AIR ENTRAINMENT AND ENERGY DISSIPATION AT STEPPED DROP STRUCTURE

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Abstract: This paper deals with oxygen transfer by air entrainment and energy dissipations by flow characteristics at the stepped drop structure. Nappe flow occurred at low flow rates and for relatively large step height. Dominant flow features included an air pocket, a free-falling nappe impact and a subsequent hydraulic jump on the downstream step. Most energy was dissipated by nappe impact and in the downstream hydraulic jump. Skimming flow occurred at larger flow rates with formation of recirculating vortices between the main flow and the step corners. Oxygen transfer was found to be proportional to the flow velocity, the flow discharge, and the Froude number. It was more related to the flow discharge than to the Froude number. Energy dissipations in both cases of nappe flow and skimming flow were proportional to the step height and were inversely proportional to the overflow depth, and were not proportional to the step slope. The stepped drop structure was found to be efficient for water treatment associated with substantial air entrainment and for energy dissipation.

Keywords: oxygen transfer, air entrainment, energy dissipation, stepped drop structure, nappe flow, skimming flow

1. INTRODUCTION

Drop structure is usually installed to protect the stream bed against scour since it is the typical case for energy dissipation. Energy dissipation is one of the most important features in the design of many hydraulic structures. Rajaratnam and Chamani (1995) have investigated the energy dissipation on the drop structures.

Drop structure may also be useful for air entrainment by the stepped type of the downstream part of the flow section. Air entrainment by macro-roughness is efficient in water treatment (Chanson, 1993). It is very efficient for water treatment because of the strong turbulent mixing associated with substantial air entrainment. It will be built along polluted and eutrophic streams to control the water quality, since it is used in water treatment for reoxygenation, denitrification and volatile organic component (VOC) removals (Henry, 1985).

The flows over the stepped drop structures are characterized by the large amount of self-entrained air. The macro roughness of the steps leads to a sharp increase in the thickness of the turbulent boundary layer. Where the boundary layer reaches the free surface, air is entrained at the so-called inception point of air entrainment.

Dissolved oxygen will be made and with this effect, plenty of algae, aquatic insects and fishes can inhabit downstream of the stepped drop structures.

Recently, river environmental works considering ecological habitats have been thought to be important, and the hydraulic studies on the ecological features of the stepped drop structures for the effective design of the river environmental works must be necessary.

The present study deals with the oxygen transfer by the air entrainment and the energy dissipation by the flow characteristics at the stepped drop structure. Hydraulic analysis on the oxygen transfer and the energy dissipation by the nappe flow and the skimming flow, and the relationships of the oxygen transfer to the hydraulic parameters were presented through the hydraulic experiments.

2. FLOW CHARACTERISTICS

Stepped drop structures may be characterized by two types of flow : nappe flow and skimming flow shown in Fig. 1 (Chanson, 1993).

At low flow rates and for relatively large step height, nappe flow occurs. The water bounces from one step onto the next one. Dominant flow features include, at each drop, an enclosed air cavity, a free-falling jet, a nappe impact and a subsequent hydraulic jump on the downstream step. Energy dissipation takes place due to nappe impact on the underlying water cushion and hydraulic jump (Fratino and Piccinni, 2000).

