Fire Plume Property from a Single Rectangular Fire Source in the Presence of an External Wind

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Abstract

Experimental study was carried out to understand the tilt angle and temperature property of a flame and fire plume from a rectangular fire source in an unconfined space with the presence of external wind. The rectangular fire sources having the aspect ratio of 1/3, 1/5 and 1/12 were used. Two setting arrangements, the long side and the short side of the rectangular fire source faced to the wind direction, were adopted as the parallel and perpendicular arrangement, respectively. The fire plume axis was estimated based on the isothermal curves in the downwind temperature field. The concept of virtual source was employed to describe the relationship between the excess temperatures, ΔT, and traveling distance normalized by $Q^{2/5}$ for parallel arrangement and those by $Q^{2/3}$ for rectangular arrangement, respectively. The decreasing modes of excess temperature along the traveling distance showed the similar but greater gradient than those from a circular/square fire source and from a rectangular without external wind, respectively. The tilt angle of the inclined flame from the source in parallel arrangement is greater than that from a circular/square fire source, and tilt angle from the perpendicular arrangement is much greater than that. The simple model to estimate the tilt angles for those fire source arrangements was established as the coupled function of Froude number, HRR, and characteristic source length. No obvious dependence on aspect ratio was recognized on the inclination behavior of the flame.

1. Introduction

The hot current behavior and thermal radiation from burning houses to the house and building is one of the governing factors when a city fire expands. In order to support the urban planning, the firefighting tactics and, the fire prevention planning against a city fire, it is very important to pursue the property of the hot current from urban fires. On a property of the fire plume in the absence of external wind, the pioneering researches by Yokoi [1] and by Morton [2] are reported. Afterward, many theoretical study and experimental results were reported by McCaffrey[3], Cox & Chitty[4], Hasemi [5], Terai & Nitta [6], Cetegen [7], Yuan & Cox [8], and others. However, in general city area, it is extremely rare to be complete windless condition. And, it is considered that some wind is always blowing. Yokoi[9], Saga[10], Oka & Sugawa[11] and others carried the research on a property of fire plume in presence of external wind. Temperature and velocity distribution and those decreasing modes along the inclined fire plume axis in presence of external wind was reported. The authors examined the height and an angle of inclination of flame which inclined by external wind, and the examination on the property of excess temperature and velocity of the hot current formed above a circular fire source was conducted, and the some results were reported [12] [13].

However, there is not enough information on the property of excess temperature along the plume axis when an attacking angle of the external wind to a rectangular fire source changes. In addition, the influence of aspect ratio on temperature property is not well known when external wind is given. The objective of this experimental study is to have a proper understanding for the excess temperature behavior along the inclined fire plume axis from a rectangular fire source with having the two typical configurations in the presence of external wind. And also we would like to establish the model to estimate the tilt angle of a flame in the presence of external wind.

2. Experiment

This series of the experiments were carried out based on the same way employed in the previous study [14] except the design and arrangement of a fire source. And the same setup, consisting of an artificial flat and horizontal floor, rakes of thermocouples and pressure sensing tubes, and the external wind generator, was used and this setup is illustrated in Figure 1.

2.1 Model fire source

The rectangular fire source was used as the model of burning row of buildings/houses, and of which aspect ratio, Ap, of 1/3 (0.1m[W]×0.3m [L]), 1/5 (0.1m[W]×0.5m [L]), and 1/12 (0.05m[W] ×0.6m [L]). Two types of setting arrangements, as shown in Figure 1-(e) and (f), were adopted to examine the influence on temperature property in the downwind when the long side or the short side of burner faces to the external wind. The center of sand gas burner was set at 0.75m apart from the edge of outlet and which was set in array along with the centerline. In this paper, the direction parallel with the external wind is introduced as "x-axis", and perpendicular to x-axis is adopted as "y-axis", and the vertical one is as "z-axis" as illustrated in Figure 1.

