Temperature Properties of the Inclined Fire Plume above a Circular Fire Source in Cross-Winds

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Abstract

Experiments with a single circular fire source were carried out in an unconfined space to understand temperature property of the fire plume in the presence of cross-wind. Three-dimensional measurement of temperature field created by the inclined fire plume was conducted and radiative heat fluxes at ground level along the centerline of the fire source whose direction is in parallel to the cross-wind were also measured. Followings become clear from a comparison between measured data and plume properties without cross-wind. Firstly, temperature along the inclined fire plume axis (ΔT_o) decreased rapidly. Secondly, plume radius based on temperature whose direction is in perpendicular to the inclined fire plume axis was larger. Furthermore, a relation between temperature in the vicinity of ground along the centerline of fire source whose direction is in parallel to the cross-wind (ΔT_{g_o}) and ΔT_o can be expected to hold regardless of the distance from the center of fire source and heat release rates.

1. Introduction[*]

Many papers concerning on temperature and velocity properties of the fire plume in a calm condition were published [1-7], and their theoretical and useful experimental results were stored and applied to the actual fire protection, such as prediction of a fire room temperature, estimation of response time of fire detector and sprinkler head,

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evacuation planning, fire fighting's strategy, and so on. As most fires occur in the situation in which winds blow except the calm in dawn and/or in the evening and in the situation without operating air conditioning system, the researches on the fire plume affected by winds were also carried out by Yokoi[8], Saga[9], Hayashi [10], and so on. We also carried out some experiments and developed some models for predicting apparent flame height and flame tilt angle considering the fire source shape [11] and made clear the relation between temperature rise and velocity along the inclined fire plume axis [12].

The purpose of current work is to understand experimentally the property of the inclined fire plume with cross-winds, and to make clear the relation between temperature rise along the inclined fire plume (ΔT_o) and temperature in the vicinity of ground along the centerline of fire source whose direction is in parallel to the cross-wind (ΔT_{g_o}). Furthermore, the effect of inclined fire plume to the downwind region by measuring the radiative heat flux at ground level was discussed.

2. Experiments

2.1 Outline of rig

Figure 1 (a) shows schematic diagrams of the experimental apparatus. The artificial floor was made to simulate the ground, whose dimension was 3.6m[L] x 1.2m[W]. The surface of the fire source with a diameter of 0.2m was flush with the artificial floor. The center of porous gas burner was positioned at 0.9m from the outlet of the ventilation duct, which coincided with the centerline of the cross-winds. The burner, ventilation duct and artificial floor were set 0.92m above the floor of the experimental facility. Propane gas was used as a fuel. Four heat release rate were used; 7.5, 15.0, 22.5 and 30.0kW. These are calculated values assuming complete combustion. These heat release rates correspond to fires ranging from 0.38 to 1.50 for Q^*. A stabilized cross-wind was supplied from the outlet of rectangular duct, whose dimension was 1.2m[W] x 1.2m[H]. The velocity, which is a representative velocity, was varied in six stages as 0.59, 1.15, 1.49, 1.64, 2.10 and 2.48 m/s that correspond to Fr of 0.15 to 3.14.

2.2 Temperature measurement

The temperature field produced by the inclined fire plume was measured using K-type thermocouples with a diameter of 0.65mm. These thermocouples were installed in the plane of A and B of H-shape wire gauze consisted of stainless steel wire with 2 mm diameter, whose dimension was 1.0m[W] x 0.6m[L] x 0.8m[H]. Fifty points of thermocouples were installed in each plane with the interval of 0.1m. The staggered arrangement of the thermocouple position