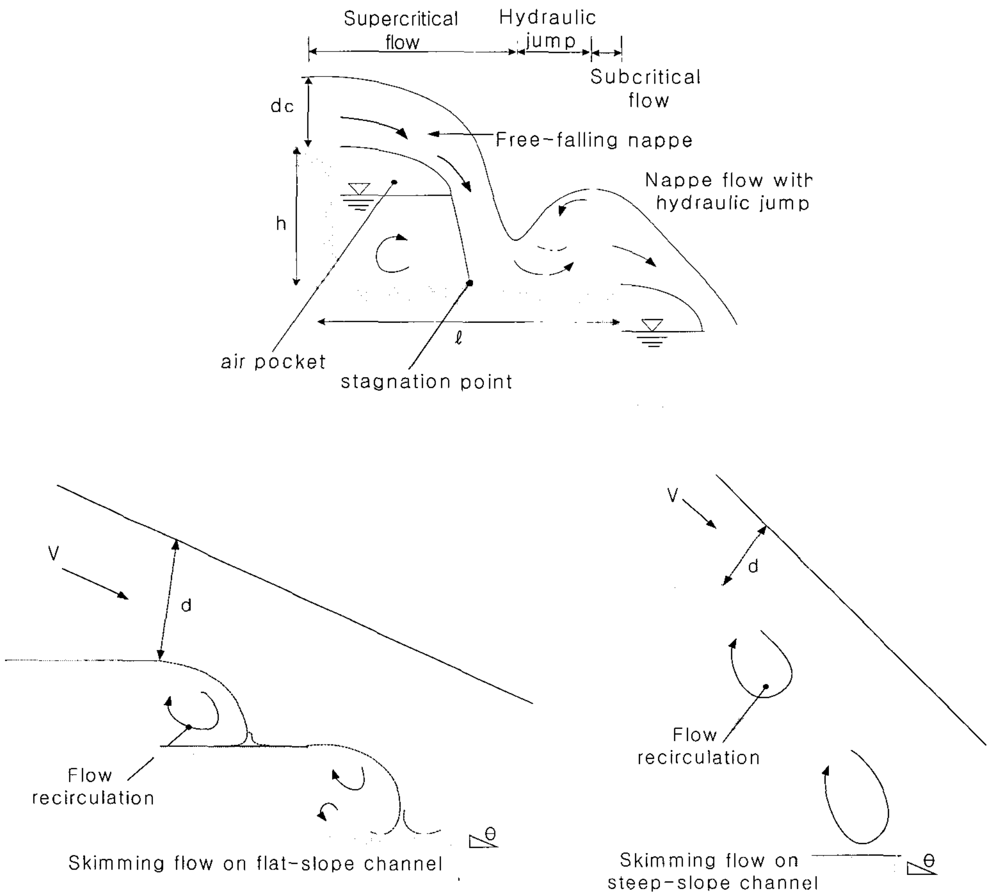

Fig. 1. Sketch of the nappe and skimming flow

At larger flow rates and for relatively steep chute, skimming flow occurs. The flow skims over the step edges with formation of recirculating vortices between the main stream and the step corners. The water flows down in a coherent stream where external edges determine a pseudo-bottom defined by the straight line that connects the edges of each step. Most energy is dissipated in maintaining the recirculation in the step cavities (Chanson, 1993).

In a skimming flow, the free surface on the upper steps is clear and transparent. A turbulent boundary layer develops along the step edges. When the outer edge of the boundary layer reaches the free surface, free surface aeration takes place.

For intermediate flow rates, the flow exhibits strong splashing and droplet ejections at any position downstream of the inception point of free surface aeration: i.e. the transition flow regime. The transition flow has a chaotic appearance with numerous drop ejections that are seen to reach heights of up to 3 to 8 times the step height (Chanson and Toombes, 2004).

The transition between nappe and skimming flow is related to the flow rate, chute slope, step geometry and local flow properties. However this distinction does not seem to create well defined limits as for each geometric configuration (Fratino and Piccinni, 2000). As far as known, there are currently no criteria to determine the occurrence of the different types of the flow.

3. AIR ENTRAINMENT AND ENERGY DISSIPATION

Oxygen transfer by air entrainment occurs mainly from behind the trailing edge of the stepped structures due to flow separation (Kim, 2003). Air bubbles form and proceed to downward direction becoming larger in volume, and finally become broken and disappeared during proceeding upward.

Abundant dissolved oxygen is stored with breaking of the air bubbles, and this would give the good habitat condition at the downstream part of the structure. Hydraulic jump makes the air entrainment more active. Occurrence interval of the air entrainment increases when the flow becomes supercritical with Froude number larger than unity.

The efficiency of the oxygen transfer E is used for representing the efficiency of the air entrainment (Avery and Novak, 1978);

$$E = (C_d - C_u)/(C_s - C_u) \tag{1}$$

where C_d and C_u are dissolved oxygen measured at downstream and upstream point, respectively, and C_s is the saturated dissolved oxygen.

Since the oxygen transfer is affected by the water temperature, E is substituted by E_{20} (Gulliver et. al., 1990);

$$\frac{\ln(1-E_T)}{\ln(1-E_{20})} = 1.0 + \alpha(T-20) + \beta(T-20)^2 \tag{2}$$

where E_T and E_{20} are the oxygen transfer efficiencies at temperature T °C and the reference temperature 20°C, respectively. α and β are constants as α =0.02103 $°C^{-1}$, $\beta=8.621\times10^{-5}$ $°C^{-2}$.