2.2 Measurement of Temperature

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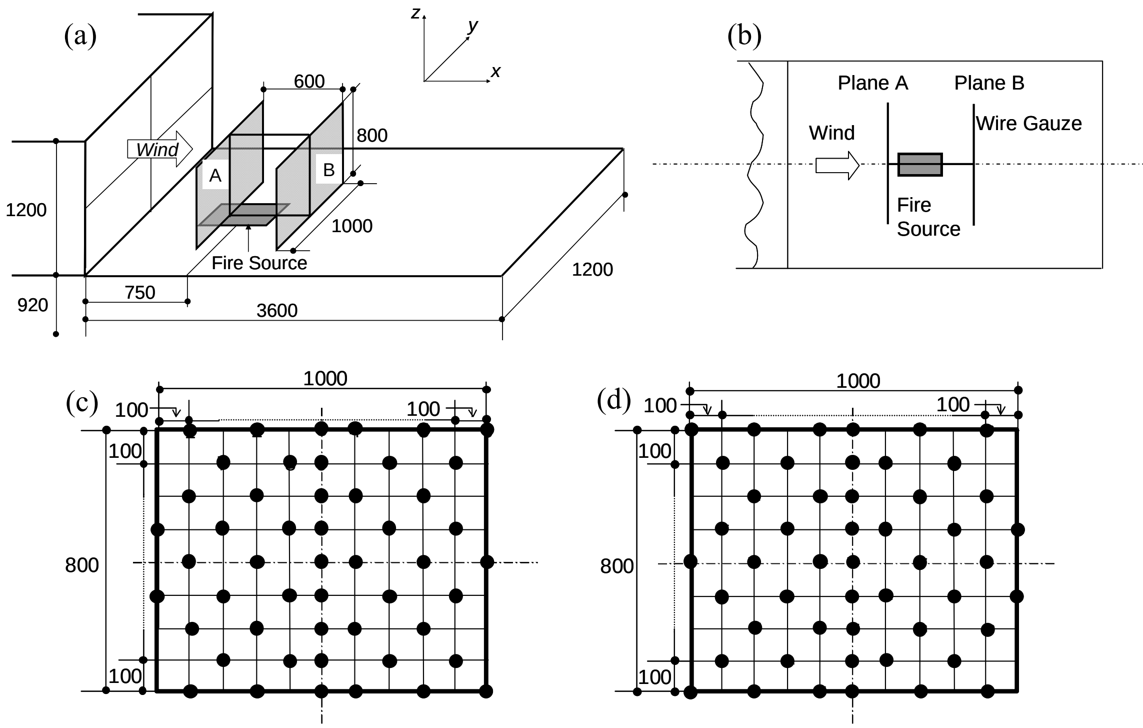


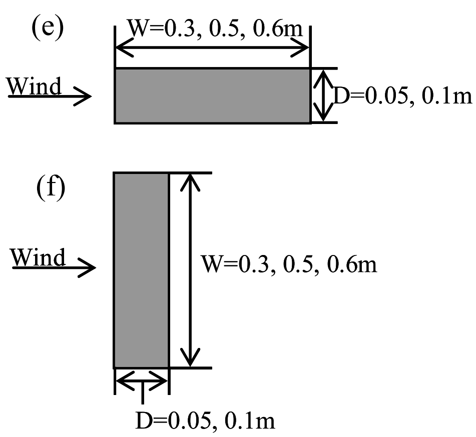


Figure 1 Schematic diagrams of experimental apparatus. Unit: mm
(a) bird's eye view (b)xy plane
(c) positions of thermocouples on the plane A
(d) positions of thermocouples on the plane B
(e) parallel arrangement
(f) perpendicular arrangement
●: Thermocouples

K-type thermocouples, 0.65mmϕ, were used for temperature measurements, and no thermal radiation effect on temperature measurement was taken into account. These thermocouples were installed in the 50 measuring points of plane A and B respectively as shown in Figure 1 (c) and (d). These thermocouples were installed alternately in the points of staggered arrangement in the right and left part of plane A and B. Fire plume, a kind of turbulent flow, was supposed to be the symmetric in its shape and behavior when time-space averaging was carried out whether the hot current had vortexes in its both sides. The set of plane A and B was shifted with 0.1m every run toward the downstream to measure the temperature along the centerline of the flow. The covering volume of temperature measured was of 2.2m [L] ×1.0m [W] ×0.8m [H]. The temperatures measured every 3 seconds were recorded and then averaged for their three minutes data, and its excess value from the initial one was adopted as the excess temperature, ΔT, and which is employed for the modeling. We assumed that the heat release rate and external wind velocity were in the quasi steady state for each run.

2.3 Experiment Conditions

Heat release rate and external wind velocity were changed according to the schedule of the experiment conditions. Fuel gas, LPG, was given to the fire source through a gas flow meter to fit the heat release rates of 7.5, 15.0, 22.5, and 30.0kW. We also employed 4 stages of external wind velocities, 0.59, 0.99, 1.49, and 1.98m/s, and three kinds of aspect ratio, Ap=1/3, 1/5 and 1/12, were applied to the rectangular sand burner.

3. External Wind Profile

The performance and distribution of the external wind velocity for horizontal and for vertical direction were presented and shown in the previous paper [10], so that, in this paper, an outline of external wind profile was explained.

The dimension of outlet is 1.2m (W)×1.2m (H). The wind velocity was measured with the anemometer (Model 6631 made by KANOMAX Co.) to estimate the distributions of vertical and horizontal directions The horizontal distribution was estimated based on the velocity data which were obtained at 0, 0.05, 0.15, 0.35, 0.55m apart from the center of the flow. And the vertical one of the external wind was estimated based on the data of 0.05, 0.15, 0.25, 0.45, 0.65, 1.05m high from an artificial floor. The same measuring system were shifted every 0.5m and measurements were carried out at the positions of 0.5, 1.0, 1.5m apart from the edge of the outlet.

