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Effect of Attachment of Buoyant Jet to Shoreline Pollution in a Confined Crossflow
가로흐름 水域에 放流되는 浮力젵의 歸還에 의한 沿岸汚染

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Abstract□The dilution and the shore attachment of buoyant effluent into a crossflow are investigated experimentally. The effluent is produced by discharging warm water through a side channel into an open channel crossflow with the same depth to the side channel flow. Buoyancy causes the effluent to lift off the bottom, spreads across the crossflow and stays as the surface layer. The geometry of the recirculating region and the dilution of the effluent depend mainly on the buoyancy. The condition of the shore attachment can be specified by the ratios of velocities and Froude numbers.

要 旨: 흐름水域으로 放流되는 側面浮力젵이 沿岸으로 歸還하는 現象과 稀釋傾向에 대해 實驗을 통하여 調査하였다. 實驗에서 低흐름의 가로흐름 水域에 warm-water를 等水深으로 側面放流하여 橫方向으로 퍼짐과 水面으로 上昇하는 熱-plume이 發生하는 浮力젵(buoyant jet)의 歸還現狀을 얻었다. 實驗에서 發生하는 歸還現狀과 汚染停滯地域인 循環領域의 幾何學的 構造 및 稀釋傾向을 Froude數(F), 密度 Froude數(F_o), 浮力 特性길이(l_b)를 利用하여 冪法則(Power law)으로 表現하였다. 實驗結果 歸還現象은 $R(U_o/U_a)<4$, $F/F_o>0.22$일 때 發生하며, 稀釋은 x/l_b에 따라 變化하고 循環領域은 速度比(R)에 따라 變化함을 알 수 있었다.

1. INTRODUCTION

The most common method of waste disposal such as waste water and heated water into rivers and coastal environment is the side channel discharge into the full depth of 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 re-attaches to the shoreline. In the recirculation region, the velocity and turbulence level are low, and thus there is a tendency for pollutant effects on the shoreline environment. A problem natually arised is to determine the conditions that the re-attachment can be avoided or reduced.

The problem has been considered in two different cases, nonbuoyant and buoyant effluents. In the case of 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 measurement that the size of eddy depends mainly on the momentum flux ratio of the effluent and the crossflow, U_o^2b/U_a^2 B. 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 buoyant effuent like the sewage discharge and

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release of heated water from a power plant, 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), Rejaratnam and Chiu (1978), Kuhlman and Prahl (1974). The Chu and Abdelwahed (1990) proposed criteria for reattachment of the buoyant effluent. The governing factors on the re-attachment in buoyant effluent are the momentum flux ratio and velocity ratio. However, the extruding length of outfall structure is perceived to be an important factor in reducing or removing the re-attachment.

Studies are continuing on the reattachment of the buoyant effluent including the extruding length. The present paper is a part of the study and the results including the extruding length are forthcoming.

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 condition of the reattactment. Important variables to 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, and the width of the crossflow, B. A g_o' is the reduced gravity, $g_o'=(\Delta\rho_o/\rho_a)g$, $\Delta\rho_o$ is the density deficiency, and $\Delta\rho_o=\rho_a-\rho_o$. Other variables are defined in Fig. 1. Hence, the functional form of the variables is

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

where H has two components; the inner width, H_i and the outer width, H_o. The latter characterizes the maxinum penetration of the effluent. The length of the recirculating region, L is defined as the distance between the side channel and the stagnation point.

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

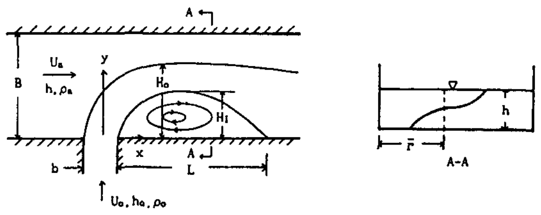

Fig. 1. Definition sketch of buoyant effluent.

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

In nonbuoyant jet, the buoyant flux and density deficiency are not present and Eq. (2) may be put in nondimensional form as

$$H/l_m,\ L/l_m=f_3(l_m/B) \quad (3)$$

where $l_m=M_o/hU_a^2$ as the momentum length scale, which relates the relative effects of jet momentum to the crossflow. That is, for $x/l_m<1$, the jet momentum will dominate and the crossflow will be of secondary importance, while for $x/l_m>1$, 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 appeared later.

