Flow Behavior of Ejected Fire Flame/Plume from an Opening Effected by External Side Wind

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ABSTRACT

A reduced-scale experimental study was carried out to collect a knowledge of the effect of external side wind on the flow behavior of a flame/plume which is ejected from an opening of a fire compartment. The external side wind was given to the flame/plume at the various speeds of 0.06m/sec to 1.88m/sec. Upward velocities and temperatures of the flame/plume were measured systematically along the wall for vertical and horizontal directions and which gave the trajectory (trace of main flow axis). Decreasing temperature and upward velocity for vertical direction showed similar behavior to those obtained in the flow from a line fire source. The slope of the trajectory inclined by side wind and of which slope was estimated based on the experimental data. A simplified model on the trajectory slope (or flame inclination slope) can be described by the coupled function of dimensionless heat release rate, Froude number and the aspect ratio of the opening base on the balance of buoyancy and inertia force of side wind as well as the aspect ratio of the opening and heat release rate.

KEY WORDS: Trajectory, Ejected Flow, Wind, Inclination, Flame Angle

INTRODUCTION

During the post-flashover fire, the flame(s) which erupt from windows give a high potential of fire propagation to upper stories as was observed in the First Interstate Bank Building fire (Los Angels, May, 1988) and was found in Kobe after the Great Hanshin-Awaji earthquake (Japan, Jan., 1995). In those cases, wind was believed to effect the flame behavior,

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especially on the flame extension and inclination behavior. Clear traces of burnt surface which showed the existence inclined flames along the building surface were found among the burnt buildings in Kobe. In building fires, the length of extended flame is comparable to the height of a story, so that the upward fire propagation via openings under the effect of external wind is significant. A knowledge of the effect of wind on flame is very important for the estimation of the fire propagation potential along the exterior wall. The main flow line, given by an ejected flame/plume from an opening, is called as "trajectory", which have been studied experimentally and theoretically by Yokoi [1,2] more than 30 years ago. He showed clearly in his pioneered work the behavior of trajectory from an opening as well as temperature decreasing profile along the trajectory. However, he carried out work in the case of no wind. Sugawa et al. [3] reported flame extension behavior ejected from multi-openings having various configuration but they also did experiments without external wind. Thomas [4] and Hamada [5] showed the correlation between the tilt angle of a flame and its burning rates using a solid fuel set on the ground in an open space condition. Raj [6] correlated flame angle for LGN pool fire when the flame was blown, and Quintiere [7] reported also the flame angle affected with a door jet. These previous works [1-7] dealt with the flame inclination in the case of a fire source set on the ground or on floor. Sugawa [8] carried out experimental work on the blown flow from an window opening considering the "front wind", and also proposed a simple model for trajectory, decreasing of upward velocity and temperature. In this experimental study, we present the flow behavior from one window opening which with "side wind". Based on the experimental data, a simple model on the flame angle of the trajectory inclined, and behavior of the vertical velocity profile and temperature along the trajectory are described. This model can be used to assists in the assessment of fire safety design for high-rise buildings.

EXPERIMENTALS

An opening, 5 cm (W) x 10cm (D), 10cm (W) x 10cm (D), 20cm (W) x 10cm (D), and 20cm (W) x 5cm (D) was attached to a reduced scale model having a compartment of 10cm (L) x 50cm (W) x 10cm (H). The experimental model, about 2.9m high and 0.75m x 0.75m is shown in Figure 1(a) along with a wind generator which gave horizontal wind to building model. This system was used in the previous work [8]. The representative cross section which includes the measuring positions of temperatures and upward velocities is shown in Figure 1(b).

A diffusion gas burner which had a vertical burning surface of 10cm(W) x 10cm(H) or 20cm(W) x 10cm(H) was set as the vertical back wall of the compartment, and a propane gas fuel was supplied giving 1.5kW, 3kW, 4kW, 7.5kW and 15kW for the system, respectively. Upward velocities were estimated using bi-directional tubes and high precision pressure gages with the air density correction. Temperatures were measured using K-type thermocouples at the same position of the velocity measurements. These data were collected every 10 seconds and recorded to estimate the time-averaged data. The wind tunnel which has an exhaust opening of 1.2m x 1.2m was controlled by an inverter to simulate the external side wind of constant velocity set up. The experimental conditions including heat release rate, velocity of side wind, and opening size are tabulated in TABLE 1. The mark of ● indicates that the experiments set the condition were carried out.