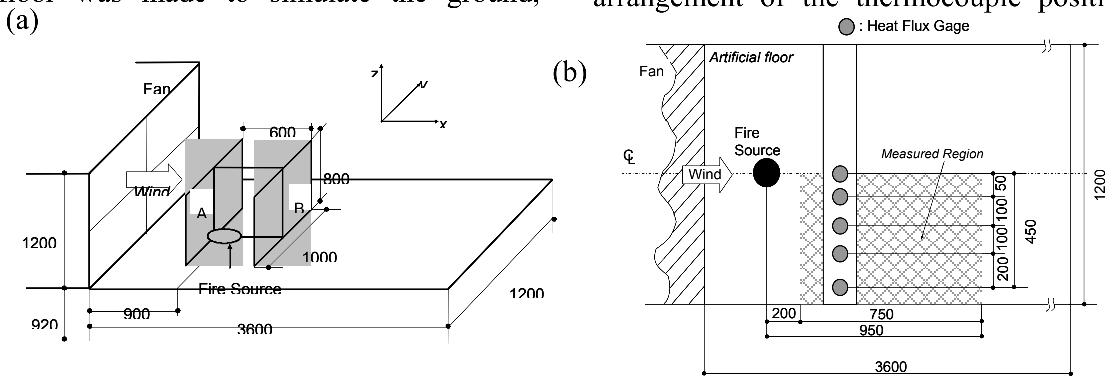


Figure 1 Schematic diagrams of experimental apparatus. Unit: mm
(a) bird's eye view (b) measured region of radiative heat flux at ground level

was employed in parallel between the planes to avoid overlap. These thermocouples were also installed in the central axis of both planes. The H-type wire gauze was moved several times along the centerline of the burner in every 0.1m to the downwind in one test. The first position at 0.7m from the ventilation duct is to be standard position for plane A. The data was obtained in every position. Therefore, the measured region was 1.0m[W] x 2.2m[L] x 0.8m[H]. The values for temperatures were averaged for last 3 minutes, one of a 10 minute test, this duration being assumed to be at a quasi steady state for both heat release rate and cross-wind velocity. The data were logged in every 3 seconds on a PC.

2.3 Radiative heat fluxes measurement

Radiative heat fluxes received at ground level were measured by water-cooled Gardon type circular heat flux gages (made by VATELL Co., Ltd., Model 1000-1). As fire plume was assumed to be symmetrical on its centerline, which coincides with the centerline of the fire source, measurements of radiative heat flux were carried out in hatching region shown in Figure 1 (b). Five radiometers were installed at 0.05, 0.15, 0.25 and 0.45m from the centerline of the fire source in perpendicular to the cross-wind and they were flush with the artificial floor. The surface of radiometers was vertical. We moved this radiometer rake in every 0.05m to the downwind. Therefore, the measured region was from 0.2m to 0.95m downwind from the center of the fire source. These values were also logged in every 3 seconds on a PC.

2.4 Cross-wind velocity measurement

The cross-wind velocity was measured using the hot wire anemometer (Model 6631 made by KANOMAX Co., Ltd.,) in the absence of fire plume. The measurement positions were placed horizontally at 5 positions as 0, 0.05, 0.15, 0.35 and 0.55m from the center of fire source and vertically 6 heights as 0.05, 0.15, 0.25, 0.45, 0.65 and 1.05m from the surface of the artificial floor. The same measurement was carried out at three positions, 0.5, 1.0 and 1.5m downwind from the outlet of a cross-wind. The representative cross-wind velocity was defined as dividing the total volumetric flow by the effective area as shown in equation (1), and used it in analysis.

