HYDRAULIC ANALYSIS OF OXYGEN TRANSFER THROUGH AIR ENTRAINMENT IN RIPARIAN RIFFLES

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Abstract: This paper presents the hydraulic analysis of the oxygen transfer through the air entrainment and the relationships between the efficiency of the oxygen transfer and the hydraulic parameters in the riparian riffles. Field survey on the pool-riffle formation of the river reach and the measurements of the oxygen transfer in the riffles were performed. Air entrainment occurred more frequently in the edged gravels rather than in the round and edgeless ones, and it was formed mainly from behind the trailing edges of the gravels. Oxygen transfer was found to be proportional to the flow velocity, the flow discharge, and the Froude number, but to be not closely related to the particle diameter. Average value of oxygen transfer in the riffles of study area was about 0.085, which shows good efficiency compared with results of smooth chute. Variation of the water level, which increases in proportion to the flow velocity and the flow discharge, seems to make the air entrainment more active, but has not been verified quantitatively. Relationships between the air entrainment and the variation of the water level must be considered in the further study.

Keywords: oxygen transfer, air entrainment, riparian riffles, pool-riffle formation, Froude number, flow discharge

INTRODUCTION

Riparian riffles are the important fish habitats. Main reason for this is the existence of the abundant dissolved oxygen in the water. The riparian riffles are characterized by high flow velocity and shallow depth. So, they have relatively high Froude number ranging 0.5~0.8, but sometimes larger than unity representing the supercritical flow and the hydraulic jump. They have large bed slopes and large gravels, and hence the oxygen transfer through the air entrainment is made into riffles, which is the similar results as an aeration enhancement by macro-roughness in in-stream cascades or stepped weirs (Chanson, 1993). Dissolved oxygen will be made and with this effect, plenty of algae, aquatic insects and fishes can inhabit in the riffles.

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

In this paper, the hydraulic analysis on the oxygen transfer through the air entrainment, and the relationships between the efficiency of the air entrainment and the hydraulic parameters of the riparian riffles are presented.

Field survey on the pool-riffle formation of a river reach and the measurement of the oxygen transfer in the riffles were performed to determine the relationships between the air entrainment and the hydraulic parameters such as the flow velocity, the flow discharge, Froude number and the particle diameter.

2. FIELD SURVEY OF POOL-RIFFLE FORMATIONS

Field survey of the pool-riffle formations was conducted at Seomjin River flowing through the mid-part of Korea (Fig. 1). This river is environmentally sound and well conserved which is not affected by the artificial human activities (Fig. 2), and hence the naturally meandering pool-riffle systems are well developed (Kim and Park, 1999).

Pool-riffle formations were surveyed at the

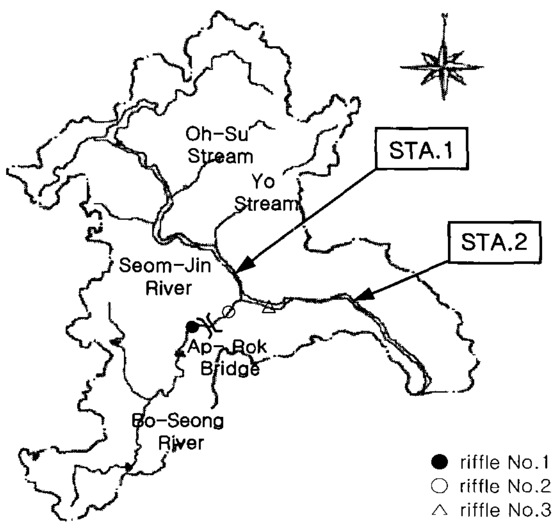

Fig. 1. Sampling sites of Seomjin River.

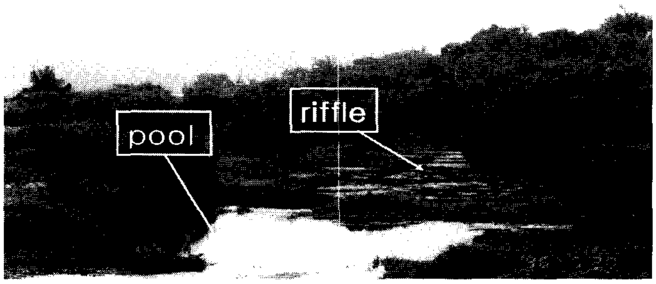

Fig. 2. Typical shape of Seomjin River.

river reach between STA.1 and STA.2, which is about 18750m long.