Stepped drop structure is the typical case for energy dissipation which is one of the most important features in the design of many hydraulic structures.

The dissipation efficiency and the mechanisms that determine and improve its effectiveness are defined using different evaluation processes for nappe and skimming flow regimes (Fratino and Piccinni, 2000). In the first case, energy dissipation is due to jet impact on the underlying water cushion and subsequent hydraulic jump. In contrast, most of the energy is dissipated in maintaining the recirculation vortices beneath the pseudo-bottom formed by the edges of the steps in the skimming flow regimes.

Dissipation equation for the nappe flow regions is represented by (Fratino and Piccinni, 2000),

$$\frac{\Delta H}{H_{\max}} = 1 - \frac{H_{res}}{H_{\max}} = 1 - \frac{\lambda + 0.5\lambda^{-2}}{H_{drop}/k + 0.5},$$

$$\lambda = \frac{\sqrt{2}}{1.06 + \sqrt{h/k} + 1.5} \tag{3}$$

where ΔH is the head difference between upstream and downstream of the stepped drop structure, $H_{\max}$ is the maximum total head upstream of the structure, H_{res} is the residual head downstream of the structure, H_{drop} is the structure height, k is the overflow depth at the crest of the structure, and h is the step height.

Dissipation equation for the skimming flow regions is represented by (Fratino and Piccinni, 2000),

$$\frac{\Delta H}{H_{\max}} = 1 - \frac{\left[\frac{f}{8\sin\alpha}\right]^{1/3}\cos\alpha + 0.5\left[\frac{f}{8\sin\alpha}\right]^{-2/3}}{\frac{H_{drop}}{k} + 1.5}$$

$$f = \frac{8g\sin\alpha d^2}{q^2} \bullet \frac{R}{4} \tag{4}$$

where α is the slope of the stepped drop structure, d is the uniform flow depth upstream of the structure, R is the hydraulic radius, q is the discharge per unit width, and f is the friction coefficient representing aeration properties at the overflow sections.

The definition of energy dissipation plays a fundamental role because it is the most important design factor. Although the nappe flow regime could, under ideal conditions, achieve the total dissipation of the head between the crest of the drop structure and the downstream river bed, the limitations imposed by environmental constraints and the approaching flow characteristics render such a structure technically infeasible. The flow regime efficiency must therefore be evaluated in relation to the external conditions imposed on the drop structure, with a design choice that is determined by technical and economic considerations (Fratino and Piccinni, 2000).

Efficiencies of the oxygen transfer and the energy dissipation are estimated by measuring the dissolved oxygen and the total head at the upstream and downstream point of the structures, respectively. Fig. 2 shows the example for measuring points of the drop structure. Here, point A and C is the right and left side of the streams, respectively. Point B is the mid-part of the stream.

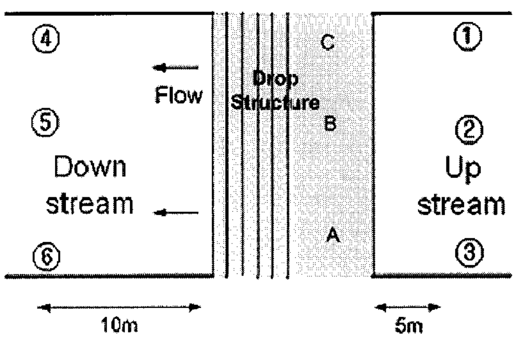

Fig. 2. Plan and measuring points at the drop structure

All the data are measured 5m upstream and 10m downstream of the structures for considering the data consistency.

4. EXPERIMENTAL TESTS

To investigate the air entrainment and the energy dissipation by the flow properties and to estimate the relationships between the air entrainment and the hydraulic parameters of the stepped drop structure, the experimental tests were performed. Fig. 3 shows the experimental arrangements.

The typical model of the stepped drop structure made of waterproof plywood was installed in a recirculatory tilting flume of 0.4m wide, 0.4m deep and 15m long. The sidewall of the flume was made of glass and a transparent scale was attached to the side wall to see the flow features well.

A damper was laid at the upstream section of the flume to reduce the turbulence and to assure the hydraulic feed having negligible kinetic components. Water level was regulated by the down-stream adjustment weir. The discharge which was controlled by a valve in a feed-back loop could be measured with a v-notch at the upper tank.