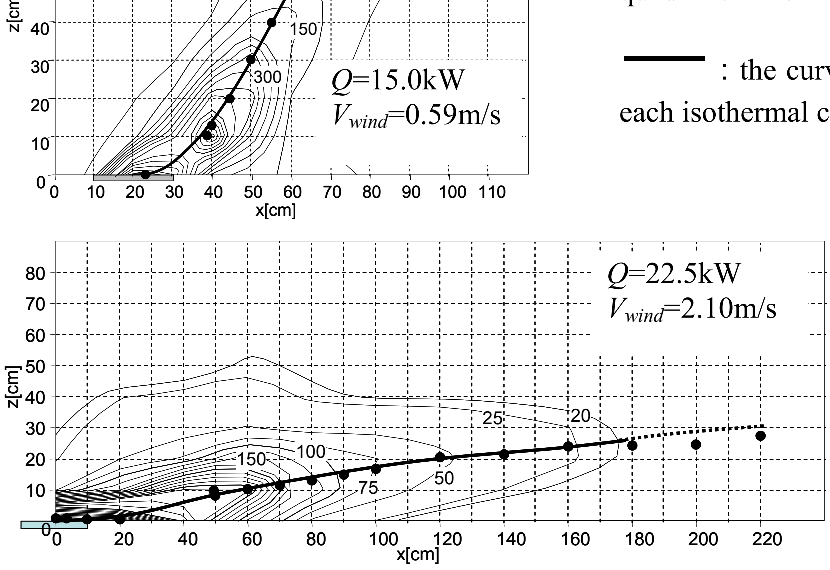
$$V_{wind} = \sum_{i=1}^{n} s_i v_i \Bigg/ \sum_{i=1}^{n} s_i \qquad (1)$$

The detail of cross-wind profile is described in reference [11].

3. Results and Discussions

3.1 Definition of the inclined fire plume axis

It is considered that the inclined fire plume pitches and rolls in response to the cross-wind. It is difficult to accurately define the position of the inclined fire plume axis. Therefore, we assumed that the position of the inclined fire plume axis almost coincided with the vicinity of the curve which was drawn as connecting the tip of each isothermal curves. These isothermal curves were constructed with the measured data on *zx* plane which passed the center of the fire source. Instead of directly reading arbitrarily position and its temperature rise along the inclined fire plume axis from the isothermal curves, the estimated maximum temperature and its position based on a quadratic fit to the measured data were employed in this study, which were illustrated in the symbol ● and superimposed on the isothermal curves as shown in Figure 2. These values were calculated based on the horizontal temperature distribution in the region where the buoyancy of the hot current was larger than the inertia force of the cross-wind, and were calculated from the vertical temperature distribution in the reverse region. These positions almost coincide with the solid curve which is connected the tip of



━ : the curve connecting the tip of each isothermal curve

each isothermal curve in Figure 2. Therefore, we adopted above mentioned method and defined the temperature rise and its position along the inclined fire plume axis (ΔT_o).

3.2 Temperature distribution on the *yz* plane at each downwind

In order to study the influence the cross-wind on the fire plume, temperature field was examined with the isotherms which were constructed at yz plane in every downwind position. Typical results are shown in Figure 3. The isothermal curves did not become a concentric circle which made the plume axis to be a center and they showed the shape which horizontally spreads further than the vertical direction. This shape of isotherm was also reported in the literature [13]. In the case of X=0.4m and X=0.6m, a pair of high temperature region which could be produced by vortex was confirmed. Although the exsistence of a pair of vortex can be confirmed, such vortex does not appear through the experimental conditions we conducted in this study and at the arbitrary position in downwind region, it is considered that the cause derives from the roughness of measurement interval in the temperature field measurement. Further study is necessary to understand the generation mechanism of vortex.

Here, we focused on the relationship between the central temperature of the vortex (ΔT_v) and temperature of the fire plume axis (ΔT_o) defined by the technique described in 3.1 section. If ΔT_v is much higher than ΔT_o, ΔT_o cannot be adopted as a representative temperature of fire plume. Then, we employed following method described in the next section.

(b) Dependence on the ratio of the ΔT_v and ΔT_o to cross-wind velocity

3.3 Relation between temperature of center of vortex and ΔTo

ΔT_v from the isothermal curves as shown in Figure 3 and it became clear that ΔT_v is higher than the temperature around the vortex. Figure 4(a) shows the variation of the ratio of $\Delta T_v/\Delta T_o$ against ΔT_o. We paied attention to the temperature range over 250K in which thermal effect to the downwind is large. This temperatre range corresponds to the flaming region, which is supported by the report that the region delineated by the isotherm curve of ΔT=250K coincides with the flaming region taken by a digital camera [11].

