Flow Characteristics in Nappe Flow over Stepped Drop Structure

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ABSTRACT: This paper deals with flow characteristics on the air entrainment and the energy dissipation in nappe flow over the stepped drop structure. Nappe flow occurred at low flow rates and for relatively large step height. Dominant flow features include an air pocket, a free-falling nappe impact and a subsequent hydraulic jump on the downstream step. Air entrainment occurred from the step edge, through a free-falling nappe impact and a hydraulic jump. Most energy was dissipated by nappe impact and in the downstream hydraulic jump. It was related with the step height and the overflow depth, but not related with step slope. The stepped drop structure was found to be efficient for water treatment and energy dissipation associated with substantial air entrainment.

1 INTRODUCTION

Drop structure which is installed to protect the stream bed against scour may be useful for air entrainment and for energy dissipation by the stepped type of the downstream part of the flow section.

Air entrainment by macro-roughness is useful in water treatment (Chanson, 1993). The stepped drop structure may be one typical example. It is very efficient for water treatment because of the strong turbulent mixing associated with substantial air entrainment. Similarly aeration cascades have been built along polluted and eutrophic streams to control the water quality. They are used in water treatment for reoxygenation, denitrification and volatile organic component (VOC) removals.

The stepped drop structure will also be useful for energy dissipation by nappe impact and the downstream hydraulic jump.

The present study deals with flow characteristics on the air entrainment and the energy dissipation in nappe flow over the stepped drop structure. Hydraulic analysis on the relationships of the air entrainment and the energy dissipation to the hydraulic parameters through the hydraulic experiments.

2 FLOW CHARACTERISTICS OVER STEPPED DROP STRUCTURE

Stepped drop structures may be characterized by two types of flow : nappe flow and skimming flow (Chanson, 1998).

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 and nappe impact and a subsequent hydraulic jump on the downstream step(Fig. 1). Most energy dissipation takes place by nappe impact and in the downstream hydraulic jump.

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(Fig. 1). 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, 1998).

In a skimming flow, the free surface on the upper steps is clear and transparent. A turbulent boundary layer develops along the chute invert. When the outer edge of the boundary layer reaches the free surface, free surface aeration takes place. Downstream the flow becomes fully developed and gradually varied. Further downstream the flow reaches uniform equilibrium.

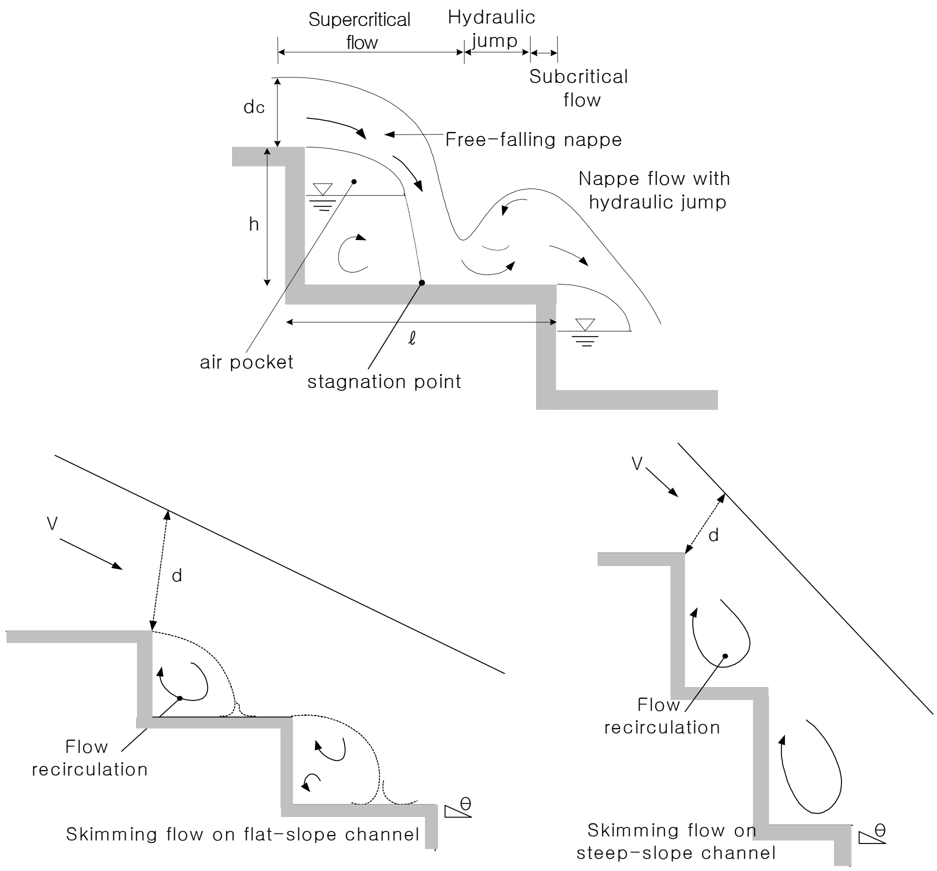

Fig. 1. Sketch of nappe and skimming flow

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).