The stepped drop model was 0.4m wide and 0.31m high, and five different slopes were selected (1:2.0, 1:1.7, 1:1.5, 1:1.2 and 1:0.7). Hence, in case of the drop model 1:2.0, the model was 0.4m wide, 0.54m long, 0.31m high and on a slope of 30°. The number of steps was 12, each step was 0.4m wide, 0.09m long and 0.052m high.

Flow velocity was measured by using an electromagnetic current meter (model; MI-ECM4). To check the flow pattern, dye injection and a digital camera (model; Olympus c-5050z) with a strong light were used.

5. RESULTS AND DISCUSSIONS

Flow regimes of nappe and skimming flow are shown in Figs. 4 and 5, respectively.

Nappe flow occurs at low flow rates and for relatively large step height. Dominant flow features include an enclosed air pocket, a free-falling nappe impact and subsequent hydraulic jump on the downstream step. Air inception occurs from the step edge, but most air is entrained through a free-falling nappe impact and hydraulic jump. Air pocket also has an important role to the air entrainment

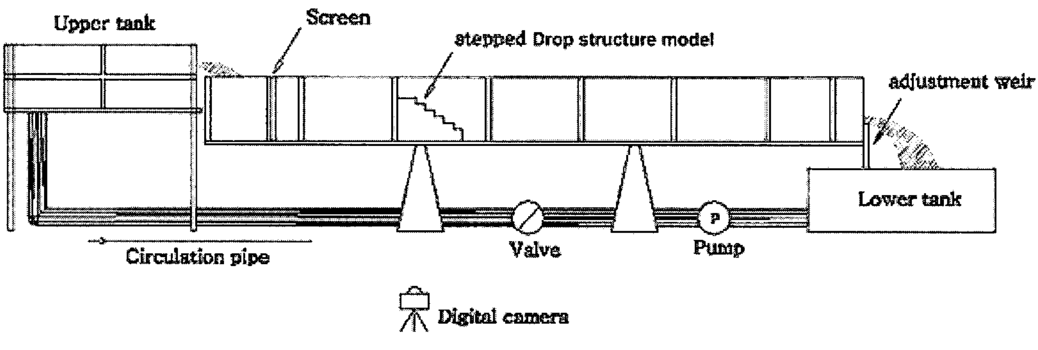

Fig. 3. Experimental arrangement

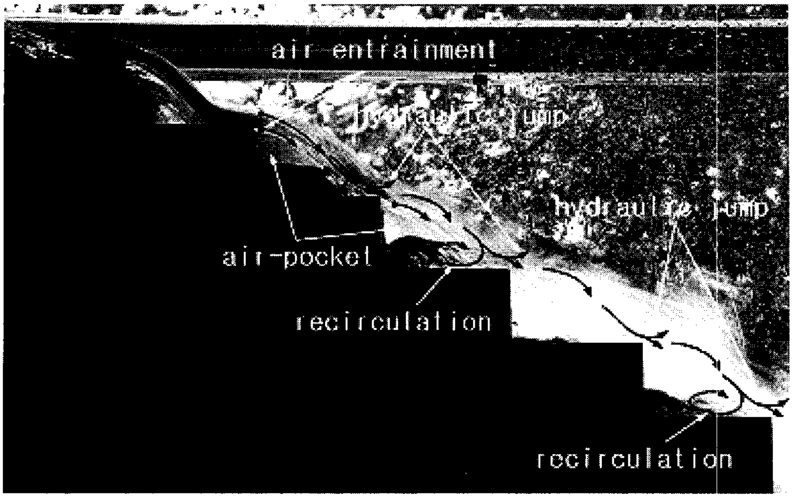

Fig. 4. Nappe flow

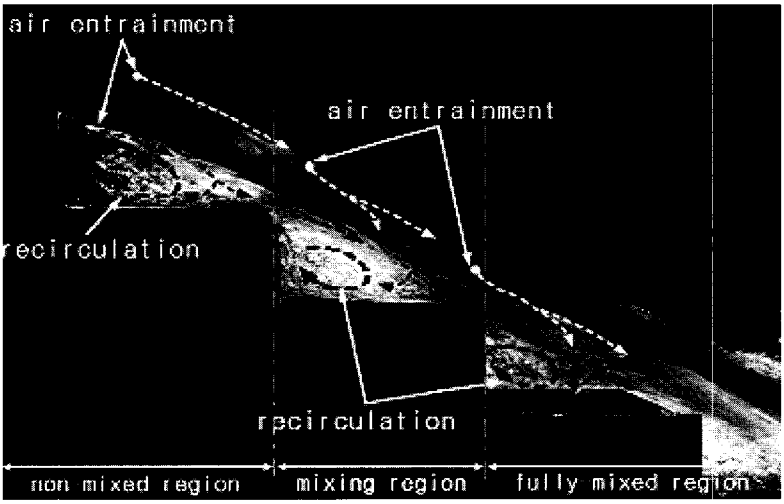

Fig. 5. Skimming flow

The flow accelerated in the downstream direction until a deflected nappe took place. At take-off, free surface aeration was observed at both upper and lower nappes with additional air entrainment at the impact followed by jet breakup. The inception of free surface aeration took place at the first deflected nappe although some bubbles were trapped in cavities immediately upstream of the nappe take-off.

At larger flow rates, skimming flow occurs with formation of recirculating vortices between the main flow and the step corners. Air entrainment occurs from the step edges. Downstream of the inception point, the flow was highly aerated at each and every step with very significant splashing. The flow direction of air-water mixture is almost parallel to the pseudo-bottom formed by the step edges although shapes of the recirculating vortices beneath the main flow alternate from step to step.

