Thermal Effluent through Extruded Side Channel

Yoon, Tae Hoon* · Yook, Woon Soo** · Yi, Yong Kon***

ABSTRACT : The reattachment of buoyant effluent to a shore in a crossflow is investigated experimentally. The effluent is produced by discharging heated water through a projected side channel into a confined crossflow of the same depth. In the projecting effluent, the size of recirculating region, which is formed by deflected thermal plume on the lee of the effluent, tends to increase, but the maximum temperature decreases in the direction of the crossflow and it has more uniform transverse spreading compared to non-projecting type. The heat flux across the crossflow is found to be independent of the projected length of the side channel under relatively high buoyancy flux on the contrary to low buoyancy flux. The reattachment of the effluent can be specified by both velocity ratio and densimetric Froude number, whereas only the velocity ratio is governing factor to the reattachment of the effluent in the case of non-projecting type.

1. Introduction

The most common method of waste disposal such as wastewater and heated water into rivers and coastal environment is the side channel discharge of the full depth into the receiving water. The effluent is deflected by the crossflow, at the same time forcing the crossflow to bend towards the far shore. The jet entrainment on the nearshore side is restricted by the presence of the solid boundary, causing a recirculation region with low pressure. Owing to this low pressure, the jet bends towards the nearshore and eventually reattaches to the shoreline. In the recirculation region, the velocity and turbulence level are low, and thus there is a tendency for pollutant trapped to settle in the region. The nature of the flow in the circulating region imposes a detrimental effects on the shoreline environment. A naturally arising problem is to determine the conditions that the reattachment can be avoided or reduced.

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The problem has been considered in two different cases, nonbuoyant and buoyant effluents. In the case of a nonbuoyant jet, Rouse (1957) found that in a plane two- dimensional jet the length of the recirculation zone increases with 3/2 power of the effluent to crossflow velocity ratio. Mikhail et al. (1975) concluded from their measurements that the size of eddy depends mainly on the momentum flux ratio of the effluent and the crossflow, U_o^2b/U_a^2B. McGuirk and Rodi (1978) employed a depth averaged k-ε model and showed that the geometry of the region is related to the momentum flux ratio.

In a buoyant effluent like the sewage discharge and release of heated water from a powerplant, there is a tendency for the buoyant jet to lift off the bottom and to spread across the crossflow. Studies on buoyant jet through a full depth the same as the crossflow were made by Carter (1969), Rajaratnam and Chu (1978), Kuhlman and Prahl (1974) and Yoon et al. (1992, 1993). Chu and Abdelwashed (1990) proposed criteria for reattachment of the buoyant effluent, and Yoon et al. (1992) expressed it in terms of velocity ratio and effluent densimetric Froude number. The governing factors on the reattachment in buoyant effluent are the momentum flux, buoyancy flux and velocity ratio. However, the extruding length of outfall structure is perceived to be an important factor in reducing or removing the reattachment.

The study is to determine experimentally the dilution and spreading characteristics of the plume, produced by buoyant effluent through an extruded side channel and to determine the conditions required for the reattachment of the plume.

2. Dimensional Analysis

Concerns about the reattachment are the geometry of the recirculating region, concentration of pollutants in the region and its downstream area, and conditions of the reattachment. Important variables of those features are volume flux, $Q_o=bh_oU_o$, momentum flux, $M_o=Q_oU_o$, buoyancy flux, $B_o=g_o'Q_o$, velocity of the crossflow, U_a, depths of the effluent and crossflow, h_o and h, the width of the crossflow, B, and length of extruded side channel, l_o. g_o' is the reduced gravity, $g_o'=(\Delta/\rho_o)g$, $\Delta\rho$ is the density deficiency, $\Delta\rho=\rho_a-\rho_o$. Other variables are defined in Fig. 1. Representative characteristics of the buoyant effluent are the length L, the width, H and the density deficiency $\Delta\rho$ of the recirculating region. Hence, the functional form of the variables is

$$H,\ L\ \text{and}\ \Delta\rho=f_1(Q_o,\ M_o,\ B_o,\ U_a,\ h,\ B,\ x) \qquad (1)$$

The length of the recirculating region, L is defined as the distance between the side channel and the stagnation point at near shore.