TABLE 1 Experimental Conditions

External Side Wind (cm/s)		0					6					12				
		1.5	3	4.5	4.8	15	1.5	3	4.5	7.5	15	1.5	3	4.5	7.5	15
W(cm)xD(cm)	5x10	●	●	●	●	●							●			●
	10x10	●	●	●	●	●	●	●	●	●		●	●	●	●	
	20x10	●	●	●	●	●							●		●	●
	20x 5	●	●	●	●	●		●		●			●		●	●
External Side Wind (cm/s)		32					36					75				
		1.5	3	4.5	4.8	15	1.5	3	4.5	7.5	15	1.5	3	4.5	7.5	15
W(cm)xD(cm)	5x10		●			●		●		●	●		●		●	●
	10x10	●	●	●	●			●			●					●
	20x10		●		●	●		●		●	●					●
	20x 5		●		●											●
External Side Wind (cm/s)		92					143					188				
		1.5	3	4.5	4.8	15	1.5	3	4.5	7.5	15	1.5	3	4.5	7.5	15
W(cm)xD(cm)	5x10		●		●	●							●		●	●
	10x10		●			●							●		●	●
	20x10		●		●	●		●		●	●					●
	20x 5		●			●							●		●	●

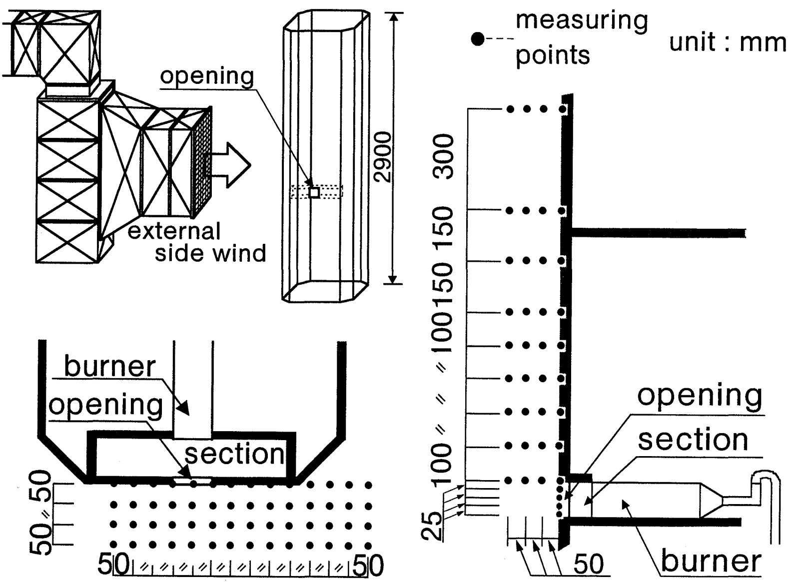

Figure 1 Schematic view of the reduced scale model and the wind generator. Representative cross sections for vertical and horizontal planes with measuring positions are illustrated by ●.