Vortex begins at the upper step and becomes developed at the subsequent downstream step. At the stage of developing vortex, vortex formation is not clear and unstable. Two or three vortices occur and disappear reciprocally. A smaller vortex near the step corner is generated with flow direction opposite to the larger one. Vortex formation is clear and stable at the stage of developed vortex.

Fig. 6 shows the transition between the nappe and skimming flow. In this case, the skimming flow and the nappe flow occurred at an upper steps and lower steps, respectively. It does not have the quasi-smooth free surface appearance of skimming flow, nor the distinctive succession of free falling nappes observed in nappe flow.

In transition flows down the step slope, the upstream flow is non-aerated as shown in Fig. 6. The free surface exhibited however an undular profile in phase with the same wave length as the stepped invert profile. The flow appeared to accelerate above filled cavities, while deceleration occurred at nappe impact immediately downstream of hydraulic jump.

Air entrainment was occurred mainly from behind the trailing edge of the drop structure due to flow separation. Air bubbles were formed and proceed to downward direction becoming larger in volume, and finally become broken and disappeared during proceeding upward. Abundant dissolved oxygen was stored with breaking of the air bubbles and this would give the good habitat condition, which is the same ecological feature as riparian riffles (Kim and Park, 1999; Lee and Kim, 1999). Hydraulic jump made the air entrainment more active. Occurrence interval of the air entrainment increased when the flow becomes super-critical with Froude number larger than unity.

Table 1 shows the experimental data and Figs 7 and 8 show the relationships between oxygen transfer and hydraulic parameters.

Where Q is the flow discharge, DO is the dissolved oxygen, T is the water temperature, V is the overflow velocity, Fr is the Froude number ($=V/(gk)^{0.5}$) and k is the overflow depth DO and pH were measured 5m upstream and