The riparian riffle is classified into the steep riffle and the plain riffle (Tamai et al., 1993). The former is located upstream of the pool and is characterized by the high flow velocity, the steep bed slope, and the shallow water depth. Water surface appears as consecutive transverse wrinkles. The latter is located downstream of the pool and is characterized by the low flow velocity and the mild bed slope. Flow velocity in the latter is not so high as in the former, but higher than in the pool. Water surface looks as white waves by aeration due to macro-roughness.

The pool is located at the curved part of the stream channel and is characterized by the relatively low flow velocity and the large water depth. The riffles are formed at the flow divergent part, while the pools are formed at the flow convergent part where scour occurs due to flow concentration.

The river reach was divided into 15 sections according to the formation of the pool and the riffle. Classification of the steep riffles and the plain riffles was made by location and appearance of water surface.

Results of the survey are summarized in Tables 1 and 2. Here, L(m) is the reach length between sections along the deepest part of the main stream, H(m) is the average value of the water depth, V(m/s) is the average value of the flow velocity, Fr is the Froude number which is defined as;

$$Fr = V / \sqrt{gH} \tag{1}$$

g (m/s^2)is the gravitational acceleration, B(m) is the flow width, A(m^2) is the section area,

Table 1. Hydraulic characteristics at river reaches (period ; Feb. 18, 2001-Feb. 21, 2001).

Section	L (m)	H (m)	V (m/s)	Fr (-)	B (m)	A (m^2)	D_{50} (mm)	Dominant Stream Type
1	510	0.6	1.2	0.49	80	40800	0.25	Steep riffle
2	270	2.8	0.3	0.06	100	27000	0.25	Pool
3-1	1510	1.0	0.5	0.16	70	105700	45.0	Plain riffle
3-2	1020	2.5	0.6	0.12	50	51000	40.0	Plain riffle
3-3	2120	1.0	1.5	0.48	30	63600	45.0	Steep riffle
4	1210	4.5	0.2	0.03	250	302500	0.20	Pool
5	1420	0.5	1.0	0.45	60	85200	0.60	Steep riffle
6-1	1630	2.0	0.1	0.02	250	407500	0.10	Pool
6-2	2110	4.0	0.2	0.03	150	316500	10.0	Pool
7	1650	0.3	0.8	0.47	60	99000	20.0	Steep riffle
8	620	1.2	0.3	0.09	150	93000	3.00	Pool
9	630	0.3	0.8	0.47	80	50400	27.0	Steep riffle
10	400	4.0	0.1	0.02	100	40000	10.0	Pool
11	460	1.3	0.3	0.08	21	9660	12.5	Plain riffle
12	320	3.0	0.2	0.04	130	41600	2.00	Pool
13	870	0.2	0.5	0.36	20	17400	9.00	Steep riffle
14	710	2.0	0.3	0.07	50	35500	1.00	Pool
15	1290	0.4	0.8	0.40	20	25800	8.50	Steep riffle

Table 2. Characteristics of water quality at river reaches (date ; Feb. 24, 2001).

Section	L (m)	DO (mg/l)	T (℃)	PH (-)	BOD (mg/l)	Turbidity (NTU)	Conductivity (mV)
1	510	7.74	14.5	8.29	1.7	8.0	0.114
2	270	7.24	14.4	8.34	1.1	7.0	0.112
3-1	1510	7.86	15.6	8.28	1.8	7.0	0.114
3-2	1020	8.73	16.1	8.19	1.5	11.0	0.112
3-3	2120	8.87	13.5	8.21	1.5	11.0	0.107
4	1210	8.60	13.1	8.24	1.9	14.0	0.120
5	1420	7.60	15.2	8.01	1.4	15.0	0.117
6-1	1630	8.26	16.8	8.30	1.2	17.0	0.119
6-2	2110	8.65	15.5	8.26	1.6	11.0	0.123
7	1650	8.08	15.7	8.21	1.7	8.0	0.108
8	620	6.97	14.0	8.39	1.8	13.0	0.110
9	630	8.43	14.6	8.21	1.9	9.0	0.108
10	400	8.15	13.7	8.34	2.0	12.0	0.106
11	460	7.63	13.8	8.31	1.9	12.0	0.133
12	320	7.53	13.9	8.39	3.3	44.0	0.113
13	870	7.56	13.5	8.40	3.7	28.0	0.112
14	710	7.63	14.2	8.40	2.6	20.0	0.114
15	1290	7.82	12.3	8.38	1.9	8.0	0.108

D_{50}(mm) is the average value of the particle diameters of the bed materials, DO(mg/l) is the concentration of the dissolved oxygen, T(℃) is the water temperature, pH is the potential of the hydrogen and BOD(mg/l) is the biological oxygen demand.