In many studies, the effect of volume flux is regarded negligible. The water depth is not an important length scale since the buoyant jet has the same depth as the crossflow, and it has been shown by Robert (1977). Thus, Eq. (1) reduces to

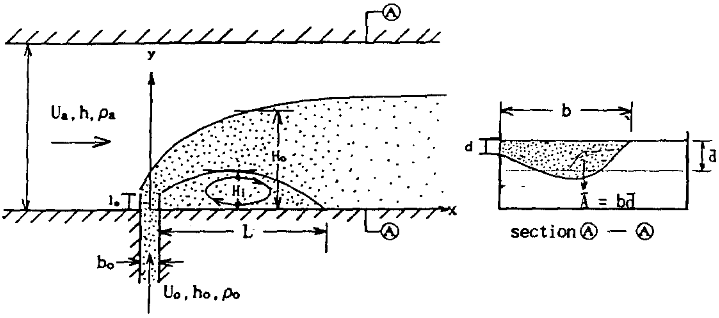


Fig. 1, Definition Sketch of Buoyant Effluent.

$$H, L, \text{ and } \Delta\rho = f_2(M_o, B_o, U_a, B, x) \tag{2}$$

2.1 Nonbuoyant Jet

In the nonbuoyant jet the buoyant flux and density deficiency are not present, and Eq. (1) may be put in nondimensional form as

$$H/l_m, L/l_m = f_3(l_m/B) \tag{3}$$

where $l_m = M_o/hU_a^2 2$ is the momentum length scale, and the distance at which the velocity in the jet decays to the order of the crossflow velocity, which relates the relative effects of jet momentum to the crossflow. That is, for $x/l_m \ll 1$, the jet momentum will dominate and the crossflow will be of secondary importance, while for $x/l_m \gg 1$ the crossflow will have a more direct influence on the jet behavior(Wright, 1977). The same argument applies to the buoyant length scale, l_b as described later.

The dimensionless parameter l_m/B is the ratio of momentum fluxes of effluent to the crossflow. Since $h = h_o$, l_m/B becomes

$$\frac{l_m}{B} = \frac{M_o}{hU_a^2 B} = \frac{hU_0^2}{BU_a^2} \tag{4}$$

2.2 Buoyant Jet

For a buoyant jet which has initial momentum and buoyancy by temperature difference, Eq. (1) can be put in nondimensional form

$$\frac{H}{l_m}, \frac{L}{l_m}, \Gamma = f_4\left(\frac{l_Q}{l_m}, \frac{l_b}{l_m}, \frac{l_m}{B}, \frac{l_0}{l_m}\right) \tag{5}$$

where l_b is a buoyant length scale defined as $l_b = B_o/U_a^3$ and indicates the distance along the jet trajectory where the velocity of the plume decays to the order of the crossflow velocity, $l_Q = Q_o/U_a h$ is a length scale associated with the initial volume flux and Γ is nondimensional temperature difference.

$$\Gamma = \frac{T - T_a}{T_o - T_a} \times 100 \tag{6}$$

in which T is the temperature of the plume, T_a the temperature of the receiving water body and T_o the effluent temperature. Nondimensional parameters in Eq. (5) can be interpreted in the following ways.

$$\frac{l_m}{l_b} = \frac{M_o}{hU_a^2} \frac{U_a^3}{B_o} = \frac{U_o U_a}{g' h} \tag{7}$$

where l_m/l_b quantifies the relative effects of buoyancy.

$$\frac{l_m}{l_h} = \frac{F_{ro}^2}{R} \tag{8}$$

where R is the velocity ratio of the exit velocity of effluent, U_o and crossflow velocity, U_a and

$$R = \frac{U_o}{U_a} \tag{9}$$

F_{ro} is the effluent densimetric Froude number.

$$F_{ro} = \frac{U_o}{\sqrt{g' h}} \tag{10}$$

$$\frac{l_m}{l_b} = \frac{U_o U_a}{g' h} = F_{ro} F_{ra} \tag{11}$$

where F_{ra} is the densimetric Froude number of the crossflow.

$$F_{ra} = \frac{U_a}{\sqrt{g' h}} \tag{12}$$

$$\frac{l_m}{B} = \frac{M_o}{U_a^2 hB} = \frac{U_0^2 A_0}{U_a^2 hB} = \frac{U_0^2 A_0}{U_a^2 A} \tag{13}$$

where A_o and A are the cross-sectional area of the side channel flow and crossflow, respectively.

Eq. (13) is the ratio of effluent momentum flux and momentum flux of the cross flow. Nondimensional parameter l_Q/l_m is turned out as the velocity ratio R.

$$\frac{l_m}{l_Q}=\frac{M_o/hU_a^2}{Q_o/hU_a}=\frac{M_o}{Q_oU_a}=\frac{U_o}{U_a} \tag{14}$$

l_m/l_Q is included in Eq. (8) or Eq. (11) as R, it is excluded in Eq. (5) as

$$\frac{H}{l_m},\ \frac{L}{l_m},\ \Gamma=f_5\left(\frac{l_m}{l_b},\ \frac{l_m}{B},\ \frac{l_o}{l_m}\right) \tag{15}$$