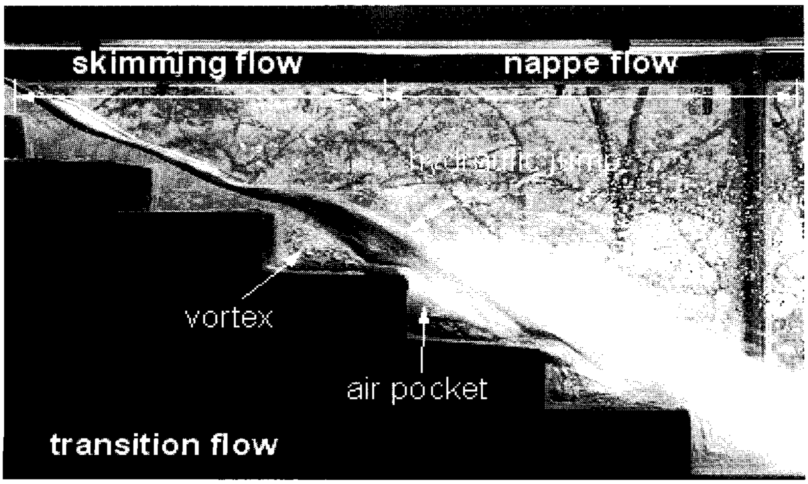

Fig. 6. Transition flow

Table 1. Experimental data on the water quality and the hydraulic parameter

Flow(run)		DO(mg/l)		pH		T	E_{20}	V	Fr	k
		up	down	up	down	(℃)	(-)	(m/s)	(-)	(cm)
All nappe flow Q=0.0032m^3/s	1	6.90	7.97	8.39	8.34	21.3	0.423	0.528	1.377	1.50
	2	6.91	7.93	8.31	8.43	21.1	0.398	0.466	1.141	1.75
	3	6.89	7.75	8.40	8.38	22.4	0.427	0.495	1.249	1.60
	4	6.90	7.81	8.36	8.39	22.0	0.458	0.495	1.250	1.60
	5	6.89	7.79	8.37	8.41	22.2	0.445	0.440	1.047	1.80
skimming flow Q=0.0064m^3/s	1	7.43	7.88	8.54	8.60	22.0	0.310	0.636	1.285	2.55
	2	7.45	7.81	8.64	8.66	22.2	0.252	0.612	1.212	2.60
	3	7.39	7.77	8.61	8.65	21.3	0.233	0.636	1.285	2.55
	4	7.41	7.83	8.57	8.62	21.2	0.261	0.663	1.366	2.40
	5	7.40	7.78	8.60	8.59	20.9	0.235	0.589	1.145	2.70
skimming flow Q=0.0086m^3/s	1	7.54	7.81	8.71	8.69	22.1	0.201	0.764	1.458	2.80
	2	7.57	7.81	8.75	8.71	22.2	0.184	0.725	1.348	2.95
	3	7.48	7.74	8.72	8.75	22.1	0.186	0.778	1.498	2.75
	4	7.52	7.79	8.69	8.71	22.1	0.198	0.738	1.383	2.90
	5	7.55	7.78	8.74	8.69	22.0	0.188	0.750	1.420	2.85
skimming flow Q=0.0112m^3/s	1	7.43	7.83	8.68	8.69	22.0	0.276	0.875	1.562	3.20
	2	7.53	7.85	8.74	8.70	22.1	0.237	0.848	1.491	3.30
	3	7.55	7.91	8.71	8.73	22.1	0.271	0.861	1.526	3.25
	4	7.48	7.89	8.69	8.71	22.2	0.294	0.823	1.426	3.40
	5	7.51	7.88	8.72	8.70	22.1	0.270	0.811	1.395	3.45
skimming flow Q=0.0138m^3/s	1	7.41	7.87	8.73	8.75	22.3	0.313	0.935	1.552	3.70
	2	7.49	7.91	8.71	8.75	22.2	0.302	0.974	1.652	3.55
	3	7.46	7.89	8.72	8.77	21.2	0.276	0.961	1.617	3.60
	4	7.42	7.88	8.75	8.73	21.1	0.289	0.988	1.687	3.50
	5	7.51	7.98	8.73	8.74	21.2	0.313	0.947	1.584	3.65