In Tables 1 and 2, average values were obtained by arithmetic mean of sampling values at 10m intervals along the deepest part of the main stream.

Ranges of the flow velocity and the flow depth of the steep riffles are 0.5–1.2(m/s) and 0.2–1.0(m), respectively, and hence the Froude number is 0.36–0.49. Ranges of the flow velocity and the flow depth of the plain riffles are 0.3–0.6(m/s) and 1.0–2.5(m), respectively, and hence the Froude number is 0.08–0.26. The critical value of the Froude number for classifying the steep riffle and the plain riffle is found to be 0.26-0.36. The water surface of the plain riffles and the steep riffles showed consecutive wrinkles and white waves, respectively.

It seems that flow types of the riffles take narrower and longer shape compared with the pools except for the section 6. The reason is that the pools are located at the curved part, while the riffles are located at the straight part between the pools. Short length of the riffle at section 1 is due to the effect of a fixed weir installed 100m upstream of the river reach. Long length and narrow width of pools at sections 4 and 14 may be uncommon, which will be further considered.

Water quality is relatively good except for the section 12, 13 and 14. High values of BOD and turbidity at these sections are due to the pollutant inflow from village and the embankment works, but these values become decreased at downstream part by self-purification of river flow representing 1.9 of BOD and 8.0 of turbidity.

It can be seen that pool-riffle formation is well developed in this river reach, especially riffle formation will lead to aeration enhancement and oxygen transfer associated with substantial air entrainment, and lead to good conditions of water quality and habitat.

3. MEASUREMENT AND INVESTIGATION OF AIR ENTRAINMENT IN RIFFLES

To investigate the influence of hydraulic characteristics on the air entrainment, the following three sampling riffle sites as the areas of the abundant dissolved oxygen were selected. Two sampling sites located at downstream part of Bo-Seong River, which is the branch of the main Seomjin River, were also selected because of substantial aeration. In these sites, the riverbeds are covered with gravels and the flow velocity is high, which shows the typical features of the riffles.

3.1 Riffle No. 1

Riffle No. 1 is located 700m upstream of the Ap-Rok Bridge shown in Fig.1. A steep riffle characterized by the shallow water depth and the high flow velocity is formed at this reach. The river bed is covered with the gravels and the air entrainment is dominant. The width and length of the riffle are 25m and 50m, respectively.

3.2 Riffle No. 2

Riffle No. 2 is located 1km downstream of the Ap-Rok Bridge. A steep riffle is also formed and the air entrainment appears. The bed slope is relatively high and covered with the gravels. Plenty of algae are attached to the bed gravels, which provide the good habitat for aquatic insects and fishes. The width and length of the riffle are 10m and 13m, respectively.

3.3 Riffle No. 3

Riffle No. 3 is located 5km downstream of the Ap-Rok Bridge and is characterized by the steep riffle and the air entrainment. The bed slope is relatively high and the riverbed is covered with the gravels. The width and length of the riffle are 80m and 30m, respectively.

3.4 Measurement of Values of Water Quality and Hydraulic Parameters

Measured points in the riffles were two along the flow direction and five along the transverse direction, and hence ten points were selected. The points were numbered from upstream to downstream and from left to right consecutively.

Table 3. Measured data at riffle No. 1 (Oct. 5, 2002).