3. Experiment

The experiments were conducted in a wide open channel of 500cm long, 60cm wide and 20cm deep. The effluent was produced by releasing heated water normal to the crossflow through a side channel of 1.0cm wide. The depth of the effluent at the exit of the side channel, 9.5cm is the same as that of the crossflow. The effluent flow was in the range of 3 to 7 liter per min., and the range of the crossflow is 50 to 130 liter per min. Discharges were measured by rotameters, and velocities were determined by discharge and flow sectional area, and a float located at mid-depth. Temperatures were

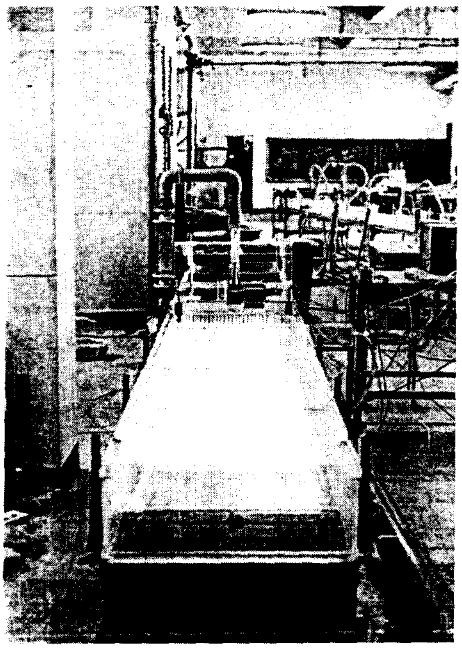


Fig. 2. Experimental Apparatus

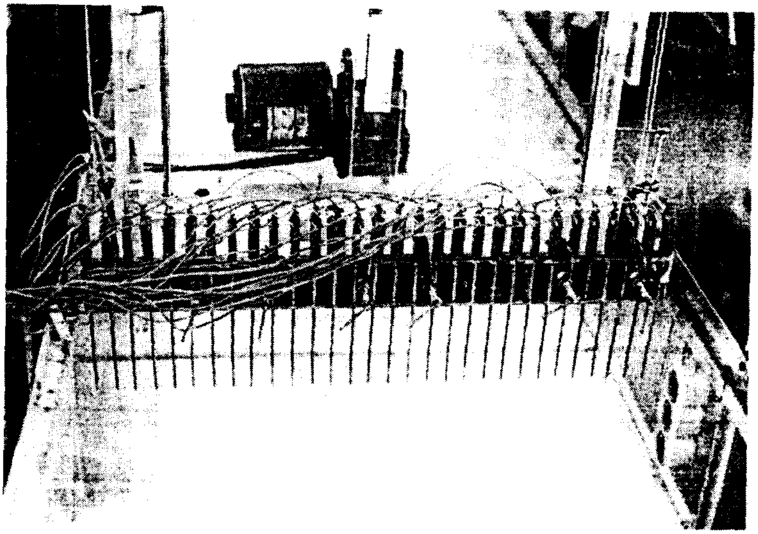


Fig. 3. Temperature Measuring Devices

measured by an array of 15 thermistor probes with 4cm intervals, shifting in horizontal and vertical directions. The thermistor probes are T-type with bead diameter of 3mm and time constant of 30sec. Dye was injected into the effluent for visual observation. The test conditions are summarized in Table 1 and the measured and computed variables are given in Table 2. The length of recirculation region was measured by dye injection at which the dyed effluent reattaches the side wall.