The value of averaged $\Delta T_v/\Delta T_o$ was plotted against cross-wind velocity as shown in Figure 4(b). Although the value of $\Delta T_v/\Delta T_o$ was varied without any dependence on the value of ΔT_o, the averaged value of $\Delta T_v/\Delta T_o$ was the value of 1.03±0.2. Furthermore, the value of averaged $\Delta T_v/\Delta T_o$ decreased with the increase of cross-wind velocity and it approaches the value of unity or became below unity. Therefore, it is considered that ΔT_o can be employed as the representative temperature of the inclined fire plume including the effects of vortex.

φ=0.2m circular burner.

3.4 Temperature decreasing mode

The estimated temperature rise based on a quadratic fit to the measured data along the inclined fire plume axis in the presence of cross-wind was plotted in Figure 5. The temperature result estimated with McCaffrey's relation [3] in the absence of cross-wind was also plotted together for comparison. The followings can be read from the value of temperature rise in ΔT_o>50K shown in Figure 5. The variable of "L" means the distance from the center of fire source to the measuring point.

1) The temperature rise along the inclined fire plume axis in the presence of cross-wind can be arranged at every cross-wind velocity using the variable which McCaffrey had employed in the absence of cross-wind.
2) In both of intermittent [illegible] regions, the ΔT_o shows the lower value and it decreases more rapidly against traveling distance than that in the case of calm.

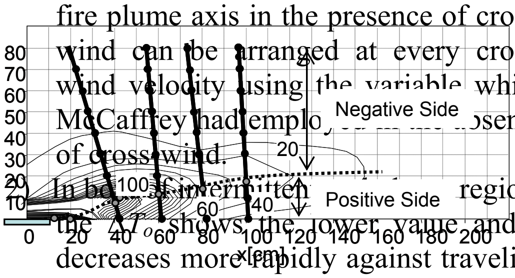
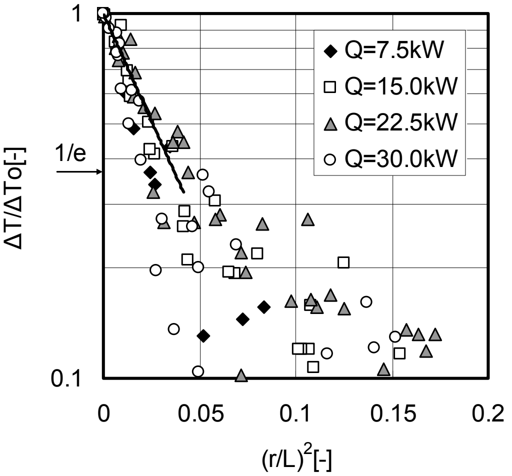


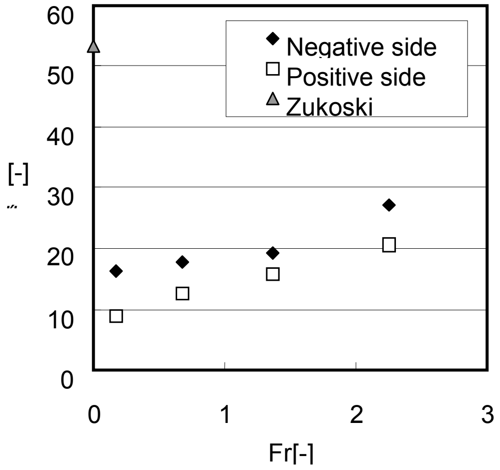
Figure 6 An example of the method of reading arbitrary positions and temperatures on the line whose direction is in perpendicular to the inclined fire plume axis. Q=15.0kW, V_{wind}=2.10m/s.
●: position of temperature at the intersection point between solid line and support line
: position of temperature along the inclined fire plume axis

3.5 Temperature distribution of inclined fire plume

In order to examine the plume width of the inclined fire plume, temperature along the solid lines which are perpendicular to the inclined fire plume axis was read from the isotherm as shown in Figure 6. We employed the temperature at the intersection point between solid line and support line, which are shown by the symbol of ● in Figure 6, because it is hard to read the temperature and distance at arbitrary position on solid line. Temperature and the distance from the plume axis are obtained by the interpolation method.