Item Point	DO (mg/l)	pH (-)	T (℃)	V (m/s)	H (m)	q (m^2/s)	D_{50} (cm)	Fr (-)
1	8.06	7.03	21.0	0.601	0.51	0.307	4.40	0.269
2	8.08	6.94	20.9	0.713	0.53	0.381	4.38	0.313
3	8.11	7.00	20.8	0.668	0.53	0.354	5.18	0.293
4	8.08	7.02	21.0	0.804	0.51	0.407	4.91	0.359
5	8.07	6.87	21.0	0.827	0.35	0.290	4.60	0.446
6	8.13	6.94	21.1	0.831	0.58	0.483	5.33	0.348
7	8.17	6.96	20.8	1.013	0.69	0.701	5.27	0.389
8	8.20	6.70	21.0	1.103	0.81	0.893	5.06	0.391
9	8.16	7.01	21.0	0.760	0.78	0.595	4.71	0.274
10	8.15	6.72	20.9	0.470	0.94	0.442	4.95	0.115

Table 4. Measured data at riffle No. 2 (Oct. 5, 2002).

Item / Point	DO (mg/l)	pH (-)	T (℃)	V (m/s)	H (m)	q (m^2/s)	D_{50} (cm)	Fr (-)
1	7.97	6.90	20.2	0.857	0.40	0.343	9.83	0.403
2	8.01	6.99	20.2	0.752	0.57	0.426	8.94	0.318
3	8.04	6.99	20.1	0.990	0.50	0.495	7.50	0.447
4	8.01	7.01	20.0	0.704	0.64	0.452	7.47	0.281
5	8.02	7.50	20.0	0.839	0.46	0.386	7.44	0.424
6	8.05	7.17	20.2	0.548	0.53	0.290	1.26	0.212
7	8.09	7.52	20.2	0.584	0.59	0.342	2.24	0.243
8	8.13	7.80	20.6	0.710	0.62	0.440	1.08	0.287
9	8.10	7.34	20.2	0.666	0.51	0.338	1.52	0.298
,10	8.09	7.22	20.2	0.402	0.68	0.273	1.77	0.176

Table 5. Measured data at riffle No. 3 (Oct. 5, 2002).

Item / Point	DO (mg/l)	pH (-)	T (℃)	V (m/s)	H (m)	q (m^2/s)	D_{50} (cm)	Fr (-)
1	8.01	6.58	21.0	0.547	0.34	0.186	9.64	0.301
2	8.07	6.61	21.2	0.612	0.57	0.347	7.98	0.259
3	8.02	6.57	21.5	0.920	0.59	0.543	8.74	0.384
4	8.05	6.82	21.0	0.814	0.50	0.404	8.14	0.367
5	8.02	6.58	21.1	0.826	0.84	0.690	9.50	0.287
6	8.10	7.64	21.0	1.004	0.94	0.944	7.84	0.331
7	8.14	6.97	20.8	0.682	0.52	0.355	8.22	0.302
8	8.11	7.75	21.0	0.747	0.44	0.329	8.59	0.360
9	8.12	7.32	21.3	0.590	0.56	0.330	8.67	0.252
10	8.07	7.56	20.9	0.355	0.15	0.053	8.56	0.295

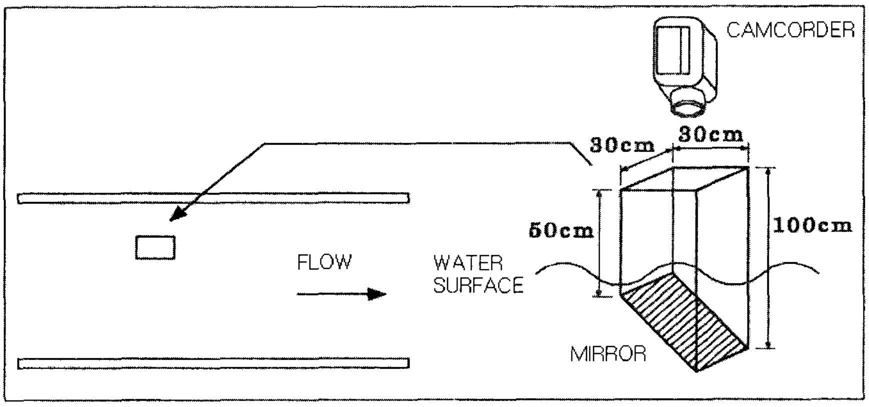

Fig. 3. Experimental apparatus for submerged photographing.

Fig. 4. Air entrainment behind trailing edge of gravels.

Distance between points along the flow direction is 20m and distance between points along the transverse direction is 2m.

Tables 3, 4 and 5 show the measured values of the water quality and the hydraulic parameters at the riffle No. 1, 2 and 3, respectively. Here, q(m^2/s) is the unit discharge and other parameters were listed in Tables 1 and 2.