Table 1. Summary of Experimental Conditions

Ex No.	l_0 cm	U_0 cm/s	U_a cm/s	h cm	Q_0 l/min	T_0 ℃	T_a ℃	ΔT ℃	M_0 cm^4/s^2	B_0 cm^4/s^3
L000-1	0.0	9.26	2.44	9.5	5.0	16.6	6.8	9.8	771.64	87.66
L000-2	0.0	3.70	1.95	9.5	2.0	18.2	12.8	5.4	123.21	26.33
L000-3	0.0	11.11	1.46	9.5	6.0	15.9	13.5	2.4	1110.89	35.78
L000-4	0.0	9.26	2.44	9.5	5.0	16.2	13.6	2.6	771.73	30.38
L025-1	2.5	9.26	2.44	9.5	5.0	16.6	7.0	9.6	771.73	86.53
L025-2	2.5	7.41	1.95	9.5	4.0	21.7	12.5	9.2	494.17	103.76
L025-3	2.5	5.56	2.44	9.5	3.0	27.1	13.3	13.8	278.22	138.43
L025-4	2.5	9.26	2.44	9.5	5.0	18.0	13.2	4.8	771.73	61.65
L050-1	5.0	5.56	2.44	9.5	3.0	27.5	10.3	16.9	278.22	159.470
L050-2	5.0	9.26	2.44	9.5	5.0	13.4	4.7	8.7	771.73	52.72
L050-3	5.0	9.26	2.44	9.5	5.0	19.1	9.1	10.0	771.73	118.78
L050-4	5.0	3.70	1.95	9.5	2.0	16.0	11.9	4.1	123.21	18.95
L075-1	7.5	5.56	2.44	9.5	3.0	25.6	12.1	13.5	278.22	125.86
L075-2	7.5	9.26	1.95	9.5	5.0	22.3	12.0	10.3	771.73	146.44
L075-3	7.5	9.26	2.44	9.5	5.0	16.1	7.0	9.1	771.73	79.72
L075-4	7.5	3.70	1.95	9.5	2.0	14.4	9.4	5.0	123.21	17.95
L100-1	10.0	9.26	1.46	9.5	5.0	17.4	11.4	6.0	771.73	70.13
L100-2	10.0	3.70	1.95	9.5	2.0	21.3	11.6	9.7	123.21	52.00
L100-3	10.0	7.41	2.92	9.5	4.0	25.6	11.8	13.8	494.17	172.62
L100-4	10.0	9.26	2.44	9.5	5.0	16.1	6.2	9.9	771.73	82.36

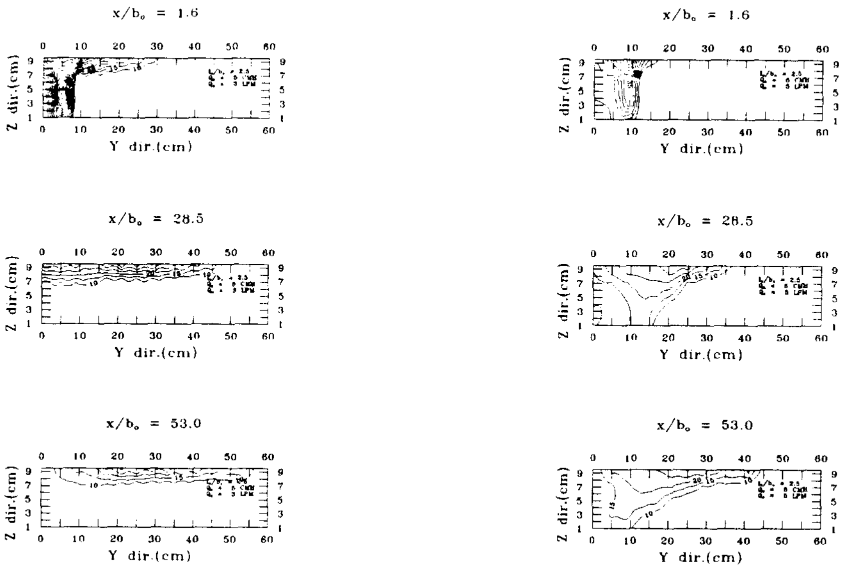
Table 2. Measured and Computed Parameters

Ex. No.	l_o cm	R	L cm	H_o cm	l_m	l_b	F_{ro}	$l_m/l_b = F_{ro}F_{ra}$
L000-1	0.0	3.80	75	15	14.44	6.04	3.01	2.39
L000-2	0.0	1.90	15	5	3.61	3.72	1.36	0.97
L000-3	0.0	7.60	105	30	57.76	11.51	6.17	5.02
L000-4	0.0	3.80	70	15	14.44	2.10	5.11	6.88
L025-1	2.5	3.80	70	17	14.44	5.98	3.03	2.42
L025-2	2.5	3.80	40	15	14.44	14.01	1.98	1.03
L125-3	2.5	2.28	30	10	5.20	9.57	1.11	0.54
L125-4	2.5	3.80	70	17	14.44	4.26	3.59	3.39
L150-1	5.0	2.28	45	15	5.20	11.02	1.04	0.47
L150-2	5.0	3.80	95	21	14.44	3.64	3.88	3.97
L050-3	5.0	3.80	85	28	14.44	7.73	2.66	1.87
L050-4	5.0	1.90	60	15	3.61	2.56	1.64	1.41
L075-1	7.5	2.28	65	15	5.20	8.79	1.16	0.59
L075-2	7.5	4.75	100	22	22.56	19.77	2.33	1.14
L075-3	7.5	3.80	88	23	14.44	5.51	3.16	2.62
L075-4	7.5	1.90	60	17	3.61	2.42	1.68	1.49
L100-1	10.0	6.33	115	32	40.11	23.41	3.36	1.71
L100-2	10.0	1.90	75	17	3.61	7.02	0.99	0.51
L100-3	10.0	2.53	95	25	6.42	6.90	1.53	0.93
L100-4	10.0	3.80	107	25	14.44	5.65	3.10	2.56

