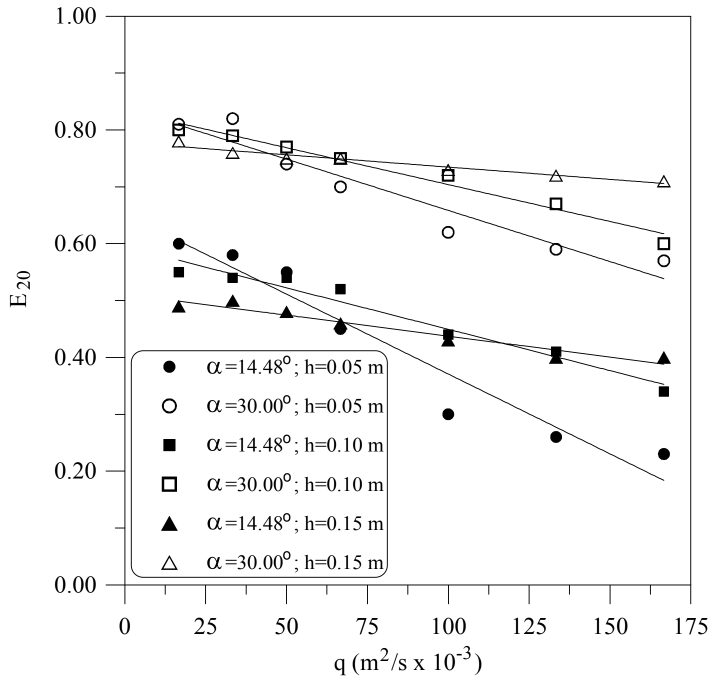

Figure 3. Aeration efficiency as a function of unit discharge for α=14.48° and α=30° (L=5 m).

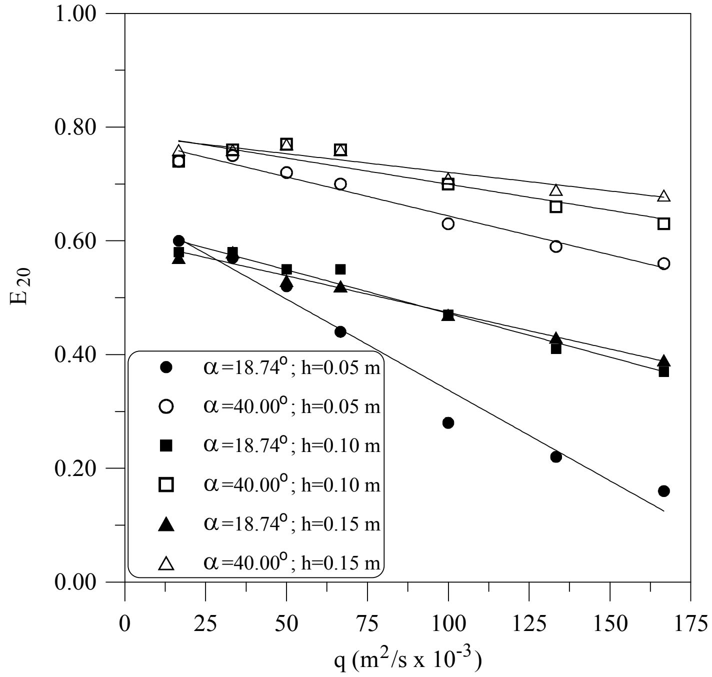

Figure 4. Aeration efficiency as a function of unit discharge for α=18.74° and α=40° (L=3.89 m).

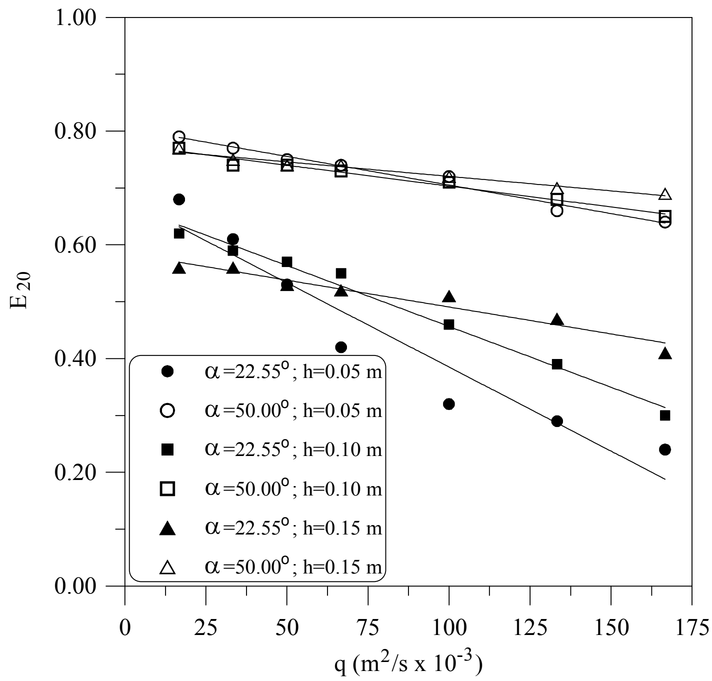

Figure 5. Aeration efficiency as a function of unit discharge for α=22.55° and α=50° (L=3.26 m).

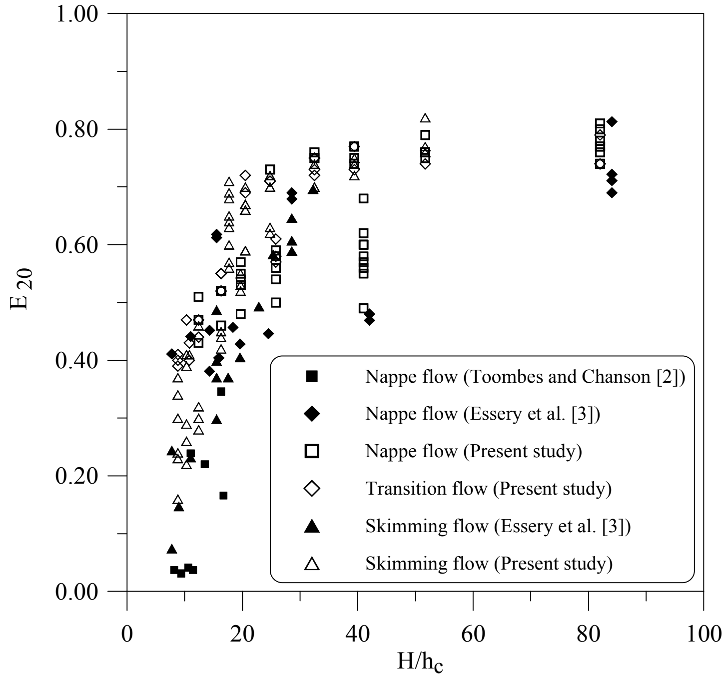

Figure 6. Comparison of aeration efficiency in nappe, transition and skimming flows.

List of Symbols

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 the 20 °C
f	exponent
h	step height
h_c	critical flow depth
H	total height of steps
K_L	liquid film coefficient for oxygen
L	length of stepped−channel chute
N	total number of steps
q	unit discharge
r	oxygen deficit ratio
t	time
T	water temperature
V	volume of water
α	stepped channel slope

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