The representative velocity of the external wind, V_{wind}, was evaluated by space-averaging as equation (1) based on the 3min time-averaged velocity of Vi at position i.

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

Figure 2(a) shows the typical horizontal profile at 1.5m downwind from the outlet in the case of no flame and plume was given. Figure 2 (a) shows that the top-hat distribution of wind velocity having the almost same velocity within the region of 0.4m for both sides from the center.

Figure 2(b) shows the typical vertical profile, showing the typical power law of $Z^{1/7} - Z^{1/8}$, at the center of the external wind at 1.5m downwind from the outlet. In the region where higher than 0.45m, the wind velocity distribution became almost flat. The same power law in the vertical distribution was

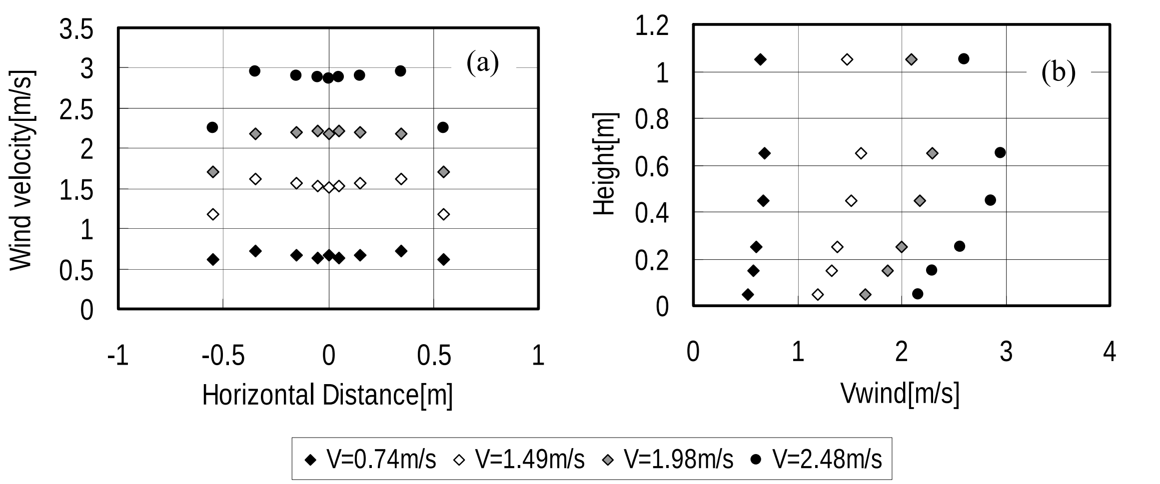


Figure 2 Typical wind profiles at 1.5m downwind from the ventilation duct.
(a) horizontal profile at z=0.45m (b)vertical profile at centerline of fire source

confirmed in other downwind measuring positions.

4. Results and Discussions

4.1 Definition of the inclined fire plume axis

Figure 3 shows isothermal contour maps of x-z plane on the centerline of the tilt flow including flame, intermittent flame, and plume based on the measured temperatures with parallel/perpendicular arrangement of the fire source. These isothermal contour maps read tilt angle of the inclined flame as a function of external wind velocity, and also showed the location of fire plume axis which was estimated as the trace line which was obtained by the connection of tip by tip, (symbol •), of the highest and further temperature point in each isotherm curve in the downwind field. The plume axis which coincided with the inclined flame axis in its base part, and then it was bent with the external wind as showing s-character or sigmoidal curve. The upper range of the plume and external wind formed a harmonious mixed flow in the downwind flow field. Figure 4 shows the schematic view of the tilt flame and plume regions which consist of the flame and intermittent