4. Results

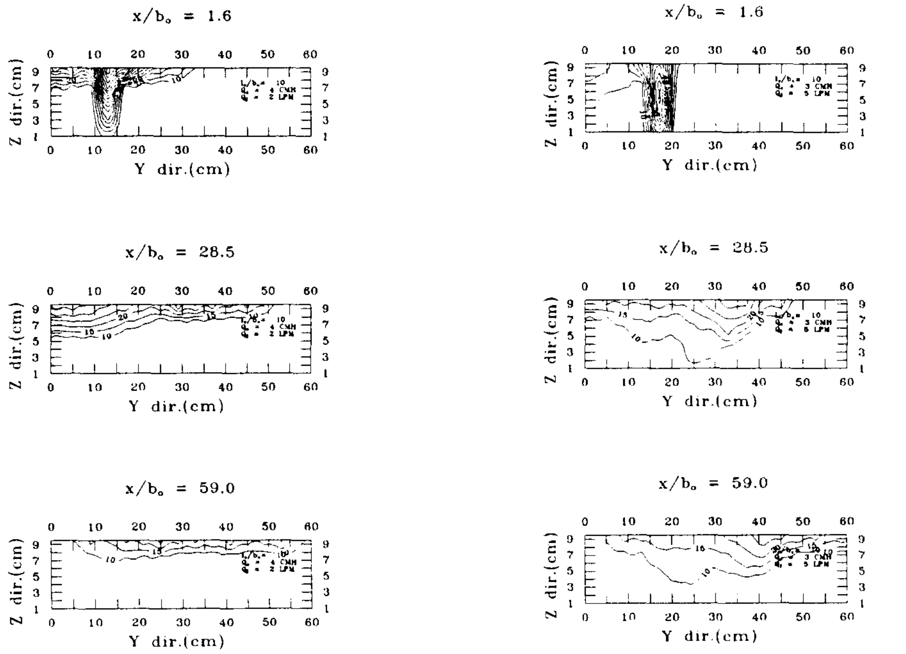
4.1 Flow Pattern

In the case of large temperature difference between the buoyant effluent and the crossflow, the buoyant effluent or plume starts to lift off the bottom at relatively short distance downstream from the exit of the effluent, and then form a surface layer. It is expected that the thickness of the sur-



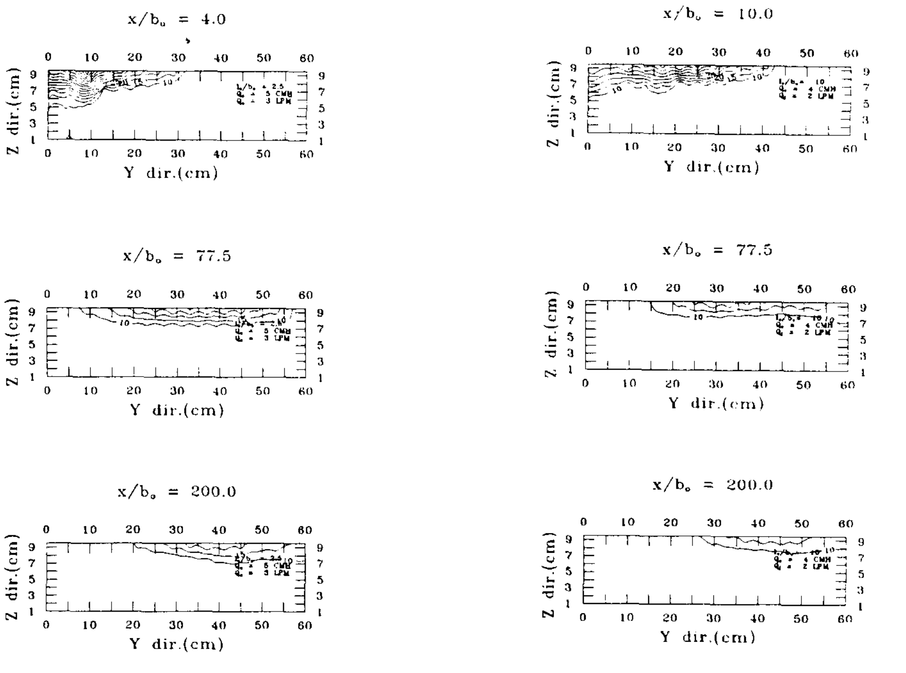
(a) $F_{ro}=1.11$, $\Delta T=13.8$℃, $F_{ro}F_{ra}=0.54$ (b) $F_{ro}=3.59$, $\Delta T=4.8$℃, $F_{ro}F_{ra}=3.39$

Fig. 4. Temperature Contours of Selected Sections of Plume at $l_o/b_o=2.5$ for Different Values of F_{ro}.