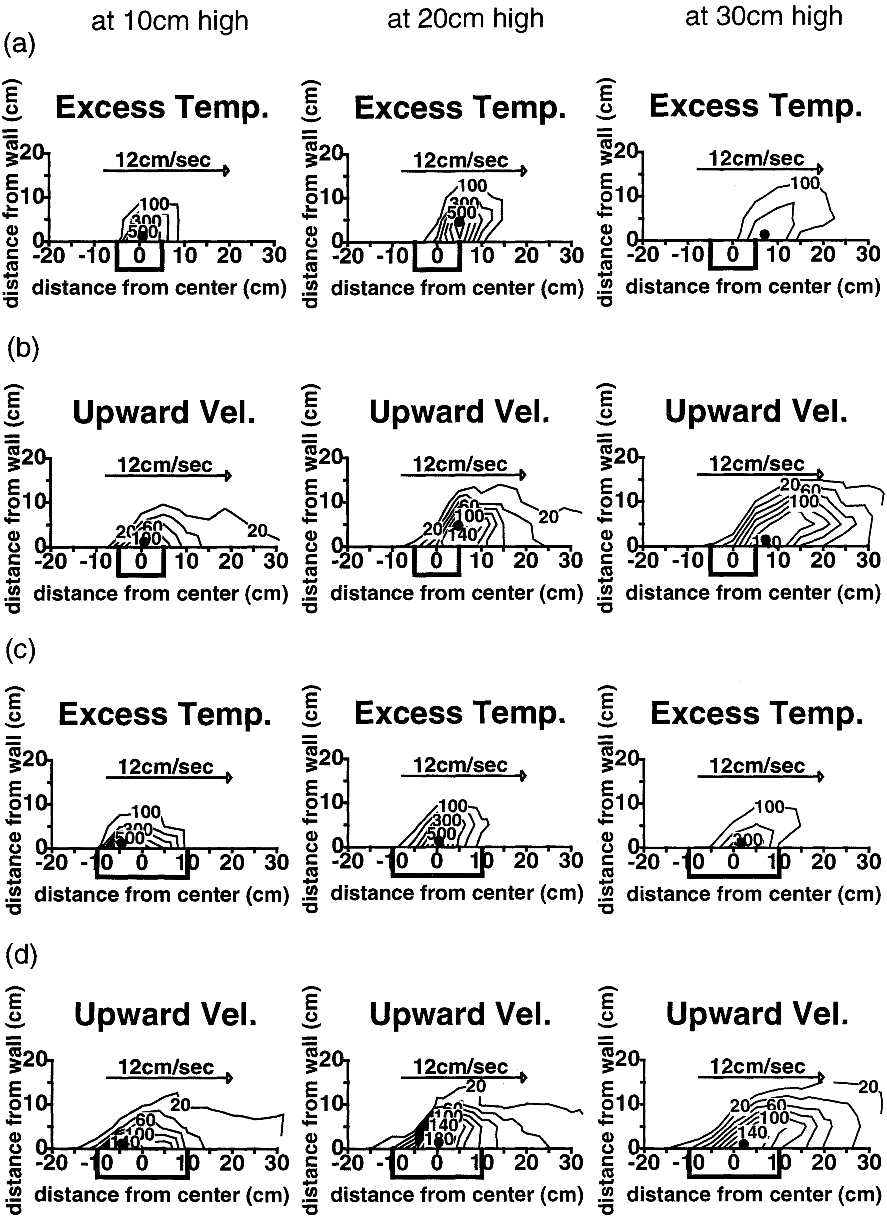

Figure 2 Representative contour maps of the vertical velocity and excess temperature at the heights of 10cm, 20cm, and 30cm with the external wind velocity of 0.12m/sec, (a) and (b) opening of 10cm(W) x 10cm(D), and (c) and (d) 20cm(W) x 10cm(D). The mark ● indicates the position where the trajectory passes in each horizontal section.

RESULTS AND DISCUSSION

Contour Maps of Upward velocity and Temperature

In order to determine the trajectory for vertical and downwind directions, we tried to estimate the slope of a flame using the visual data which were recorded by a video system. However this process gave no clear inclination angle, since the ejected flame, effected by the external side wind, showed great fluctuations. Upward velocity and temperature of the flow in each plane were averaged for 3 min and were used to estimate the contour maps. Then the trajectory was estimated from the position where the time-averaged highest velocity or temperature appeared in each contour maps. Figure 2 shows the typical contour maps estimated by this process and which indicate the area of the hot flow shifted downwind as it flowed upward. The black dot, in Figure 2, indicates the position of the trajectory at each plane so that the trajectory for vertical direction was traced and then its slope was estimated based on the distance for vertical and downwind directions. The vertical position was taken from the upper side of opening and downwind position from the center of the opening. The slope of the trajectory in flame region showed almost linear as shown in Figure 3 representatively in the vertical the plane composed from vertical and downwind directions. In spite of the ejected flow was affected with side wind and was not a purely two-dimensional flow, the ejected flame/plume turned back toward the vertical wall and reattachment occurred. This is the same behavior, as known as Coanda Effect, and was also observed experimentally in the previous paper [2,8]. These contour maps indicate that the opening as its aspect ratio wider gave smaller separation between the wall and trajectory showing turn back of the trajectory toward the vertical wall.