3 AIR ENTRAINMENT AND OXYGEN TRANSFER

Air entrainment through the oxygen transfer occurs mainly from behind the trailing edge of the overflow weir 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 oxygen transfer efficiency 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, respective-ly, 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);

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

where, E_T and E_{20} are the oxygen transfer efficiencies at temperature T ºC and the reference temperature (20ºC), respectively. α and β are constants as α =0.02103 ºC^{-1} , β=8.621×10^{-5} ºC^{-2} .

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

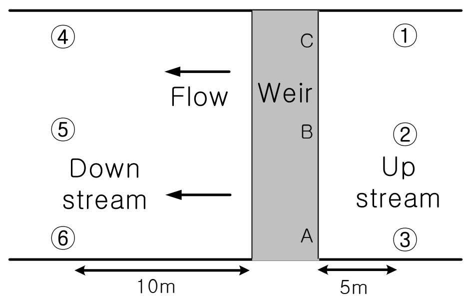

Fig. 2. Plan and measuring points of the drop structure.

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

4 ENERGY DISSIPATION IN NAPPE FLOW

Energy dissipation is one of the most important features in the design of many hydraulic structures. Drop structures may be the typical case for energy dissipation. Rajaratnam and Chamani (1995) have investigated the energy dissipation on the drop 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 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.

The definition of 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).

5 EXPERIMENTAL TESTS

To investigate the flow characteristics and their 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.

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

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

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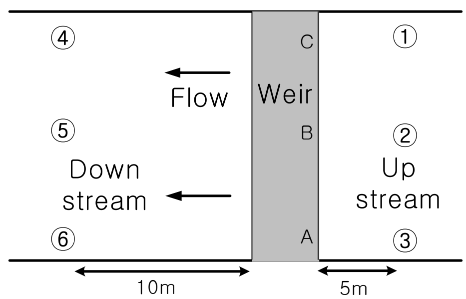

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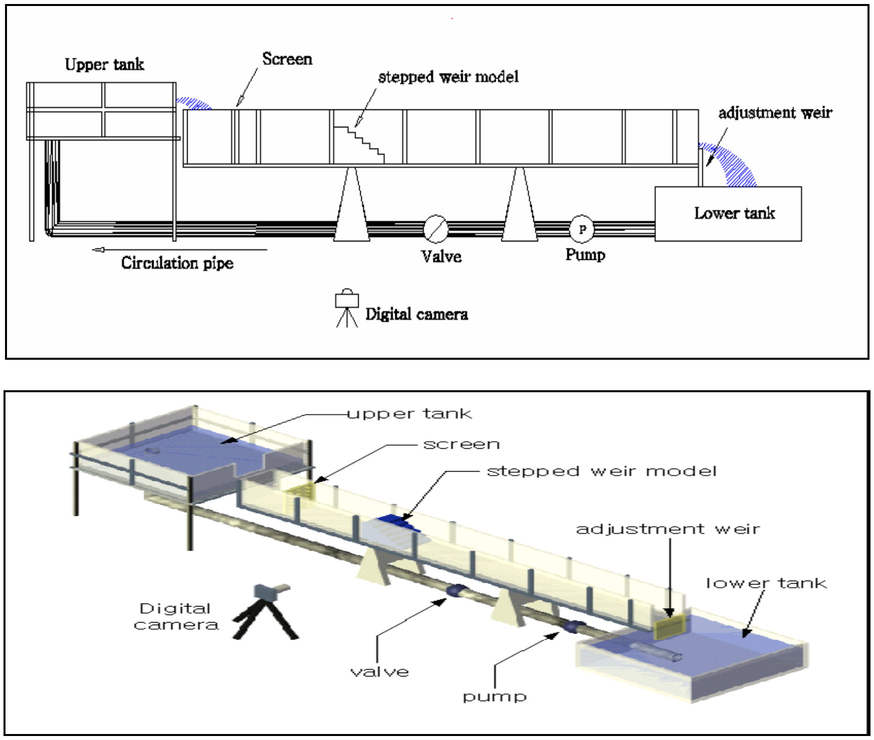

Fig. 3. Experimental arrangement

The typical stepped drop structure model 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 a laser Doppler velocimeter 10MHz of laser frequency. To check the flow pattern, dye injection and a digital camera (model; Olympus c-5050z) with a strong light were used.

6 RESULTS AND DISCUSSIONS

Fig. 4 shows the nappe flow regime.

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.

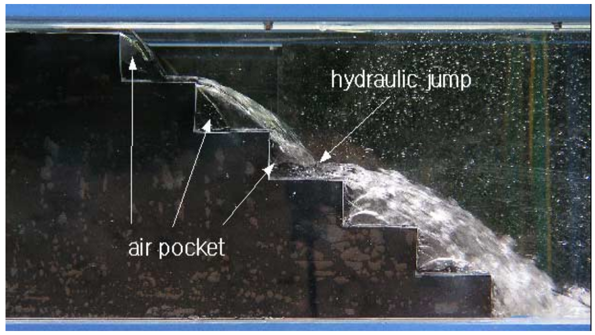

Fig. 4. Nappe flow

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. 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. 5 and 6 show the relationships between oxygen transfer and hydraulic parameters.