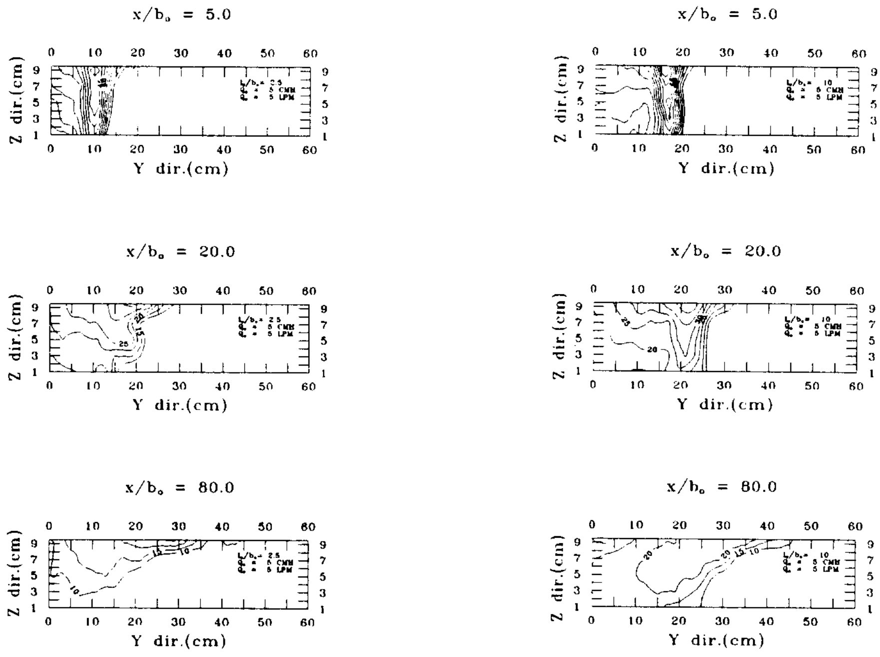
(a) $F_{ro}=0.99$, $\Delta T=9.7$℃, $F_{ro}F_{ra}=0.51$ (b) $F_{ro}=3.36$, $\Delta T=6.0$℃, $F_{ro}F_{ra}=1.71$

Fig. 5. Temperature Contours of Selected Sections of Plume at $l_o/b_o=10.0$



(a) $l_o/b_o=2.5$ (b) $l_o/b_o=10.0$

Fig. 6. Temperature Contours at Selected Sections for Different Extrusion Length and for $F_{ro}F_{ra}\simeq0.51$



(a) $l_o/b_o=2.5$ (b) $l_o/b_o=10.0$

Fig. 7. Temperature Contours at Selected Sections for Different Extrusion Length and for $F_{ro}F_{ra}\simeq 2.50$

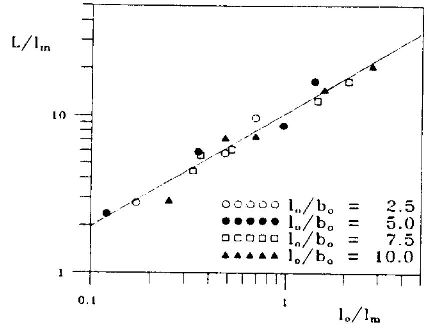


Fig. 8. Length of Recirculating Region

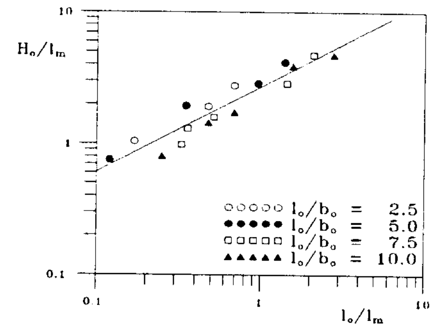


Fig. 9. Width of Recirculating Region

face layer decreases rapidly while moving downstream. Fig. 4(a) and (b) show the temperature distributions at selected sections for extrusion length of $l_o/b_o=2.5$ and temperature differences of $\Delta T=13.8$℃ ($F_{ra}F_{ro}=0.54$) and $\Delta T=4.8$℃($F_{ra}F_{ro}=3.39$) and explain the aforementioned facts. The isotherms in Fig. 4 are defined by Eq. (6). Fig. 5 stands for $l_o/b_o=10.0$, $\Delta T=9.7$℃($F_{ra}F_{ro}=0.51$) and $\Delta T=6.0$℃($F_{ra}F_{ro}=1.71$) and shows similar distributions to the case of $l_o/b_o=2.5$.