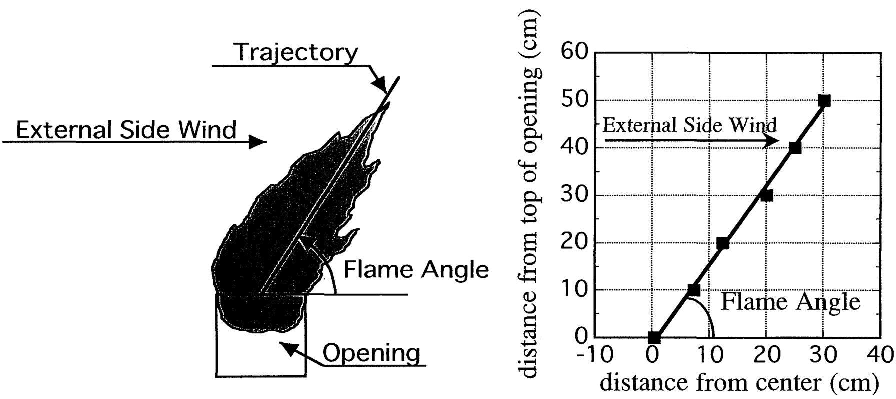

Figure 3 Definition of the flame angle. The right graph shows the flame/plume angle with the side wind of 0.12m/sec using an 10cm x 10cm opening.

Decreasing Modes of Upward Velocity and Excess Temperature for Vertical Direction

Heat transfer from attached or separated flame/plume is very important for the fire safety assessment, since ignition of the surface is critical to vertical fire spread and is also important to the estimation of the window glass breakage which relates to the structural fires. The behavior of vertical velocity and temperature along the wall or along the trajectory is supposed to tend to those of the classical line plume which has been discussed by many researchers. [8,9,10,11].

(a) Decreasing Modes of Upward Velocity

In order to estimate the decreasing vertical velocity (V) along the trajectory, vertical velocities were normalized by $\dot{Q}^{1/3}$ with and without external side wind (V_{wind}) and are plotted against the distance along trajectory as shown in Figure 4(a) - 4(d). These normalized upward velocities, $V/\dot{Q}^{1/3}$, described clearly in the classical way as ;

$$V = \alpha(g\cdot Q/\rho_\infty\cdot Cp_\infty\cdot T_\infty\cdot W)^{1/3} = u^{*1/3} \quad (1)$$

where Q is heat release rate given to the system, g is the gravitational constant, ρ_∞ and Cp_∞ are ambient air density and specific heat, ambient air temperature, T_∞, and W is width of the opening. The coefficient, α, is experimentally determined, such as α=0.74 for the case of no side wind, and α=0.56 for side wind of about 0.32m/sec.

(b) Decreasing Excess Temperature

Figure 5 show the excess temperatures (ΔT) normalized by $\dot{Q}^{2/3}$ against the traveling distance, Z, in log-log scale. Figure 5 shows the excess temperature decreased with increase of distance along the trajectory as described also in the classical way as,

$$\Delta T/T_\infty = \beta(Q^2/g\cdot\rho_\infty{}^2\cdot Cp_\infty{}^2\cdot T_\infty{}^2\cdot W^2)^{1/3}\cdot(1/Z) \quad (2\text{-}1)$$

where β is also experimentally determined constant. Increase of the side wind velocity resulted in the greater decreasing mode on excess temperature for traveling distance along the trajectory, as shown in Figure 5(b) - 5(d).

$$\Delta T/T_\infty = \beta'(Q^2/g\cdot\rho_\infty{}^2\cdot Cp_\infty{}^2\cdot T_\infty{}^2\cdot W^2)^{1/3}\cdot(Z)^n \quad (2\text{-}2)$$

Excess temperature along the trajectory decreased with the traveling distance, $\Delta T/T_\infty \propto Z^{-1}$, and if we adopt this slope as the reference, "***n***=1", ***n*** is a function of side wind velocity and it changed with proportional to the 1/3 power of external side wind velocity in the range of our data. Figure 6 shows the change of ***n*** against side wind velocity.

Flame Length

Estimation of the flame length based on a video record is difficult with side wind due to large fluctuations of flame shape observed. Flame tip height and horizontal distance for downwind were estimated from the 300 successive frames on the recorded flame data. Figure 7 shows the correlation between the dimensionless flame tip height ejected from the opening of 10cm x 10cm and dimensionless heat release rate which was estimated ignoring heat loss. When no side wind is given, as shown Figure 8(a), the slope indicated 1/1 for small Q* range and the slope approached to 2/3 power of Q* in the rage of Q* >1. The slope obtained between dimensionless flame tip height and Q* for Q* >1 range is the similar correlation that was obtained in the flame from a rectangular (or line) fire source, but the flame length of ejected from an opening is about 1/4 shorter than that observed in an open field if we adopt the correlation $L_f/D=4.2\cdot Q^{*2/3}$ [8]. As we gave the higher side wide velocity to the system, as shown in Figures 8(b) and 8(c), flame length in smaller range of Q* changed longer than that of without side wind. Flame lengths, however, over Q*=1 showed almost same length or little shorter as those were observed without and with lower velocity of wind. The slope between L_f/D and Q* approached to 2/3 for all range of Q*. The flame length behavior dependence on

Q* as well as the decreasing modes of upward velocity and temperature showed clearly that the ejected flame from an opening has the similar behavior of that from a rectangular (or line) fire source with and without side wind affection.