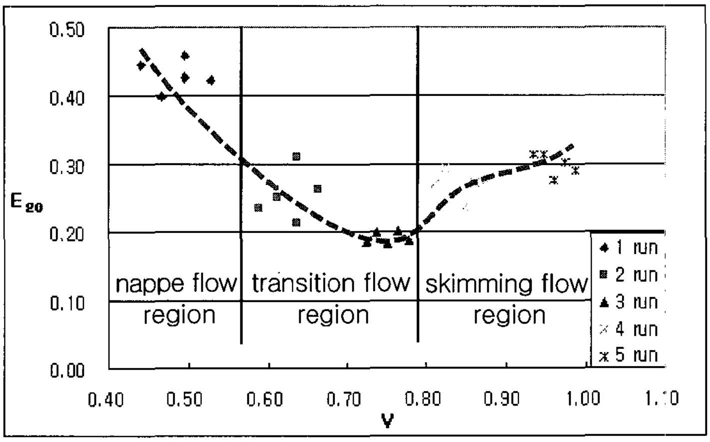

Fig. 7. Relationship between oxygen transfer and Flow velocity

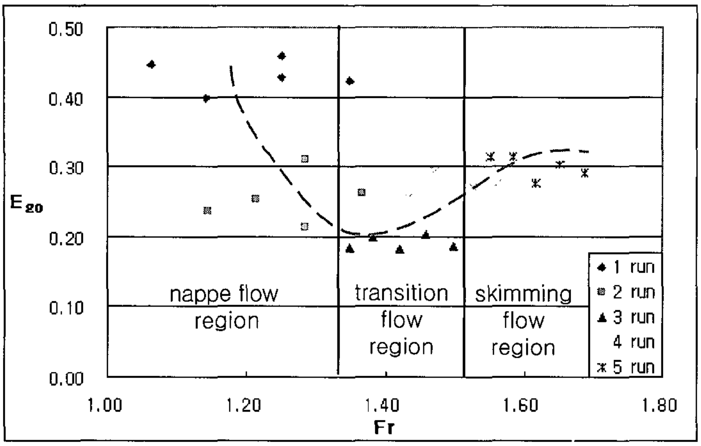

Fig. 8. Relationship between oxygen transfer and Froude number

10m downstream of the structures. V and k were estimated at the overflow section upstream of the drop structure.

Oxygen transfer is proportional to the flow velocity, the flow discharge, and the Froude number. It was more related to the flow discharge than to the Froude number, which means that the oxygen transfer increases when the flow depth decreases.

Figs. 7 and 8 show that flow condition changes from a nappe flow to a skimming flow as the flow velocity and Froude number increase. The transition between nappe and skimming flow was shown to occur at region of v=0.56~0.79(m/s) and Fr=1.32~1.51. However this distinction did not create well defined limits as was suggested by Fratino and Piccinni (2000)

Oxygen transfer becomes smaller and reaches to minimum value at the beginning stage of a skimming flow, but becomes larger in the region of skimming flow because air entrainment is made mainly through a free-falling nappe impact, a hydraulic jump and an air pocket in the region of nappe flow.

The average values of the oxygen transfer efficiency in the region of the nappe flow and in the region of the skimming flow are about 0.45 and 0.28, respectively. The stepped drop structure is found to be efficient for water treatment associated with substantial air entrainment.

Fig. 9 shows the relationships between the energy dissipation and the ratio of overflow depth and step height in the region of nappe flow. Here, ΔH is the head difference between upstream and downstream of the stepped drop structure, $H_{\max}$ is the maximum total head upstream of the structure, k is the overflow depth at the crest of the structure, h is the step height, and L is the step length. Hence, h/L means the step slope. The straight line is the theoretical results of equation (3).

Energy dissipation is proportional to the step height and is inversely proportional to the overflow depth, and is not proportional to the step slope, which means that it takes place through the jet impact on the underlying water cushion and the subsequent hydraulic jump.

Experimental values except for those of *h/L*=0.50 showed the similar results to those of Fratino and Piccinni(2000), and the theoretical results, which is due to the longer interval of

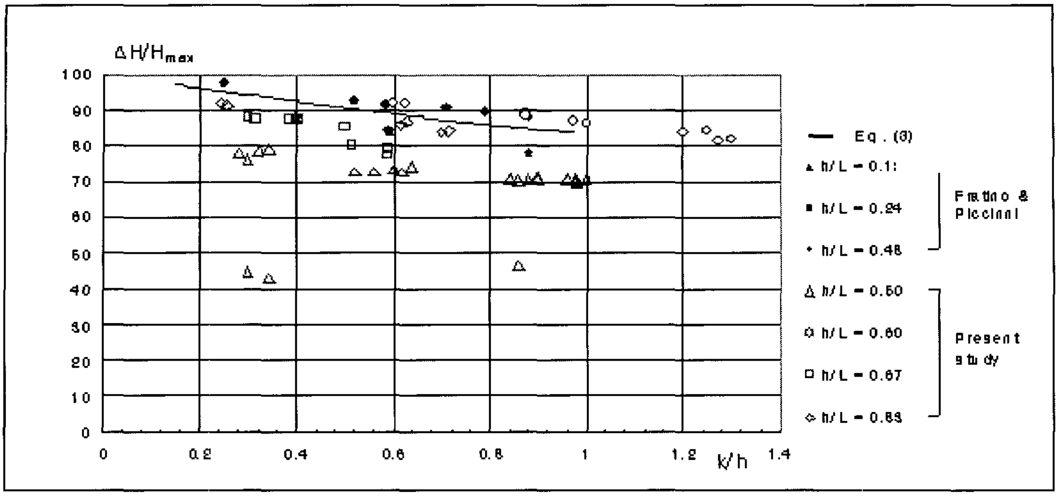

Fig. 9. Energy dissipation in the nappe flow

occurrence of the hydraulic jump. But this must be verified quantitatively through further more experimental results.