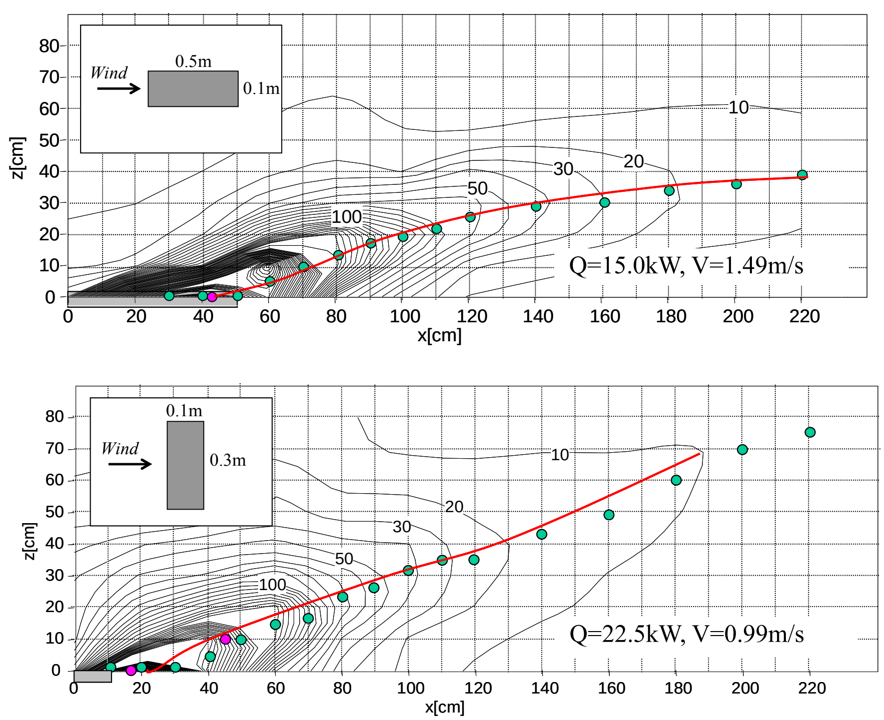


Figure 3 Isothermal curves on the plane whose direction is in parallel to the wind direction and passing the centerline of fire source.

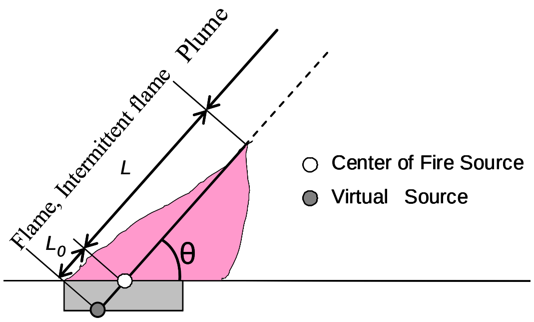


Figure 4. Model of L, L_0 related to the flame property

flame length having the length of L, and Lo as the distance to the virtual origin from the center of the rectangular fire source.

4.2 Tilt Angle of the Flame

Flame from the rectangular fire source in parallel and in perpendicular arrangement deflected by external wind depending on the setting arrangement, HRR(heat release rate), and wind velocity, V_{wind}. The relationship between flame tilt angle and external wind velocity was also reported by Quintiere [14] for a circular fire source using liquefied natural gas as a fuel. In order to compare the behavior on tilt angle depending on the fire source configuration, the tilt angle were plotted against the dimensionless wind velocity of V_{wind}/v^* [14] and are shown in Figure 5. Here, u*is defined as [14];

$$u^* = 1.9Q^{1/5} \quad (2)$$

Figure 5 shows clearly that the tilt angle of the flame depends on the fire source configuration and not depend on aspect ratio of the rectangular fire source. Tilt angle from the rectangular fire source is deeper than that from the square/circular fire source, and the tilt angle from perpendicular arrangement gave the deepest one in these three configurations. In the case of the flame from the single rectangular fire source, we could clarify the flame tilt angle performance into two types; that is, flame from the parallel arrangement and from the perpendicular arrangement. These two types are clearly different from that from the single square/circular fire source when they set in a external wind. However, we could not find any apparent difference between the tilt angle performances which was given by the rectangular fire source having three kinds of aspect ratios. It is supposed that the tilt angle of a flame depends on not only setting configuration but also on the HRR as well as wind velocity. In order to estimate the relationship between the tilt angle and these two main factors of HRR and V_{wind}, which act competitively on the inclination of flame, the tilt angle (in tangent form, $\tan\theta$)

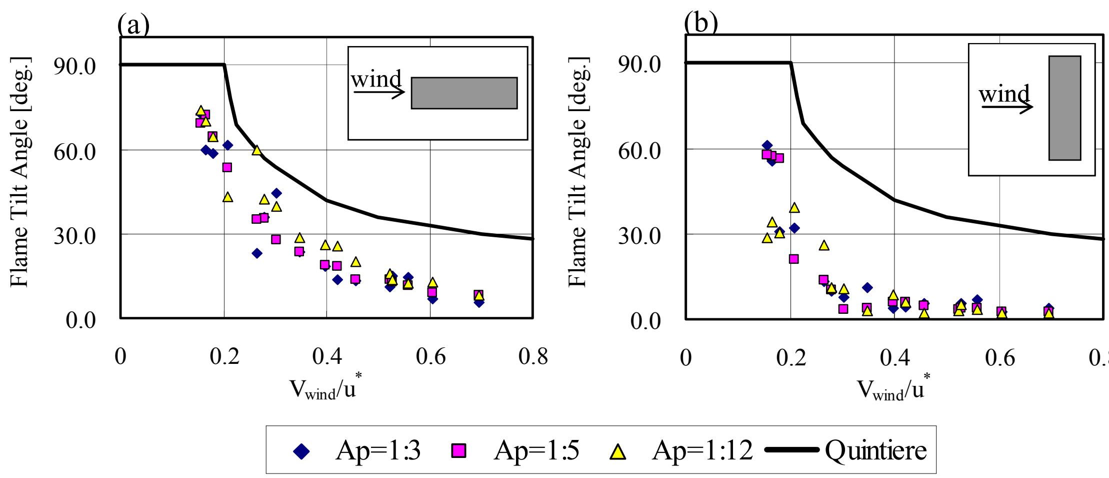


Figure 5 Relationship between Flame Tilt Angle and V_{wind}/u^*.
(a) parallel arrangement, (b) perpendicular arrangement