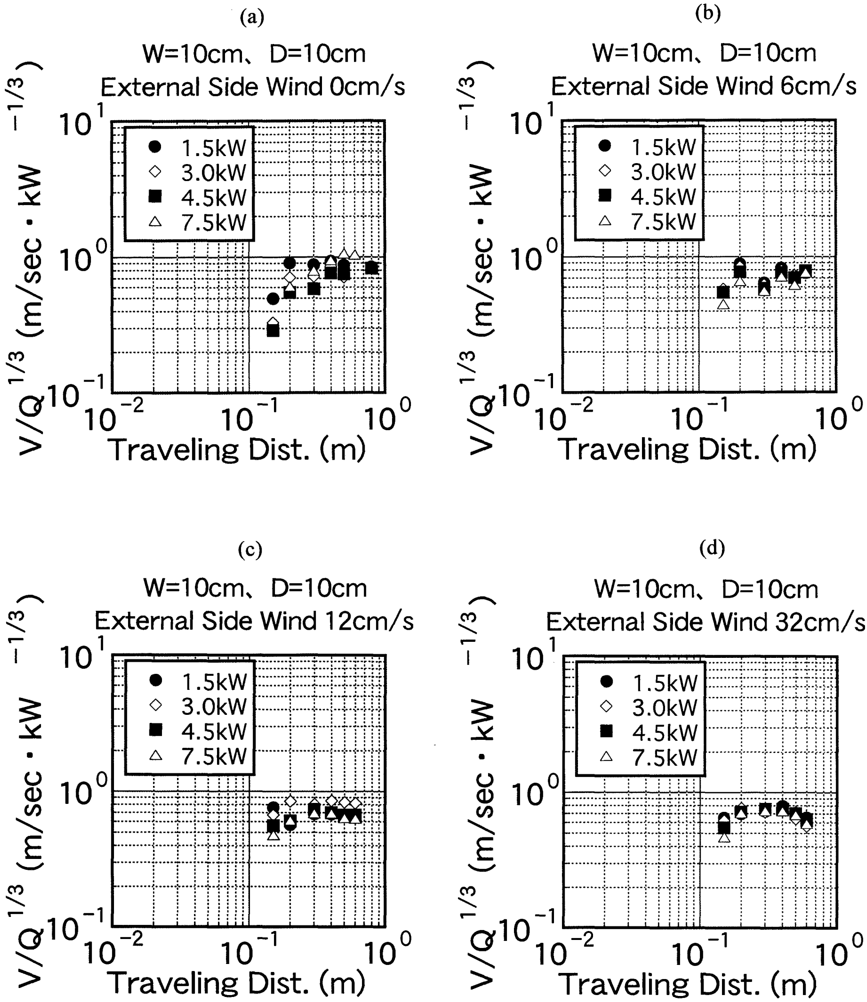

Figure 4 Upward velocities normalized by $Q^{1/3}$ are plotted against the traveling distance of the trajectory. The flame/plume was ejected from a 10cm(W) x 10cm(D) opening with the external wind of (a) 0m/sec, (b) 0.06m/sec, (c) 0.12m/sec, and (d) 0.32m/sec, respectively.