It is well known that the temperature distribution of the plume in the absence of cross-wind can be approximated in Gaussian distribution and is expressed in Eq.(2).





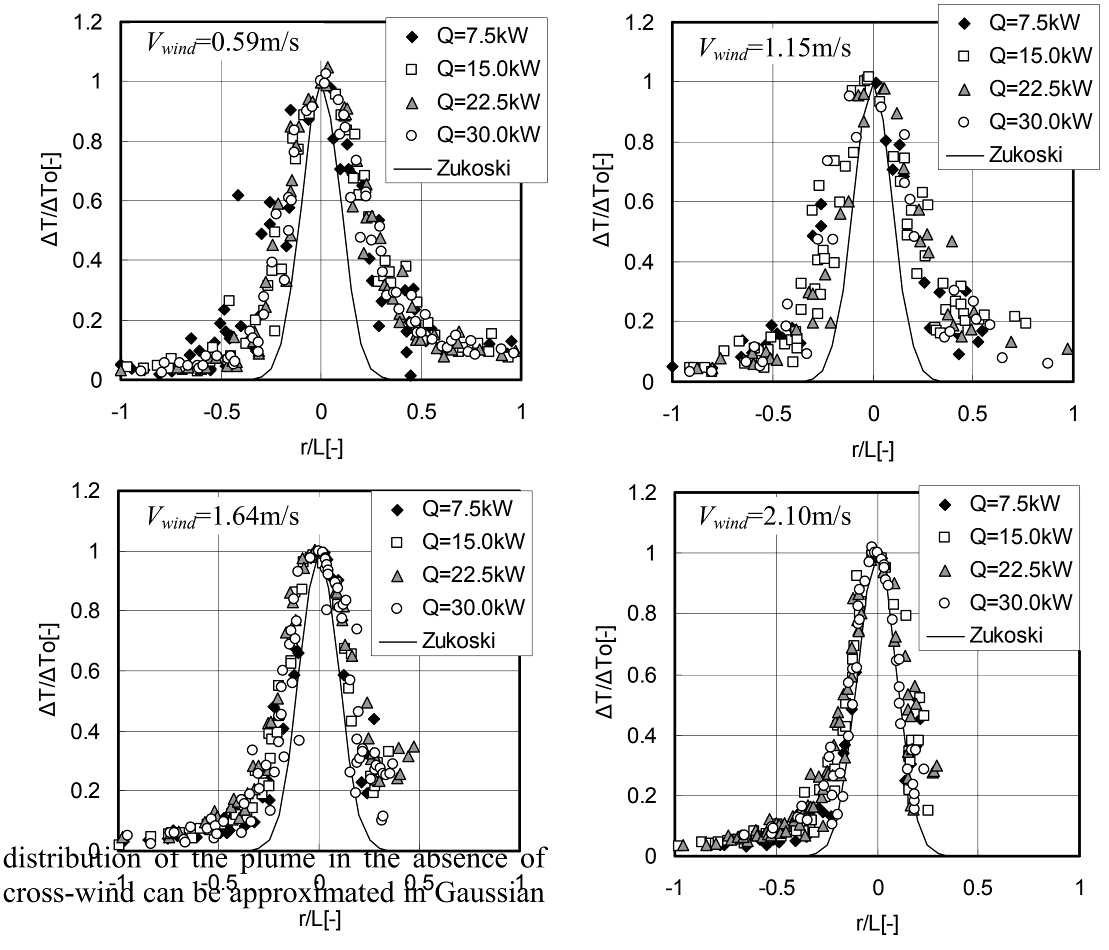


Figure 7 Temperature distribution in perpendicular to the inclined fire plume axis. φ=0.2m circular burner.