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

$$\frac{l_m}{B}=\frac{M_o}{hU_a^2B}=\frac{bU_o^2}{BU_a^2} \quad (4)$$

In buoyant jet into crossflow, Eq. (2) can be written in nondimensional form

$$H/l_m,\ L/l_m \text{ and } \Delta\rho/\Delta\rho_o=f_4(l_b/l_m,\ x/l_b) \quad (5)$$

where $l_b=B_o/U_a^3$ as the buoyant length scale.

3. EXPERIMENT

Experiments were conducted in a wide open channel of 500 cm long, 60 cm wide and 20 cm deep. The effluent was produced by releasing heated water normal to the crossflow through a side channel of 1.0 cm wide. The depth of the effluent at the exit of the side channel, 9.5 cm 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 crossf-

Table 1. Test condition

Test No.	Q_a [m^3/h]	Q_o [LPM]	U_a [cm/sec]	U_o [℃]	T_a [℃]	T_o	F_o
1	5	4	2.41	7.33	19.1	25.2	3.20
3	5	3	2.41	80.4	19.7	21.8	4.20
4	6	5	2.89	9.16	17.3	23.7	2.53
5	5	6	2.89	10.99	13.1	19.1	3.73
6	4	4	1.93	7.33	13.7	24.0	1.78
7	4	5	1.93	9.16	10.6	27.8	1.65
8	4	4	1.93	7.33	11.0	29.0	1.17
9	4	4	1.93	7.33	11.0	25.2	1.53
10	4	3	1.93	6.04	10.5	25.9	1.08
11	4	5	1.93	9.18	11.0	26.0	1.82
13	5	4	2.41	7.33	11.0	25.0	1.34
14	4	4	1.93	7.33	10.2	20.8	1.88
15	4	5	1.93	9.16	10.0	22.0	2.21
16	5	4	2.41	7.33	11.0	27.7	1.36

low is 50 to 130 liter per min. Discharges were measured by rotometers. Velocities were determined by discharge and flow sectional area, and a float located at mid depth. Temperatures were measured by an array of 10 thermistor probes with 2 cm intervals, shifting in horizontal and vertical directions. The thermistor probes are platinum RTd type with bead diameter of 3 mm and time constant of 30 sec. The length of recirculation region was measured by dye injection at the dyed effluent reattaches the side wall. The laboratory experimental conditions and data are given in Table 1.

4. RESULTS

Figure 2 shows nondimensional excess temperature, Γ, which is given by $\Gamma=(T-Ta)/(To\text{-}Ta)$, at $Fo=1.88$, $Bo=111.6\ cm^4/sec^3$ and velocity ratio of effluent to crossflow, $R=Uo/Ua=3.8$ over different flow sections. At the immediate downstream from the exit, the effluent concentrates at the wall over full depth. It is because the buoyancy is weak compared with momentum and there is only a mixing and advection. As flowing downstream, the effluent lifts the bottom and spreads laterally due to buoyancy. At far downstream (Fig. 2), the effluent is transported in drift at water surface layer over the entire width of the channel. At this flow region in drift, the effluent momentum is almost entirely dissipated and the effluent is governed mainly by buoyancy and crossflow.

Experimental data for H_i and H_o are plotted in Fig. 3. Based on these laboratory results, Eq. (3) can be expressed by an explicit form as

$$H_i/l_m=0.37(l_m/B)^{-0.41} \quad (6)$$

$$H_o/l_m=0.52(l_m/B)^{-0.66} \quad (7)$$

In the figure also shown are the results of Chu and Abdelwahed (1990). There exists clear difference between two studies, but its reason is not known.

Figure 4 shows the length of the recirculation zone and according to Eq. (3) the data points are expressed as

$$L/l_m=2.09(l_m/B)^{-0.55} \quad (8)$$

Chu and Abdelwahed (1990) have shown that $L=7H_i$. Figures 3 and 4 provide that $L=5.6\sim7.8H_i$ for the range of $lm/B=0.1\sim1.0$, which is close to $L=7H_i$.