Fig. 10 shows the relationships between the energy dissipation and the ratio of structure height and overflow depth with parameters of step slope in the region of skimming flow. Two curves are the theoretical results of equation (4), the upper one and lower one correspond to slope angle α =60°and α =6°, respectively.

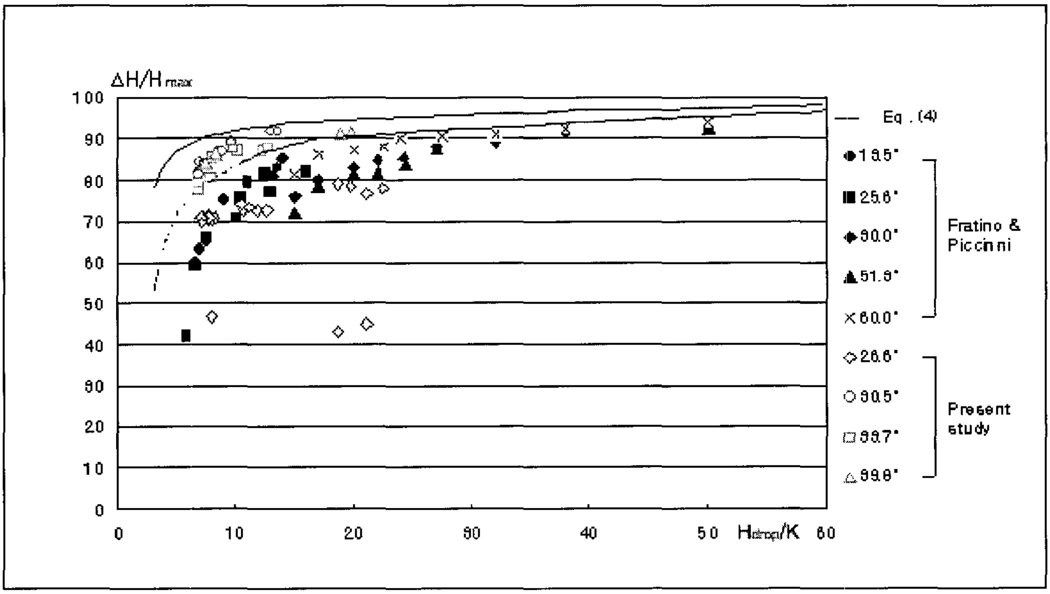

Fig. 10. Energy dissipation in the skimming flow

Energy dissipation is proportional to the height of the stepped drop structure and is inversely proportional to the overflow depth, and is not proportional to the step slope. Significant energy dissipation takes place through the maintenance of recirculating vortices and the variations of free surface water profile.

Experimental values except for those of slope angle 50°and 26°showed the similar results to those of Fratino and Piccinni(2000), and the theoretical results of α =6°, which is almost the same results as those of the nappe flow. Experimental results on the energy dissipation of nappe and skimming flow must be verified quantitatively through further more results.

6. CONCLUSIONS

Nappe flow occurred at low flow rates and for relatively large step height. Dominant flow features included an enclosed air pocket, a free-falling nappe impact and subsequent hydraulic jump on the downstream step. Air inception occurred from the step edge, but most air was entrained through a free-falling nappe impact and a hydraulic jump. Air pocket also had an important role to the air entrainment.

At larger flow rates, skimming flow occurred with formation of recirculating vortices between the main flow and the step corners. The flow direction of air-water mixture was almost parallel to the pseudo-bottom formed by the step edges although shapes of the recirculating vortices beneath the main flow alternate from step to step.

In transition flows down the step slope, the upstream flow was non-aerated. The free surface exhibited however an undular profile in phase with the same wave length as the stepped invert profile.

Oxygen transfer was found to be proportional to the flow velocity, the flow discharge, and the Froude number. It was more related to the flow discharge than to the Froude number. It became smaller and reached to the minimum value at the beginning stage of a skimming flow, but became larger in the region of skimming flow. The average values of the oxygen transfer efficiency in the region of the nappe flow and in the region of the skimming flow were about 0.45 and 0.28, respectively.

Energy dissipations in both cases of nappe flow and skimming flow were proportional to the step height and were inversely proportional to the overflow depth, and were not proportional to the step slope. Experimental values showed the similar results as the theoretical ones, but they must be verified quantitatively through further more results.

The stepped drop structure was found to be efficient for water treatment associated with substantial air entrainment and for energy dissipation.

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