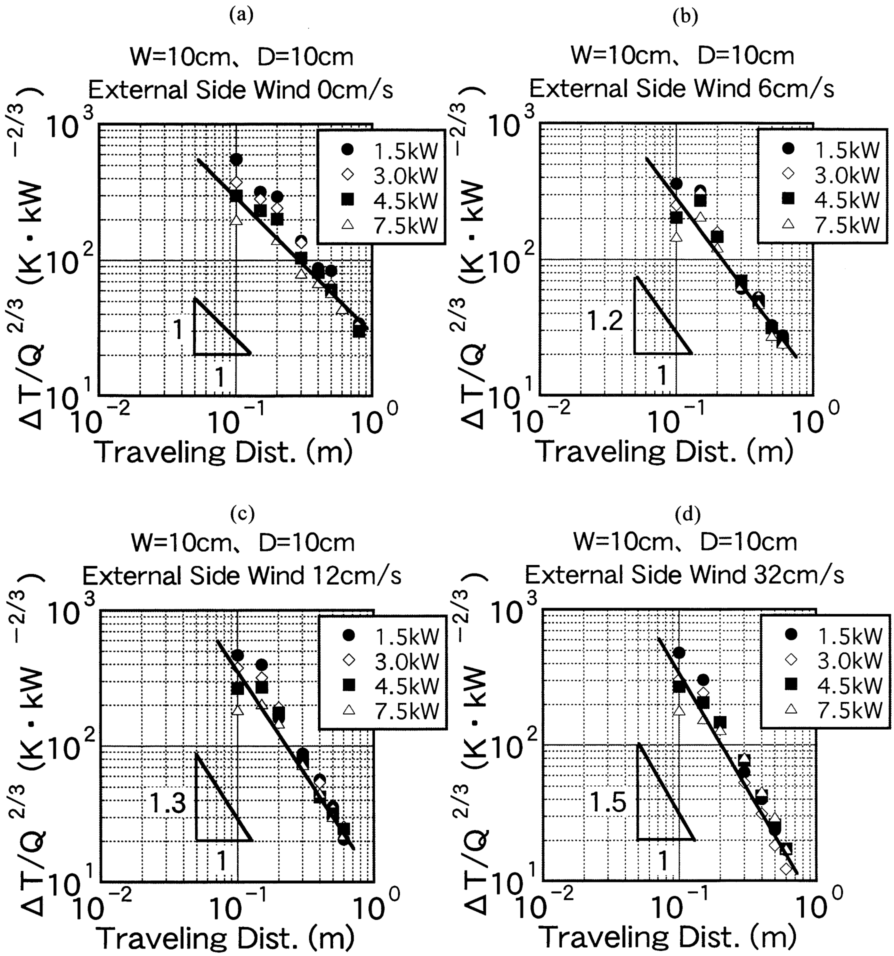

Figure 5 Excess temperature normalized by $Q^{2/3}$ are plotted against the traveling distance along the trajectory. The flame/plume was ejected from an opening of 10cm(W) x 10cm(D) under the external wind of (a) 0m/sec, (b) 0.06m/sec, (c) 0.12m/sec, and (d) 0.32m/sec, respectively. Decreasing slope in each side-wide case is also illustrated.

Slope of Trajectory affected with Side Wind

In building fires, the length of ejected flame is almost the same size of the height of a story, so that a knowledge of the flow behavior on ejected flame is important for the fire development via external combustible wall. Figure 8 shows the typical slopes of the flame as a function of dimensionless side wind velocity V_{wind}/u^*. Where u^* is velocity based on heat

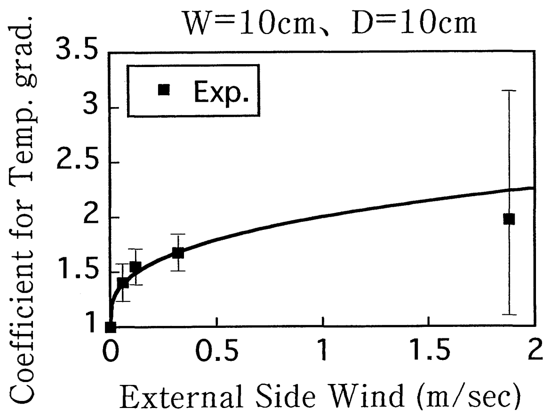

Figure 6 Change of the slope of the excess temperature against traveling distance. Slopes are shown in Figure 5. The slopes are normalized by the one obtained without side wind.

release rate and is defined as $u^* = (Q \cdot g/\rho_\infty \cdot T_\infty \cdot Cp \cdot W)^{1/3}$ adopting the opening width, W, as characteristic length. Figure 8(a) shows the flame angle as a function of V_{wind}/u^*, and the curves are not only affected with side wind velocity but also affected by the shape of opening width and depth. The flame angle must be a function of the balance between inertia of the wind and buoyancy of the flame/plume, and also a function of aspect ratio of the opening, thus,

$$\theta \propto \frac{\text{Inertia}}{\text{Buoyancy}} = \frac{\rho \cdot L_f \cdot D \cdot V_{wind}^3}{\Delta\rho \cdot g \cdot L_f \cdot D \cdot W \cdot u_{eject}} = \frac{V_{wind}}{(gQ/\rho CpTW)^{1/3} \cdot (D/W)^{1/3}} = \frac{V_{wind}}{u^* \cdot (D/W)^{1/3}} \quad .(3)$$