For comparisions with existing data, Fig. 4 is replotted in terms of L/B instead of L/l_m.

It is found that the present data points follow the trend given by McGuirk and Rodi (1978) through the $k-\varepsilon$ turbulence model. In buoyant jet the reattachment length is seen to be a function of l_b/l_m from Eq. (5) and it is confirmed by the data points in Fig. 6. Since the data shown in Fig.

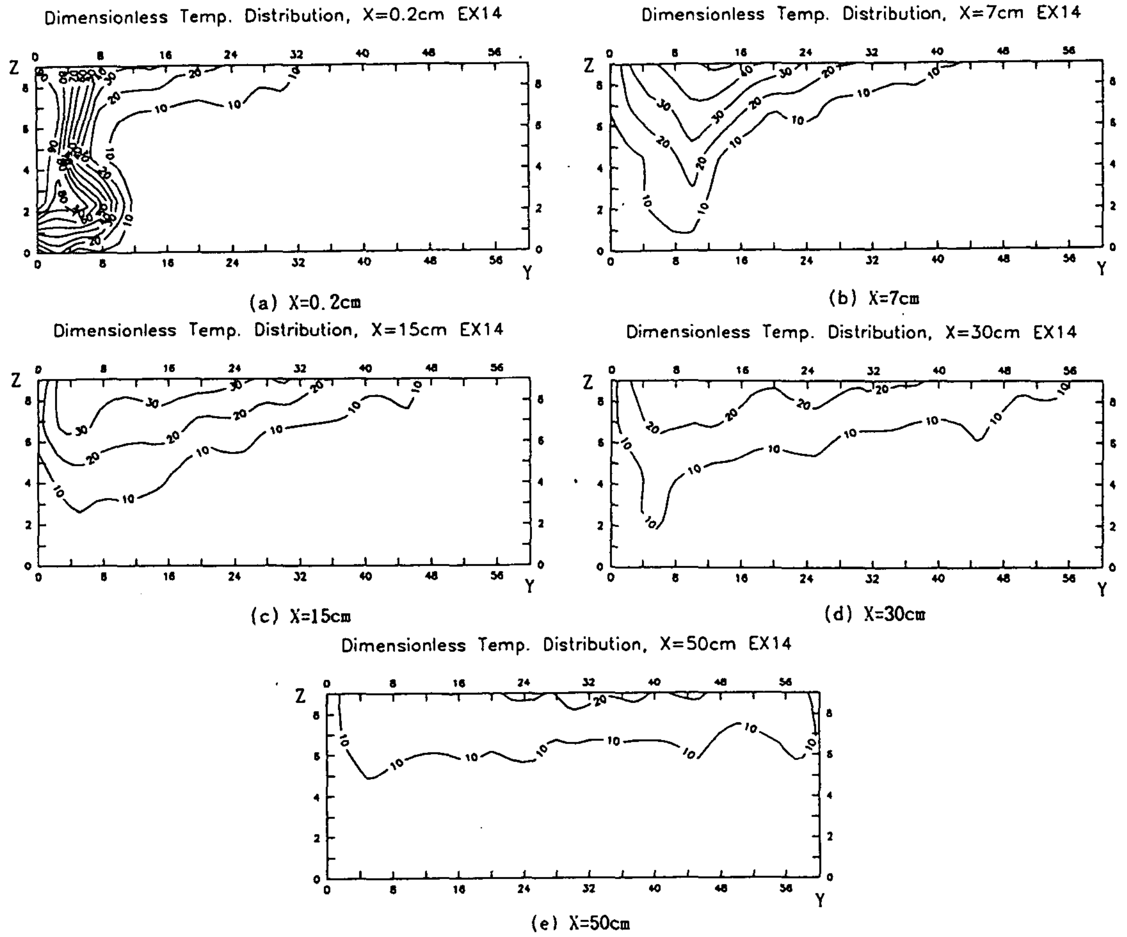

Fig. 2. Contours of nondimensional excess temperature at different flow sections.