$$\frac{\Delta T}{\Delta T_o} = \exp\left\{-\beta \cdot \left(\frac{r}{b}\right)^2\right\} \qquad (2)$$

where $b = C_1 z$ $\quad C_1$: constant

Eq.(2) can be transformed into Eq.(3);

$$\frac{\Delta T}{\Delta T_o} = \exp\left\{-\beta^* \cdot \left(\frac{r}{z}\right)^2\right\} \qquad (3)$$

where $\beta^* = \beta \cdot \frac{1}{C_1^2}$

Zukoski reported 0.131 and 0.913 for the values of C_1 and β, respectively[14]. Then, estimating the value of β^* based on Zukoski's data is 53.2. We also estimated the value of β^* based on the present experimental data in the presence of cross-wind. The term of r/z in Eq.(3) was converted into r/L.

Figure 7 shows the temperature distributions with the data of four kinds of heat release rates in every cross-wind velocity. The temperature result estimated with Zukoski's relation[14] in the absence of cross-wind was also plotted together for comparison. The positive value of x axis means the positive side and negative value does negative side as shown in Figure 6. The plume width differed in the positive and the negative side, and that the plume width at positive side was wider than negative side, because positive sides received the thermal effect from upwind side. In the case of 0.59m/s cross-wind velocity, the plume width was much wider than in the case of calm, but the plume width gradually became narrow with the increase of cross-wind velocity and the difference of plume width in each side decreased. The reason of this tendency is followings; it is considered that plume fluctuation created by collision of cross-wind is varied depending on the cross-wind velocity. In other words, fluctuation of plume decrease with the increase of cross-wind velocity this is supported by the literature that the fluctuation of the apparent flame height became smaller with the increase of cross-wind velocity [15]. Furthermore, the data in positive side which were in the vicinity of an artificial floor were piling up at the value of almost 0.2~0.3 for $\Delta T/\Delta T_o$. It is considered that the region of positive side was received the influence of re-radiation heat from the artificial floor and also received convection heat the by the hot current from the upwind side.

Figure 8 shows the relation between the value of $\ln(\Delta T/\Delta T_o)$ and $(r/L)^2$, we focused the region where the value of $\Delta T/\Delta T_o$ is over $1/e$ region. It was considered that the slope

Figure 8 Relation between the value of $\Delta T/\Delta T_o$ and $(r/L)^2$. Negative side, V_{wind}=2.10m/s.

Figure 9 Depe
on the *Fr*.

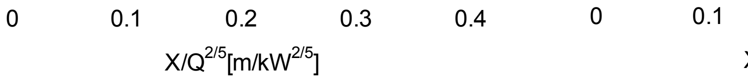


Figure 10 Relation between the value of temperature ratio Δ
distance from the center of fire source.

means the value of β^*. The value of β^* was estimated in each of negative and positive sides. Figure 9 shows the dependence of β^* on cross-wind velocity. The value of β^* was decreased rapidly until 0.59m/s cross-wind velocity, but in case of over 0.59m/s, the value of β^* increased with the increase of cross-wind velocity.

3.6 Ground temperature in the vicinity of artificial floor

In order to study the thermal hazards created by the inclined fire plume to the ground from the viewpoint of temperature, we employed the ΔT_{g_o}. ΔT_{g_o} means temperature in the vicinity of ground along the centerline of fire source whose direction is in parallel to the cross-wind. Figure 10 shows the ratio of $\Delta T_{g\_o}/\Delta T_o$ against distance from the center of fire source. Both of ΔT_{g_o} and ΔT_o are defined as the temperature at the same distance from the center of fire source along the each axis. A relation between $\Delta T_{g\_o}/\Delta T_o$ and distance was maintained in every cross-wind velocities. The value of $\Delta T_{g\_o}/\Delta T_o$ was almost 1 because this region corresponds to the flaming region. The region where $\Delta T_{g\_o}/\Delta T_o$ was 1 was extended to the downwind with the increase of cross-wind velocity. The value of $\Delta T_{g\_o}/\Delta T_o$ decreased with a power function with the increase of distance from the center of fire source, and decreasing rate of $\Delta T_{g\_o}/\Delta T_o$ against distance increased with the increase of cross-wind velocity. And the value of $\Delta T_{g\_o}/\Delta T_o$ finally approaches to 0.2~0.3. This range coincides with the results of temperature distribution.