where $\mathbf{u}_{eject}$ is the eject velocity at the opening and is presented by u*. The first term of denominator is the heat release based dimensionless velocity, and the second is the aspect ratio of the opening. It is apparent that the V_{wind}/u^* is a part of Froude number and dimensionless heat release rate. Flame angle is able to be estimated based on the flame length and its height when the flame was blew down by the external side wind. Fortunately, light side wind gave the small inclination of flame angle and of which angle looked like almost vertical. These situation suggest that the flame angle can be described by Sin function. And this behavior will be simplified as;

$$\mathrm{Sin}\theta = \frac{V_{wind}}{u^* \cdot (D/W)^{1/3}} \qquad (4)$$

Figure 8(b), therefore, is illustrated to show the one of the simple expressions to describe the flame angles against the coupled function of dimensionless wind velocity, V_{wind}/u^* and aspect ratio of the opening, $(D/W)^{1/3}$ at various side wind velocities and heat release rates conditions. This figure shows all of the plots followed a line so that the simple model presented the above is useful to estimate the flame angle when the flame is effected by external side wind.

Mass Flux along the Plume

If the air entrainment into the ejected flame/plume is enforced by the side wind, the line of mass flux along the trajectory estimated based on experimental data is greater than that of estimated by the flow model proposed based on a line fire source. On the other hand, if the vertical wall restricts the ambient air to entrain into the flame/plume, the mass flux along the trajectory will be lower than that of estimated by the model. In order to evaluate which situation contribute more to the entrainment, upward mass flux at each horizontal cross section is estimated based on the measured data. Figures 9(a) - 9(c) show typical mass flux against the distance along the trajectory. To compare the measured mass flux with the estimated one based on the free line source model, equations (6) and (7) in reference [10,11],

were employed and calculated assuming 6kW fire which corresponded to 3kW for the model fire. Near the source of the flame/plume, within the distance to D - 1.5D, mass flux obtained experimentally are greater than the mass fluxes estimated. In this region, theoretical treatment presents problems in its approximations [10] . Uncertainties in the measured data may give the uncertainties in mass flux estimation. However, these comparison indicated air entrainment into the flame/plume. In summary, near the source the external side wind may force surrounding air into the flow. However, upper part of the flow, distance greater than 1.5D - 2D, entrainment may be restricted by wall.

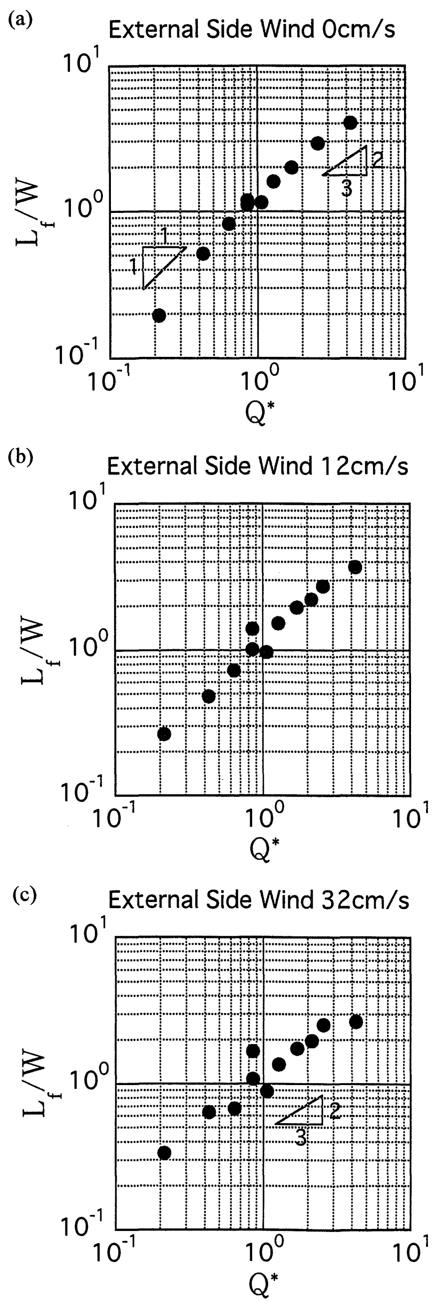

Figure 7 Dimensionless flame tip height as a function of dimensionless heat release rate, Q* which is defined as $Q^* = \dot{Q}/\rho_\infty \cdot Cp_\infty \cdot T_\infty \cdot \sqrt{gD} \cdot D \cdot W$. The slope changes with the intensity of side wind velocity.