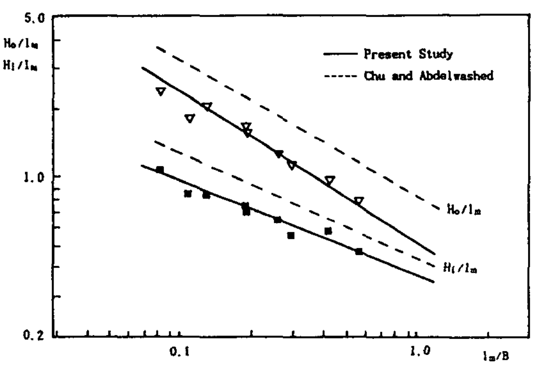

Fig. 3. Width of recirculation region.

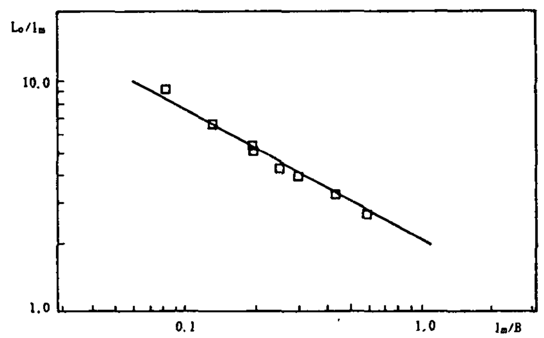

Fig. 4. Length of recirculation region.

6 are in the range of $l_b/l_m>1$, the region is found to be in the strong influence of buoyancy.

The depth average of the buoyant jet increases with longitudinal distance. But the rate of increase is different for the recirculating zone ($x/L<1$) and its wake ($x/L>1$). In the recirculating zone, it is

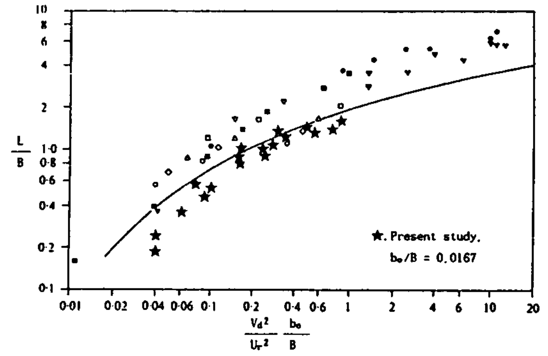

Fig. 5. Reattachment length ▦, $b_o/B=0.0105$; ▼, $b_o/B=0.0417$; ●, $b_o/B=0/0150$; (Mikhail *et al.*, 1975); ○, $b_o/B=0.0139$; ◇, $b_o/B=0.0182$; △, $b_o/B=0.0238$; □, $b_o/B=0.0345$; ▽, $b_o/B=0.0556$ (Strazisar & Prahl 1973); —, $b_o/B=0.105$(McGuirk & Rodi, 1978).

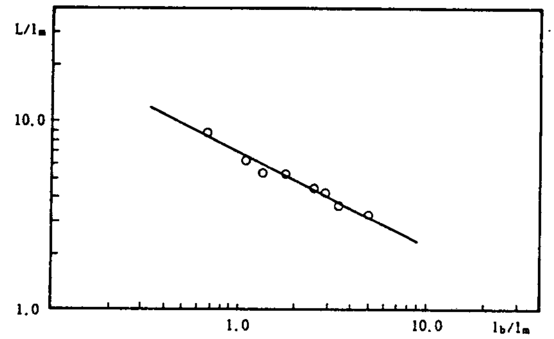

Fig. 6. Reattachment length in buoyant jet.