Fig. 6(a) and (b) are the temperature contours at selected sections for the cases of identical condition of effluent and crossflow, and different extrusion length. At high effluent temperature or low value of $F_{ro}F_{ra}$, the behavior of the plume is more or less independent of the extrusion length. Howev-

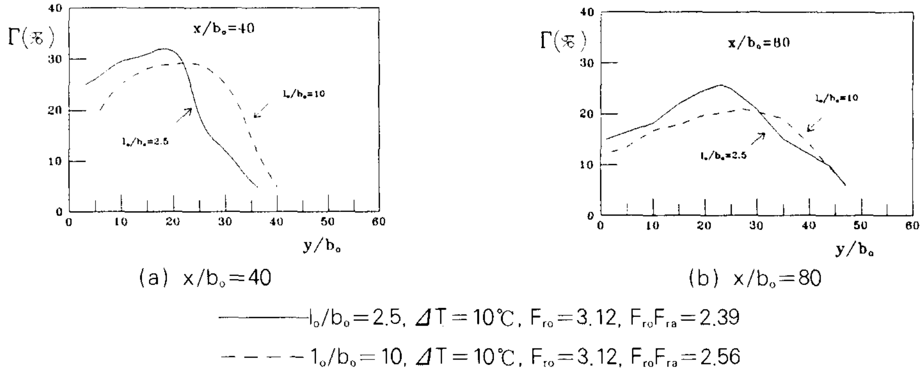


Fig. 10. Lateral Temperature Variation at Water Surface

er, at high values of $F_{ro}F_{ra}=2.41\sim2.56$ or low buoyancy, the lifting of the plume from the bottom is slow but the lateral spreading increases(see Fig. 7).

4.2 Geometry of Recirculating Region and Lateral Temperature Variation

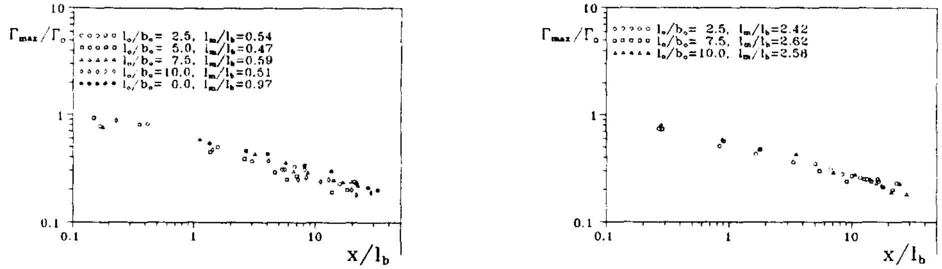
The length and the width of the recirculating region due to horizontal bend of the plume increase with the extrusion length(see Figs. 8 and 9). These features are ascribed to the fact that the enlargement of near field increases the initial mixing and makes the dilution effective. This can be explained in Fig. 10, which shows lateral temperature distribution at water surface. In the case of longer extrusion length, the temperature distribution is evener and the maximum temperature becomes lower. These can be interpreted as the substantial temperature fall at longer extrusion and may be resulted in increased dilution.

4.3 Dilution

As a measure of dilution of the plume, sectional mean temperature can be used. The boundaries of the plume are defined by temperature contour of 10% of the effluent temperature, and the section area of the plume determined in such a way is denoted by $\overline{A}$. The sectional mean temperature Γ is determined by isotherms constructed at 5% interval on the plume sectional area $\overline{A}$ using point temperatures at 15×5 points.

$$\Gamma=\frac{\Sigma\Gamma_i A_i}{A} \tag{16}$$

where Γ_i and A_i are the average temperature and area between temperature contours on $\overline{A}$, respectively. Heat flux for the plume sectional mean temperature is defined as $\Gamma U_a\overline{A}$, nondimensionalized by effluent heat flux $\Gamma_0 Q_0$ and plotted in Fig. 12 for different extrusion length and for $F_{ro}F_{ra}\simeq0.55$. It is noted in Fig. 12 that the heat flux is low at longer extrusion length. This implies that the dilution is effective with low section mean temperature. At high $F_{ro}F_{ra}=2.5$, heat



(a) $F_{ro}F_{ra} \fallingdotseq 0.5$ (b) $F_{ro}F_{ra} \fallingdotseq 2.6$

Fig. 11. Section Maximum Temperature of Plume

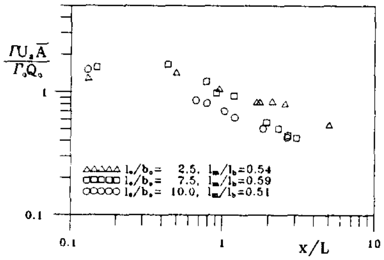


Fig. 12. Heat Flux of Plume for Different Extrusion Length and $F_{ro}F_{ra}=0.55$

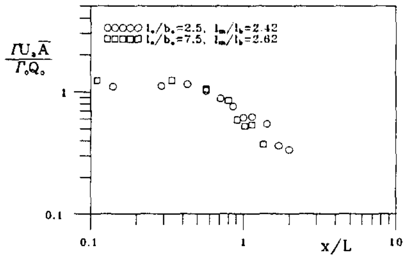


Fig. 13. Heat Flux of Plume at $F_{ro}F_{ra}=2.5$

flux or dilution is nearly independent of the extrusion length(see Fig. 13).