were plotted against the coupled dimensionless term of $Fr^{n/3}/Q^{*1/2}$ as shown in Figure 6. Where, Fr is Froude number $Fr=(V_{wind})^2/gD$, and Q* is dimensionless heat release rate. We could evaluate the following relations based on Figure 6.

The tilt angle in tangent form is modeled as

$$\tan\theta = \alpha \cdot \left(\frac{Fr^{n/3}}{Q^{*1/2}} \right)^{\beta}$$

In the case of parallel arrangement, we obtain;

$$\alpha = \begin{Bmatrix} 0.59(Ap = 1:3) \\ 1.01(Ap = 1:5) \\ 1.40(Ap = 1:12) \end{Bmatrix},$$

$$\beta = -3/2,$$

$$n = 2$$

In the case of perpendicular arrangement, we obtain;

$$\alpha = \begin{Bmatrix} 0.13(Ap = 1:3) \\ 0.24(Ap = 1:5) \\ 0.12(Ap = 1:12) \end{Bmatrix},$$

$$\beta = -3,$$

$$n = 1$$

4.3 Virtual Source

Whether the external wind is present or not, it could be supposed a single virtual source, as the apparent source point of the hot current, to estimate the temperature property in the regions of flame, intermittent flame, and plume. The virtual source point is illustrated schematically in Figure 4 with having the apparent distance L_0 from the center of fire source. We have to estimate L_0 firstly before we discuss on the decreasing modes of the temperature in downwind region. Let us assume that the flame region lays in 450K or higher temperature and as well as the intermittent flame region lays in between 250K to 450K temperature region. Thus, we could expect

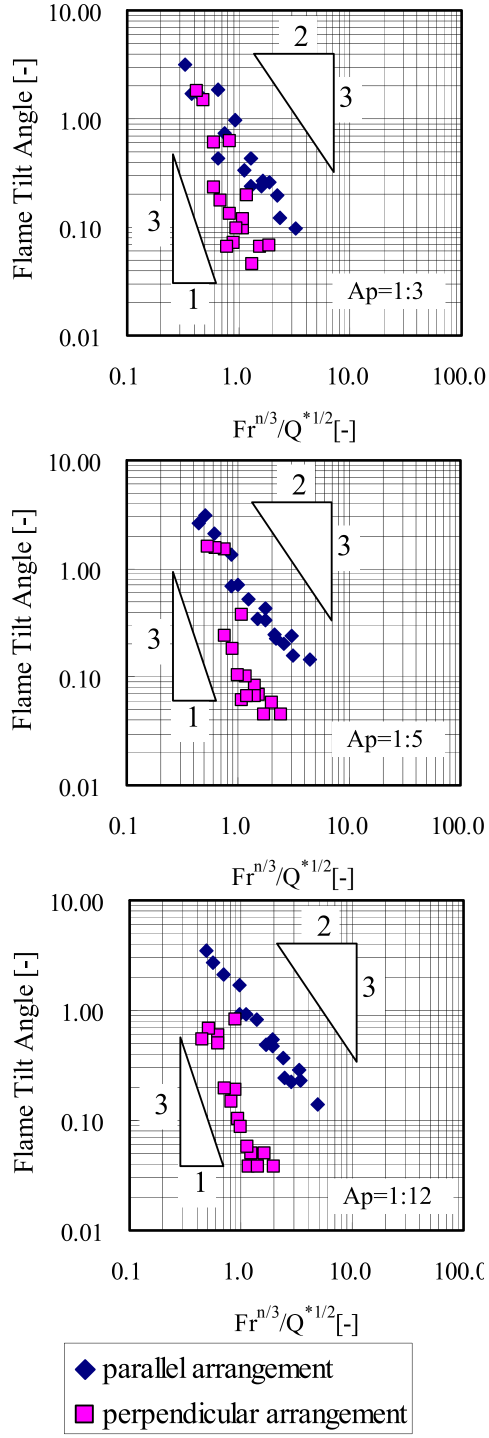


Figure 6 Relationship between flame tilt angle, tanθ, and $Fr^{n/3}/Q^{*1/2}$.
parallel arrangement : n=2
perpendicular arrangement : n=1

the temperature decreasing mode for traveling distance changes its gradient at

450K for flame and 450K - 250K for intermittent flame, and lower than 250K for plume. Therefore, we evaluate the length of L_0 for all experimental cases to fit the temperature gradient for the traveling distance into three or two regions. It must be considered that some influence on L_0 which resulted by the turbulent wind and aspect ratio of the rectangular fire source, we plotted L_0/A against Froude number as shown in Figure 7. And also we observed;