3.5 Observation of Air Entrainment

Submerged photographing was used to observe the procedure of air entrainment. Fig. 3 shows the experimental apparatus. The hexagonal box made with the transparent acryl plates and a mirror attached to the inclined bottom was prepared and the digital video camcorder was installed inside the hexagonal box for submerged photographing. Observation areas were illuminated by the strong light to get clean views (Lee and Kim, 1999).

4. RESULTS AND DISCUSSIONS

Quantitative relationships between the air entrainment and the hydraulic parameters such as the flow velocity, Froude number, the flow discharge and the average value of the particle diameters of the bed materials were analyzed.

Fig. 4 shows the occurrence of the air entrainment observed by using the above-mentioned method of submerged photographing.

Air entrainment occurred mainly from behind the trailing edges of the gravels due to flow separation. It occurred behind the edged gravels more frequently rather than behind the round and edgeless ones. Air bubbles were formed and swept in the downward direction becoming larger in volume, and finally broke and disappeared. Abundant dissolved oxygen seemed to be stored due to breaking of air bubbles, and this would give the good habitat condition.

Figs. 5 – 8 show the quantitative relationships between the efficiency of the oxygen transfer and the hydraulic parameters using data of Tables 1, 2 and 3. Here the riffle numbers 1, 2 and 3 were mentioned in 3.1, 3.2 and 3.3, respectively, and the measurement of values were mentioned in 3.4. The efficiency of the oxygen transfer, E, was defined as follows (Avery and Novak, 1978);

$$E = (C_d - C_u)/(C_s - C_u) \tag{2}$$

where, C_d and C_u are concentrations of the dissolved oxygen measured at downstream and upstream points, respectively, and C_s is the saturated concentration of the dissolved oxygen. Since the oxygen transfer is affected by water temperature, E is substituted by E_{20} (Gulliver et. al., 1990);