3.7 Radiative heat fluxes

In order to study thermal influence of cross-wind at ground level, we employed the radiative heat flux along the centerline of fire source. Therefore, the view factor was varied with the heat release rate, cross-wind velocity and measuring point from the fire source. Figure 11 shows the value of measured radiative heat flux against distance from the center of fire source. The value of ΔT_{g_o} was also plotted together. Distance from the center of fire source was

Figure 11 Radiative heat flux decreasing mode against distanc

Table 1 Value
case of the valu
$\Delta T_{g\_o}/\Delta T_o$ beco

Vwind [m/s]	X/ [m/k
0.59	0.
1.15	0.
1.64	0.
2.10	0.

normalized by the value of $Q^{2/5}$. The data was gathered for a curve. In the case of 0.59m/s, the radiative heat flux decreased rapidly comparing with ΔT_{g_o}.

Although being in the far field from the center of fire source, as mentioned above, ΔT_{g_o} was almost 0.2~0.3 times of ΔT_o. Then, the value of radiative heat flux was read from Figure 11 employing the value of $X/Q^{2/5}$ which the value of $\Delta T_{g\_o}/\Delta T_o$ becomes 0.3, and these values were listed in Table 1. The value of radiative heat flux in Table 1 corresponds to 1~2kW/m^2 regardless of cross-wind velocities. It has been reported that the radiation tolerance criterion of people is 2.1~2.7kW/m^2 [16]. Therefore, it is considered that the region where the value of $X/Q^{2/5}$ is less than the values listed in Table 1 is radiative hazards region.

4. Conclusions

1. It was confirmed that vortex was generated by the collision of cross-wind to

the fire plume and it was horizontally apart from the plume axis. This generated vortex did not give the considerable effect to the temperature along the fire plume axis from the comparison of central temperature of this vortex and plume axis temperature at the same distance from the center of the fire source.

2. Temperature along the inclined fire plume axis was lower than the value in the absence of the cross-wind, the temperature decreasing rate against distance from the center of fire source was larger with the increase of cross-wind velocity.

3. Plume width whose direction is in perpendicular to the inclined fire plume axis was compared with the Zukoski's relation in the absence of cross-wind. Plume width was larger than that in the absence of cross-wind. The plume width becomes small with the increase of cross-wind.

4. There was a relation between ΔT_{g_o} and ΔT_o in every cross-wind velocity regardless of heat release rates. The value of $\Delta T_{g\_o}/\Delta T_o$ decreases with a power function and approaches the value of 0.2~0.3 in the far region from the fire source.

5. The value of radiative heat flux which the value of $\Delta T_{g\_o}/\Delta T_o$ becomes 0.3 corresponds to 1~2kW/m^2 regardless of cross-wind velocities. Radiatve hazards region becomes larger depending on the cross-wind velocity.

Nomenclature

A: area of received radiation heat [m^2]
b: half width in Gaussian profiles for ΔT
C_p: specific heat at constant pressure [$\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$]
D: representative length of burner [m]
Fr: Froude number [-]
g: acceleration due to gravity [m/s^2]
L: traveling distance from the center of fire source to on the fire plume axis [m]
Q: heat release rate [kW]
Q^*: normalized heat release rate [-]
r: plume radius [m]
s_i: minute area [m^2]
T: surface temperature [K]
T_∞: temperature of ambient air [K]
ΔT: excess temperature [K]
v_i: cross-wind velocity passing through the minute area s_i [m/s]
V_{wind}: representative cross-wind velocity [m/s]
X: horizontal distance to downwind from the center of fire source [m]
β: scale constant in eqn.(2)
ρ_a: density of ambient air [kg/m^3]
$Fr=V_{wind}^2/(gD)$[-] , $Q^*=Q/(\rho_a C_p T_\infty g^{1/2} D^{5/2})$[-]

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