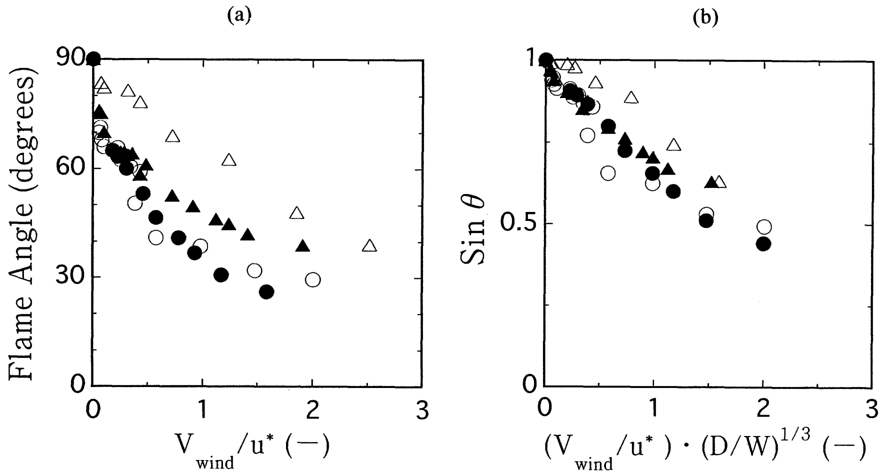

Figure 8(a) Flame angle against dimensionless wind velocity V_{wind} normalized by u* which is estimated based on heat release rate as $u^* = \left(g\dot{Q}/\rho_\infty \cdot Cp_\infty \cdot T_\infty \cdot W\right)^{1/3}$, and (b) flame angle is plotted against dimensionless wind velocity modified with aspect ratio of the opening.

SUMMARY

The flow behavior observed in the ejected flame/plume is similar to the one from a line fire source showing and are its upward velocity and temperature are described by equation (1) and (2). The simple model for flame angle along the trajectory is presented in equation (3) and (4) and which are useful to estimate the inclination angle of the wind blown trajectory by the external side wind.

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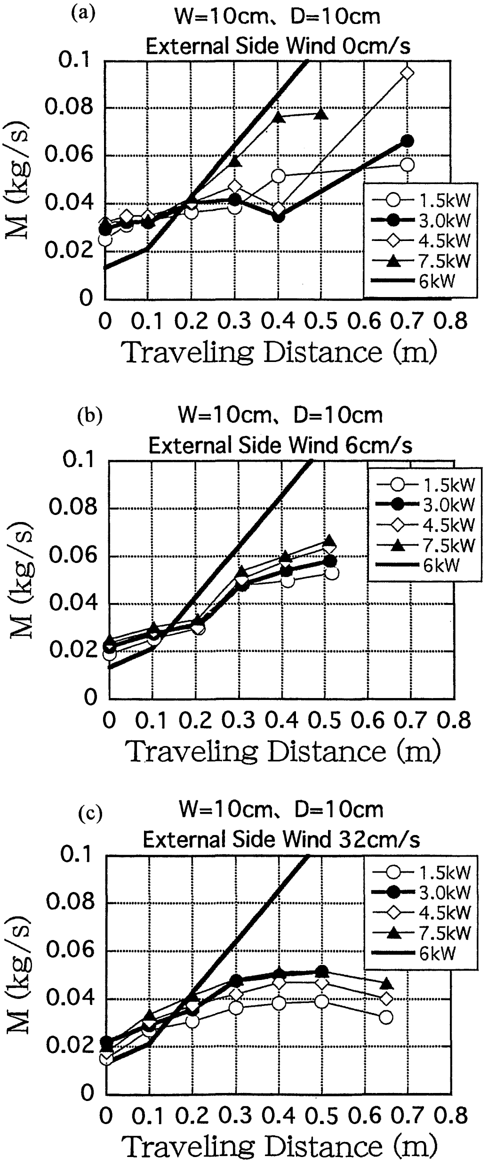

Figure 9 Mass fluxes are plotted against traveling distance of the trajectory, (a) without side wind velocity, (b) effected by the side wind velocity of 0.06m/sec, and (c) of 0.36m/sec. Thick line was estimated by the equation presented by Thomas[10] assuming a 6kW fire which is corresponds to a 3kW fire from an opening with a wall.

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