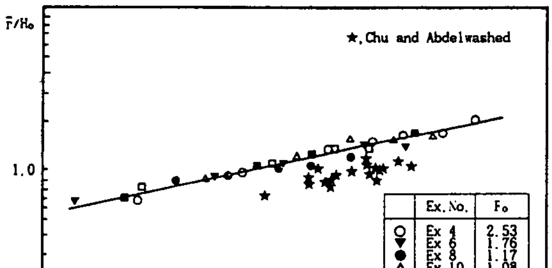

Fig. 7. Depth averaged width of buoyant jet.

approximated as

$$\bar{r}/H_o=1.6(x/L)^{0.23} \tag{9}$$

which is shown in Fig. 7 as a straight line fitted

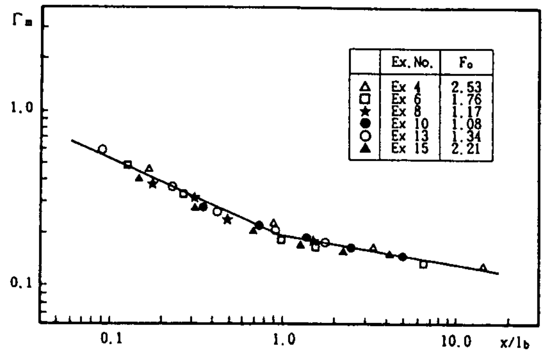

Fig. 8. Flow sectional average of non-dimensional excess temperature.

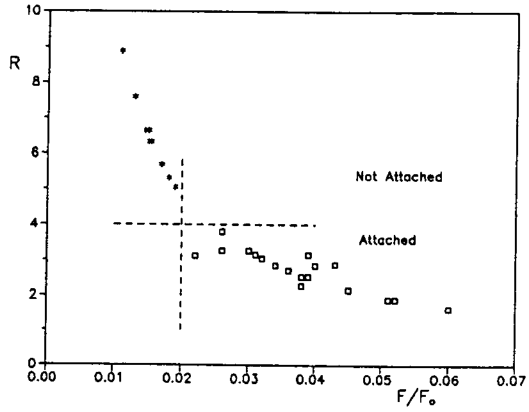

Fig. 9. Conditions of reattachment.

to the data. Meanwhile, in the wake of the recirculating region, flow is expanding and r increases at higher rate. It has been confirmed by Chu and Abdelwahed (1990) as

$$\bar{r}/H_o=1.6(x/L)^{0.5} \tag{10}$$

A dilution can be defined as $(\rho_a-\rho_o)/(\rho_a-\rho)$ and the relationship between excess temperature and density deficiency is given $(\rho_a-\rho_o)/\rho_a=\beta(T-T_a)/T_a$, in which β is an expansion coefficient. Hence, nondimensional excess temperature Γ can be used for dilution. Average nondimensional excess temperature over the flow section, Γ_m might be a measure of the effluent dilution. Γ_m is determined by the formula

$$\Gamma_m=\Sigma\Gamma_i A_i/\Sigma A_i \tag{11}$$

in which A_i and Γ_m are the areas between the nondimensional excess temperature contours consisted by 180 temperature data and average of Γ over A_i, respectively.

Figure 8 shows the data of Γ_m and suggests that the dilution characteristics is dependent upon the buoyancy. The first region is governed mainly by buoyancy and may be termed as buoyancy dominated near field. In the latter region, the effect of buoyancy is weak and the crossflow may be dominant. The region may be called as buoyancy dominated far field.

The shore attachment was observed by eye for each experiment, and is shown with the velocity ratio R=Uo/Ua and ratio of Froude numbers, F/Fo in Fig. 9 with data by Chu and Abdelwahed. F is the Froude number of the crossflow.

$$F=U_o/\sqrt{gh} \qquad (12)$$

and F_o is the effluent densimetric Froude number

$$F_o=U_o/\sqrt{g_o'h_o} \qquad (13)$$

It may be concluded from Fig. 9 that the shore attachment occur if $R<4.0$ (or $U_o<4U_a$) and $F/F_o>0.22$.

5. CONCLUSION

Buoyant jet was produced by releasing water through a side channel into open channel crossflow of the same depth to investigate experimentally the geometry of recirculation region, shore attachment, and dilution of the effluent. The size of recirculating region depends on momentum flux ratio of effluent to crossflow. In buoyant jet, the effluent lifts off the bottom, spreads across the crossflow and stays at the surface layer. Important factor on the length of the region is found to be relative buoyancy to momentum. The effluent densimetric Froude number has negligible effect. Dilution of the buoyant jet is related directly to the buoyant length scale, x/l_b. *Under conditions of* $R(=U_o/U_a)<4$ *and* $F/F_o>0.22$, the effluent reattaches to the shoreline.

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