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

Flow(run)		DO(mg/l)		pH		T (□)	E_{20} (-)	V (m/s)	Fr (-)	k (cm)
		up	down	up	down					
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
1 step-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
2 step-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
3 step-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
4 step-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

Where, Q is the flow discharge(m^3/s), DO is the dissolved oxygen(mg/l), T is the water temperature(□), V is the overflow velocity(m/s), Fr is the Froude number ($=V/(gk)^{0.5}$) and k is the overflow depth(cm).

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.

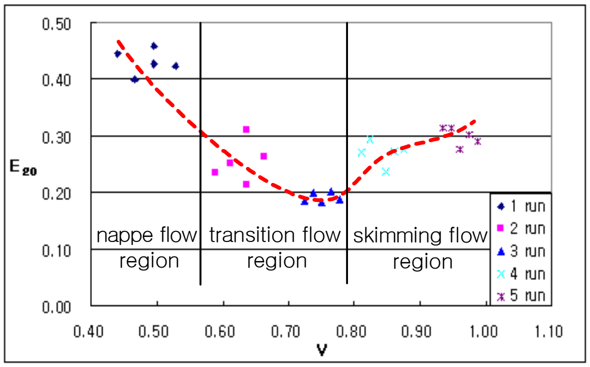

Fig. 5. Relationship between oxygen transfer and Flow velocity

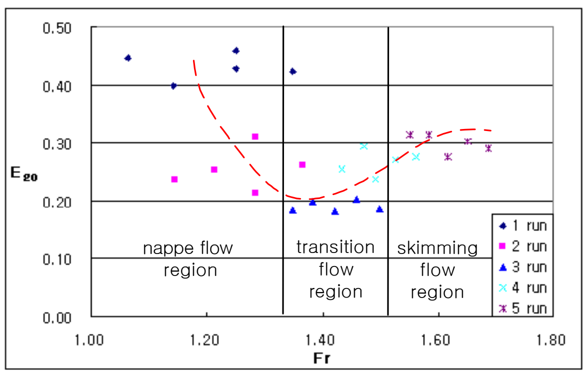

Fig. 6. Relationship between oxygen transfer and Froude number

Figures 5 and 6 show that flow condition changes from a nappe flow to a skimming flow as the flow velocity and Froude number increase. 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. 7 shows the relationships between the energy dissipation and the ratio of overflow depth and step height in the region of nappe flow. Here, H_{max} is the maximum total head at the upstream part of the drop structure, $\Delta H = H_{max} - H_2$, H_2 is the total head downstream of the drop structure, k is the overflow depth at the crest of the drop structure, h is the step height and L is the step length. Hence, h/L means the step slope.

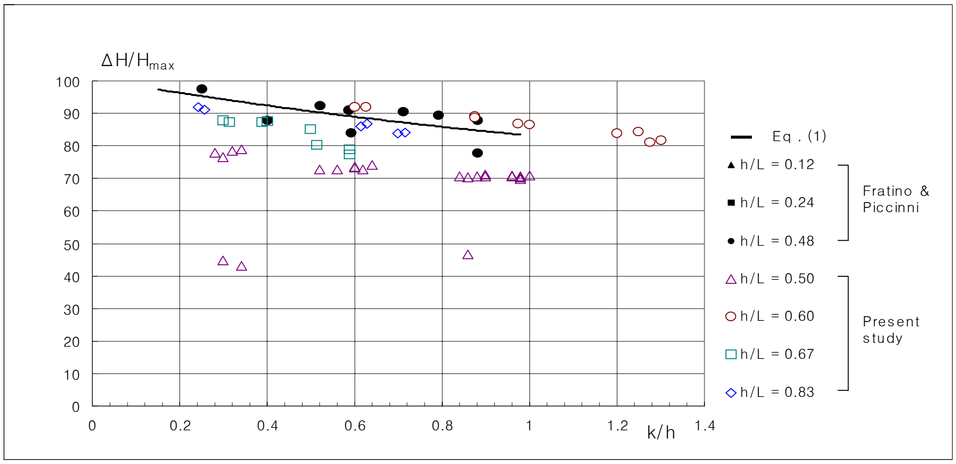

Fig. 7 Energy dissipation in the nappe flow

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

7 CONCLUSIONS

Nappe flow occurred 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 a hydraulic jump. Air pocket also has an important role to the air entrainment.

At larger flow rates, skimming flow occurs with formation of recirculating vortices between the main flow and the step corners.

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 downstream of the drop structure, and this gave the good habitat condition. Hydraulic jump made the air entrainment more active. Occurrence interval of the air entrainment increased when the flow becomes supercritical with Froude number larger than unity.

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.

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8 ACKNOWLEDGEMENT

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