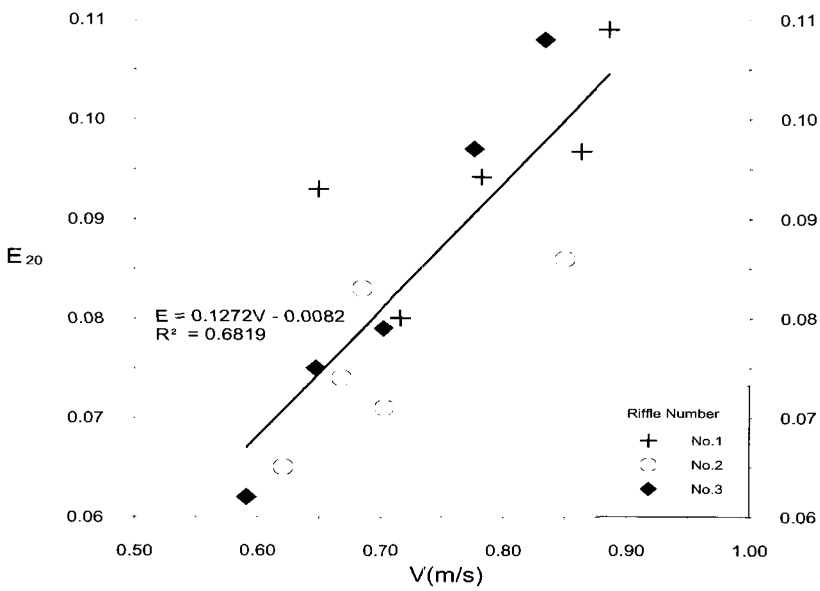

Fig. 5. Relationship between oxygen transfer efficiency and flow velocity

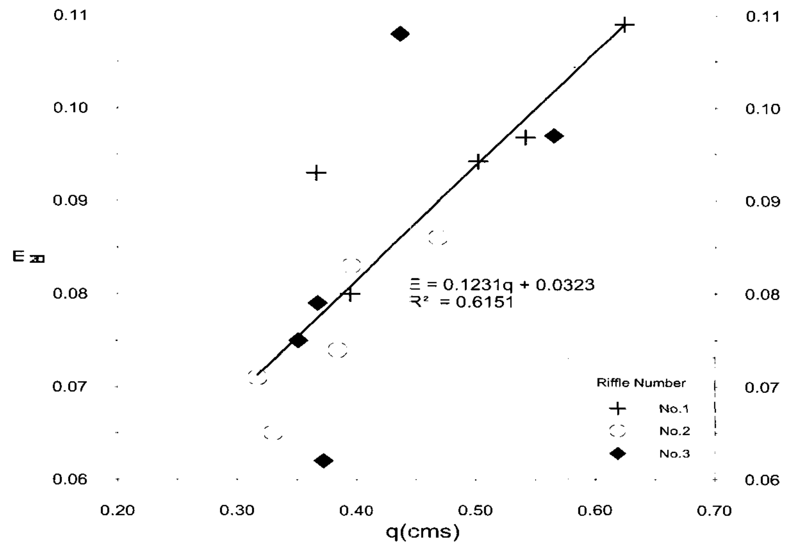

Fig. 6. Relationship between oxygen transfer efficiency and flow discharge

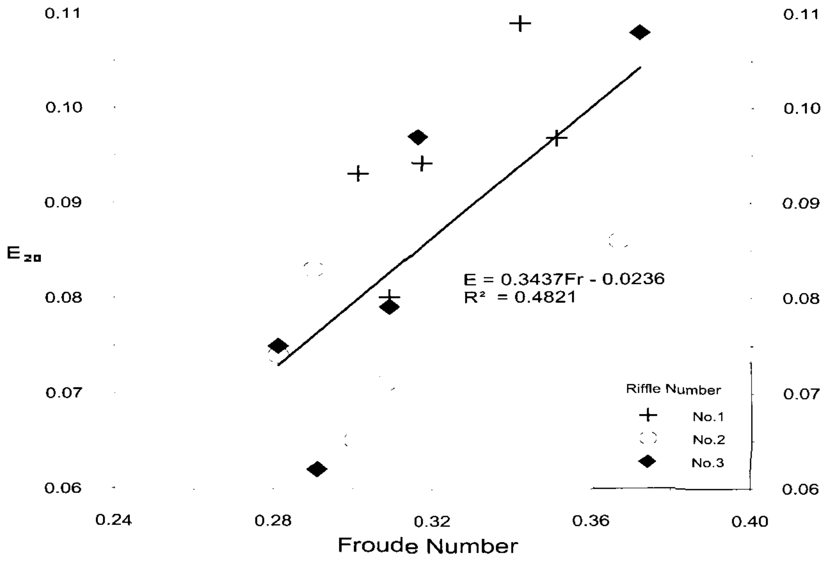

Fig. 7. Relationship between oxygen transfer efficiency and Froude number

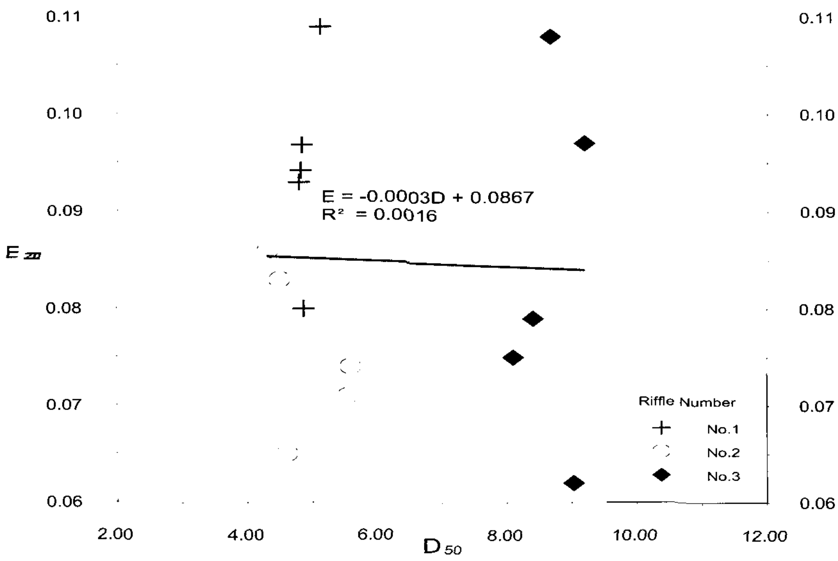

Fig. 8. Relationship between oxygen transfer efficiency andparticle diameter

$$\frac{\ln(1-E_T)}{\ln(1-E_{20})} = 1.0 + \alpha(T-20) + \beta(T-20)^2 \quad (3)$$

where, E_t and E_{20} are efficiencies of the oxygen transfer at a temperature of T°C and the reference temperature (20°C), respectively. α and β are constants given α =0.02103 °C^{-1} and β=8.621×10^{-5} °C^{-2}.