1) When external wind becomes faster, value of L_0 becomes large. And this tendency does not depend on fire source arrangement.
2) The value of L_0 obtained in the parallel arrangement is larger than that in perpendicular arrangement, and this tendency showed no obvious dependence on the aspect ratio of rectangular fire source.
3) In the case of parallel arrangement, as an aspect ratio becomes large, L_0 becomes large. On the other hand, in the case of perpendicular arrangement, the value of L_0 becomes large as an aspect ratio becomes small.

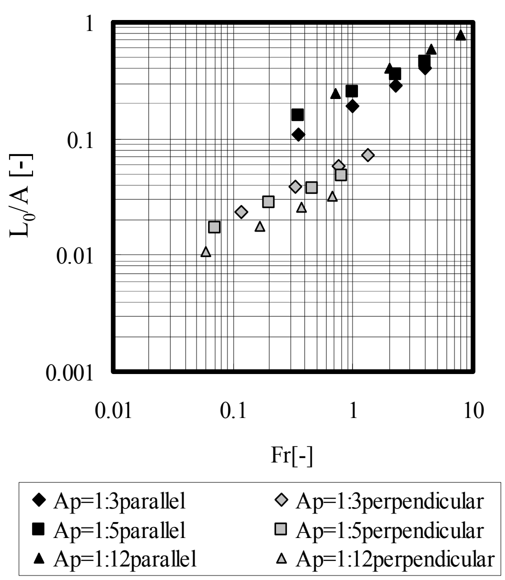


Figure 7 Relationship between L_0/A and *Fr*

4.4 Decreasing mode of temperature on fire plume axis

The temperatures along the fire plume axis, which was schematically illustrated in Figure 3, were plotted against the traveling distance of (L_0+L) with the modification of $Q^{-2/5}$ for parallel arrangement, $(L_0+L)/Q^{2/5}$, and $(L_0+L)/Q_l^{2/3}$ for perpendicular arrangement, respectively as are shown in Figure 8 and 9.

<u>In the case of parallel arrangement</u>

As shown in Figure 8, the relationship between temperature and traveling distance normalized with $Q^{2/5}$ in the parallel arrangement are similar with, but not same to those relations without wind. Solid lines were calculated based on the model presented by McCaffrey and plotted as the case of no wind given to the system. Comparing these temperatures with and without external wind, we observed;

1) Temperatures in the plume region with external wind are lower than those without wind.
2) As an aspect ratio becomes smaller (Ap=1/3 to 1/12), discrepancy between temperatures with wind and those without wind becomes large.

<u>In the case of perpendicular arrangement</u>

The temperatures were plotted against $(L_0+L)/Q_l^{2/3}$ as shown in Figure 9, and these decreasing modes are quite similar but not the same manner to those from a single line fire source without external wind. As based on decreasing modes in Figure 9, we could classify the hot current into three regions of flame, intermittent flame, and plume region. The classification manner having these three regions is quite similar to those from circular/square and to those from rectangular fire source in parallel arrangement, but the normalization on traveling distance is differ from those for circular/square and rectangular fire source in parallel arrangement.

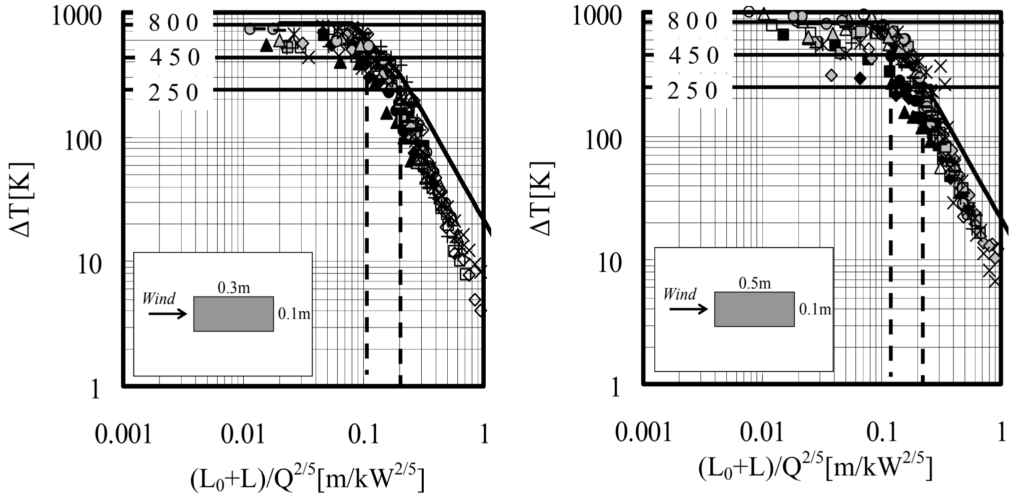
1) As an aspect ratio becomes smaller (Ap=1/3 to 1/12), temperature along the fire plume axis shifted lower temperature.