The experiments of the plume discharged at the edge of receiving water body($l_o/b_o=0$) indicate that the heat flux can be expressed as (Yoon, 1992)

$$\frac{\Gamma U_a h H_o}{Q_o \Gamma_o} = 0.7\left(\frac{x}{L}\right)^{-0.23} \tag{17}$$

For the comparison with Eq. (17), the heat flux of the flow area, hHo was constructed in Fig. 14. The slope of -0.3 indicates slightly higher decrease in temperature at the discharge off the edge than the case of discharge at the edge. But the effect of the extrusion is somewhat obscured in the heat flux for whole flow area.

Since the longitudinal velocity decreases and a reverse flow is generated locally in the downstream region from the extrusion channel, actual velocity in the plume area, $\overline{A}$ is less than Ua. Yoon (1992) has shown that the depth averaged width, $\bar{r}$ in the case of $l_o/b_o=0$ can be expressed as

$$\frac{\bar{r}}{H_o} = 1.6\left(\frac{x}{L}\right)^{0.23} \tag{18}$$

The product of Eqs.(17) and (18) is $\Gamma U_a \overline{A}/Q_o\Gamma_o=1.12$. The velocity of an wake, U_a-u is less than the velocity of the crossflow, U_a and u is a velocity defect. Therefore, actual heat flux is equal to Γ

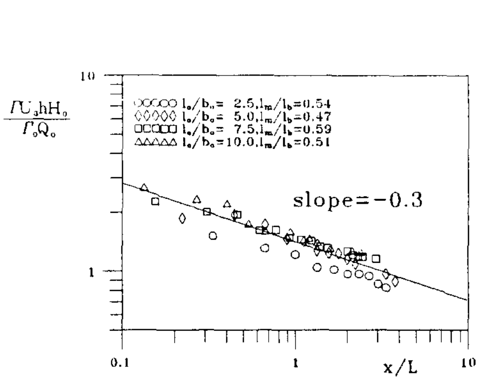


Fig. 14. Heat Flux of Flow Area

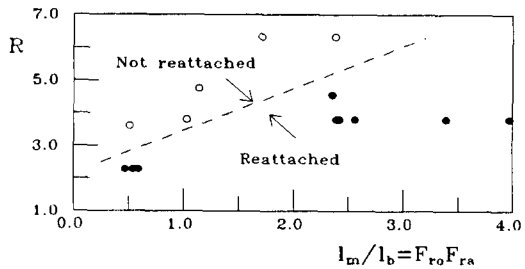


Fig. 15. R and $F_{ro}F_{ra}$ for Reattachment

$(U_a-u)\overline{A}$. Considering that the heat flux is expressed as $\Gamma U_a\overline{A}$, the velocity defect is about 12% of the crossflow velocity, U_a.

4.4 Reattachment Condition for Extruding Effluent

For the nonextruding effluent, condition for reattachment has been given in terms of velocity ratio R(=effluent velocity/crossflow velocity) and densimetric Froude number(Yoon, 1993). For the extruding effluent, the reattachment condition can be specified by the velocity ratio and densimetric Froude number product $F_{ro}F_{ra}$ (see Fig. 15). For the case of the nonextruding effluent, the velocity ratio was found to be dominant factor for the reattachment. But for the extruding discharge, both the velocity ratio and $F_{ro}F_{ra}$ are important factors and the effect of the length of the extruding channel is insignificant.

5. Conclusions

The buoyant effluent was produced by releasing heated water at right angle to an open channel of the same depth through a side channel to investigate experimentally the behavior, reattachment and dilution of the effluent. At low $F_{ro}F_{ra}$(or high buoyancy) the role of extruded effluent is insignificant in lifting off the bottom and in spreading of the plume. By contraries, at high $F_{ro}F_{ra}$(or low buoyancy), earlier lifting off and wider spreading of the plume were observed at longer extrusion length. Discharge off the edge generally improves the dilution by decreasing the heat flux along the plume trajectory. Reattachment can be specified by the velocity ratio and densimetric Froude number product excluding the length of extruded side channel.

Acknowledgment

This research was supported by Korea Electric Power Co., Grant No. 93-92.

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