In Figs. 5-8, E_{20} was evaluated per unit length to relate them to the hydraulic parameters quantitatively.

Oxygen transfer was found to be proportional to the flow velocity, the flow discharge and the Froude number. It was not found to be proportional to the particle size of the bed materials as shown in Fig. 8, which can be seen from the fact that air entrainment occurred more frequently behind the edged gravels rather than behind the round and edgeless ones. Therefore, it is related to the particle shape of the bed materials rather than to the particle size.

As can be seen in Figs. 6 and 7, the efficiency of the oxygen transfer seems to be more related to the flow discharge than to the Froude number, although the oxygen transfer increases when the flow depth decreases (Avery and Novak, 1978). Their relationship was not clarified exactly in this study, since the flow depth is proportional to the flow discharge but inversely proportional to the Froude number.

It revealed that verage value of oxygen transfer, E_{20} in the riffles of study area was about 0.085, which shows good efficiency compared with results of smooth chute (Chanson, 1997).

The variation of the water level was found to increase with flow velocity, flow discharge and the particle size of the bed materials and it made the oxygen transfer more active, but was not clarified quantitatively due to rain and strong wind. It is known to be proportional to the oxygen transfer (Henry, 1985). Their relationships must be investigated quantitatively through the site measurements and the hydraulic model tests.

5. CONCLUSIONS

Hydraulic analysis on the oxygen transfer through the air entrainment and the relationships between the oxygen transfer and the hydraulic parameters in the riparian riffles have been presented. Field survey on the pool-riffle formation of a river reach and the measurement of the oxygen transfer were performed to determine the quantitative relationships.

Air entrainment occurred in the edged gravels more frequently rather than in the round and edgeless ones, and it occurred mainly from behind the trailing edge of the gravels. Average value of oxygen transfer in the riffles of study area was about 0.085, which shows good efficiency compared with results of smooth chute.

Oxygen transfer was found to be proportional to the flow velocity, the flow discharge and the Froude number. It was closely related to the flow velocity and the flow discharge more than to the Froude number, but was not proportional to the particle diameter.

Variation of the water level, which increased in proportion to the flow velocity and the flow discharge, made the air entrainment more active, but was not clarified quantitatively. Relationships between the oxygen transfer and the variation of the water level must be considered in the future study.

ACKNOWLEDGEMENT

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Reply to comments

I would like to express my deep gratitude for reading my paper thoroughly and for comments on it. I have revised manuscript in accordance with your comments as follows;

Paper No ; 03-07 B

Title : Hydraulic Analysis of Oxygen Transfer through Air Entrainment in Riparian Riffles

1. Classification criteria of steep riffles and plain riffles used in the field measurements and analysis of the results should be clearly presented in this paper.

- Classification criteria are not definite because many parameters such as flow velocity, flow depth, Froude number, location, and appearance of water surface are included. In this study, classification of the steep riffles and the plain riffles was made by location and appearance of water surface. These statements are described in this manuscript.

2. The measurement method of riffles, pools and several items of water quality in this paper should be explained in definitive. What is the letter L in Table 1. Is the symbol L meaning the length of reach between each sections? If L is meaning the length of riffles or pools, the result of Sections 3-1, 3-2, and 3-3 may be uncommon in natural river because the total length of riffle reach is over 4.65km.

- The terms "In Tables 1 and 2, average values were obtained by arithmetic mean of sampling values at 10m intervals along the deepest part of the main stream." were included.

- The terms "L(m) is the reach length between sections along the deepest part of the main stream" were included.

- B is the flow width, and the river width was not mentioned in this manuscript because the flow itself is concern of air entrainment and oxygen transfer. The river width in this study reach is about 300-800 m and thus the total length 4.65km of section 3-1, 3-2, and 3-3 may be right for considering the results of Newbury and Gaboury (1997), " the interval length of the riffles are 4-6 times of the river width".

3. Range of the flow velocity in steep riffles, 0.5-1.2, is not equal with values in Table 1.

- "0.5-1.2" was revised as "0.5-1.5".