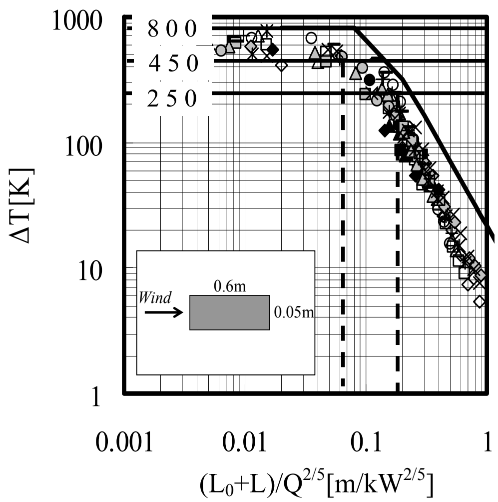
2) Temperature in the intermittent region decreased with increase of traveling distance.

3) In addition, it is clearly understood that property of temperature decreasing mode for traveling distance inherits from the property of line fire source without external wind.

Figure 10 shows the slope in the plume region as a function of fire source aspect ratio for respective arrangement. From Figure 10, we could present the following rough model to estimate the temperature in downwind region along the traveling distance.

In the case of parallel arrangement, we obtain;





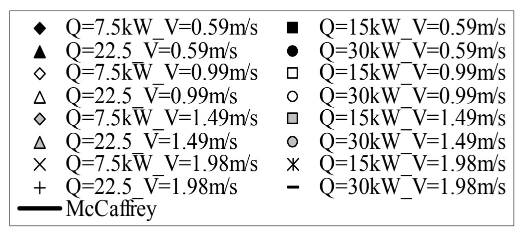


Figure 8 Temperature rise along the inclined fire plume axis in the presence of external wind in parallel arrangeme

$\Delta T = 450 - 800K$ for flame region,

$$\Delta T = 19.1\left(\frac{L_0 + L}{Q^{2/5}}\right)^{-1.47}$$

for intermittent flame region,

$$\Delta T = 5.3\left(\frac{L_0 + L}{Q^{2/5}}\right)^{-2.17}$$

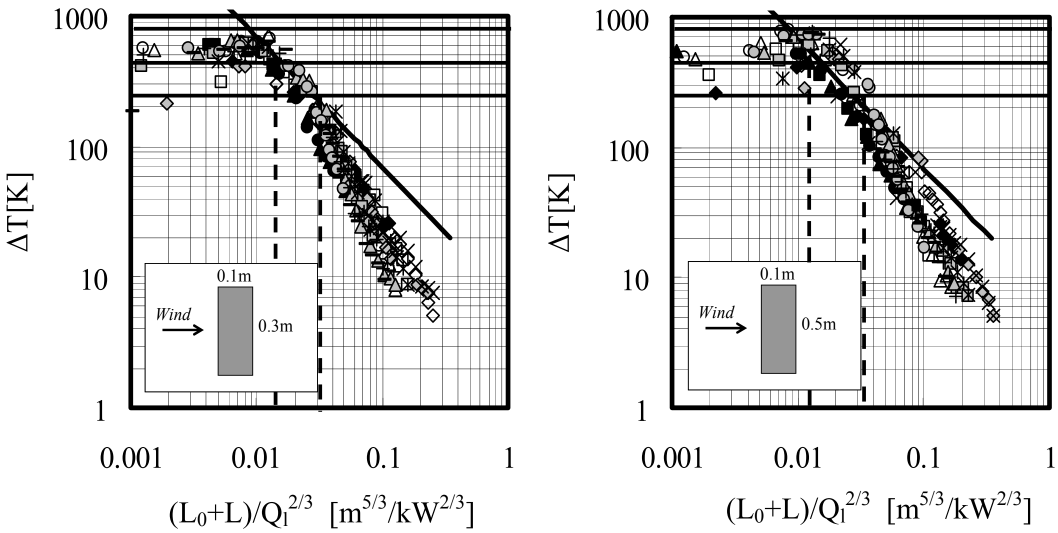
for fire plume region.