4. Author emphasizes that riffles except Section 6 is narrower and longer shape compare with the pools, but the short length riffle of Section 1, the long length pool of Section 4, and the narrow B pool of section 14 are also except.

- Short length of the riffle at section 1 is due to the effect of a fixed weir installed 100m upstream of the river reach and long length and narrow width of pools at sections 4 and 14 may be uncommon for the present. These will be further considered and studied through the site survey. The terms "Short length of the riffle at section 1 is due to the effect of a fixed weir installed 100m upstream of the river reach. Long length and narrow width of pools at sections 4 and 14 may be uncommon, which will be further considered." were included.

5. It should be reconsidered that the items of water quality of Table 2 are not related to explain "2. Field Survey of Pool-Riffle Formation" and these are not used in other parts of this paper.

- Well-developed pool-riffle formation is effective for river stability and good conditions of water quality. If the river channel becomes straight through the river channel (or embankment) works, the pool-riffle formation will occur from the lower part of the channel. Substantial air entrainment and oxygen transfer occur in the areas of well-developed pool-riffle formations, which will be good conditions of water quality.

- The terms "It can be seen that pool-riffle formation is well developed in this river reach, especially riffle formation will lead to aeration enhancement and oxygen transfer associated with substantial air entrainment, and lead to good conditions of water quality and habitat." were included.

6. Author stresses BOD of Section 12, section 13, and Section 14 are high due to embankment works. The basis should be presented in paper because BOD explains the intensity of organic materials including in water and BOD of downstream Section 15 is measure as 1.9.

- High values of BOD at these sections seem to be the pollutant inflow from village. But these values become decreased along the flow direction by self-purification of river flow representing 2.6 and 1.9 at sections 14 and 15, respectively. The terms "High values of BOD and turbidity at these sections are due to the pollutant inflow from village and the embankment works, but these values become decreased at downstream part by self-purification of river flow representing 1.9 of BOD and 8.0 of turbidity." were included.

7. Estimation 0.26-0.36 of critical Fr for steep riffles and plain riffles should be based on the more data.

- Classification criteria for steep riffles and plain riffles are not definite because many parameters such as flow velocity, flow depth, Froude number, location, and appearance of water surface are included. Estimation of critical value for Fr for steep riffles and plain riffles is also not definite, but is the first trial in this study. Your comments are quite right. It must be studied and modified by more data through the site measurement and the hydraulic model test.

8. It should be explained why are not the surveying sites of riffles included in study reach of main Seomjin River?

- The term "Two sampling sites located at downstream part of Bo-Seong River, which is the branch of the main Seomjin River, were also selected because of substantial aeration." Was included.

9. Data and point locations for calculation of the efficiency of oxygen transfer, E_{20}, in making Figs. 5-8 should hopefully be presented. Also some additional explanations for the estimated values of E_{20} in this paper are needed.

- The term "Figs. 5 – 8 show the quantitative relationships between the efficiency of the oxygen transfer and the hydraulic parameters using data of Tables 1, 2 and 3. Here the riffle numbers 1, 2 and 3 were mentioned in 3.1, 3.2 and 3.3, respectively, and the measurement of values were mentioned in 3.4." was included

- "It revealed that average value of oxygen transfer, E_{20} in the riffles of study area was about 0.085, which shows good efficiency compared with results of smooth chute (Chanson, 1997)." was included.

10. "Occurrence interval of the air entrainment was increased when the flow becomes supercritical" in 5. Conclusions is not enough because the flow conditions of collected data are not included in supercritical.

- It is quite right for your comments. The condition of supercritical flow often occurs in the trailing edge of riffles, but is small and local. As you mentioned, collected data are in the range of subcritical region and thus incorrect statements were removed.

Reply to comments

I would like to express my deep gratitude for reading my paper thoroughly and for comments on it. I have revised manuscript in accordance with your comments as follows;

Paper No ; 03-07 C

Title : Hydraulic Analysis of Oxygen Transfer through Air Entrainment in Riparian Riffles

1. Q(m^3/s) was revised as q(m^2/s) and the flow discharge was revised as the unit discharge.

2. Measured points and distance were revised as ;

- Measured points in the riffles were two along the flow direction and five along the transverse direction, and hence ten points were selected. The points were numbered from upstream to downstream and from left to right consecutively. Distance between points along the flow direction is 20m and distance between points along the transverse direction is 2m.

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