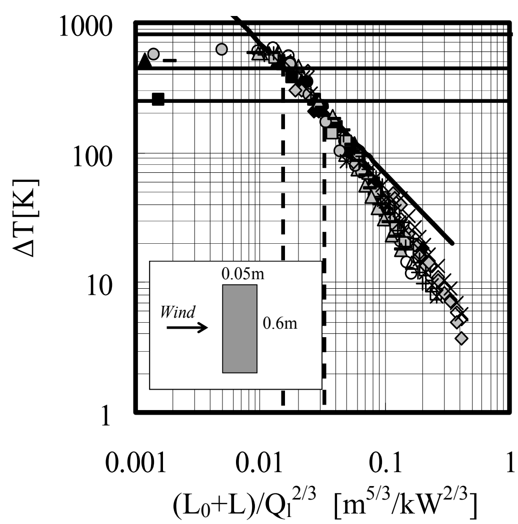
In the case of perpendicular arrangement, we obtain;

$\Delta T = 450 - 800K$ for flame region,

$$\Delta T = 0.65\left(\frac{L_0 + L}{Q_l^{2/3}}\right)^{-1.65}$$

for intermittent flame region,





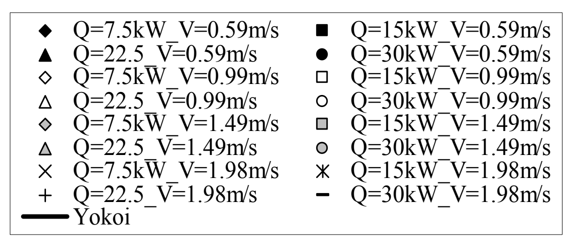


Figure 9 Temperature rise along the inclined fire plume axis in the presence of external wind in perpendicular arran gement.

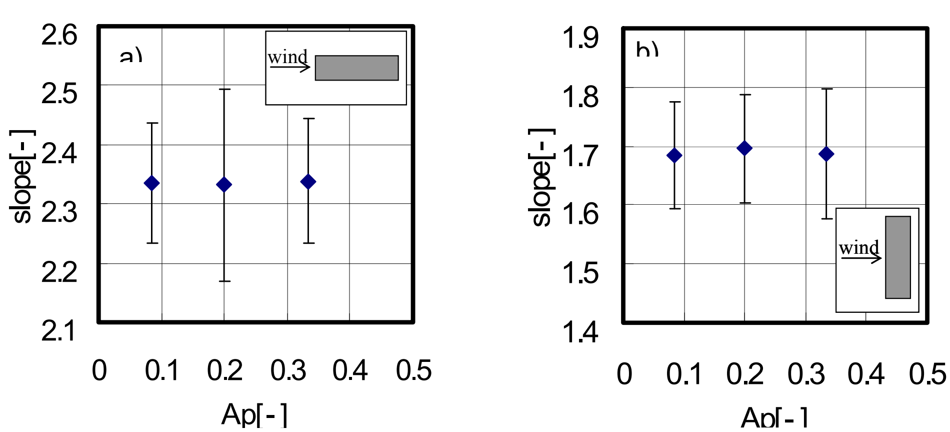


Figure 10 The value of slope in plume region were plotted against the value of aspect ratio, Ap.

(a) parallel arrangement, (b) perpendicular arrangement

$$\Delta T = 0.49\left(\frac{L_0 + L}{Q_l^{2/3}}\right)^{-1.72}$$

for fire plume region.

5. Conclusion

1. In parallel arrangement, temperature along the inclined fire plume axis was lower than the value in the absence of the external wind.

2. In parallel arrangement, even if normalization by $Q^{2/5}$ is aspect ratio 1:12, influence of heat release rate is revised well. This tendency means that the fire plume which left rectangular fire source loses property of original fire source form by external wind.

3. It is considered that it is succeeded to property of rectangular fire source in perpendicular arrangement. However, in aspect ratio 1:3, 1:5, it is guessed that property of rectangle fire source is lost in a fire plume region.

4. As an aspect ratio becomes large, temperature along fire plume axis becomes low. This tendency does not depend on setting arrangement.

5 As an aspect ratio becomes large, decreasing mode of temperature become large. This tendency does not depend on arrangement..

Nomenclature

L: traveling distance from center of fire source to arbitrary position along the inclined fire plume axis [m]
L_0: traveling distance from center of fire source to virtual source [m]
θ: angle of the inclined flame by external wind[degree]
Q: heat release rate [kW],
Q^*: normalized heat release rate [-]
Q_l: heat release rate per unit length [kW/m], $Q_l=Q/W$
ΔT: excess temperature from ambient [K]
V: external wind velocity [m/s]
u^*:characteristic plume velocity [m/s] by McCaffrey's data
A: represent length of the fire source which faces to the external wind [m]. A is D in parallel arrangement, and A is W in perpendicular arrangement.
W: long side of rectangular fire source [m],
D: short side of rectangular fire source [m],
g: gravitational acceleration [m/s^2]
Fr: Froude number [-], $Fr=V^2/(gD)$ [-]
s_i: minute area [m^2]
v_i: external wind velocity passing through the minute area s_i [m/s]

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