CHARACTERIZATION OF FLOW BEHAVIOR OF HOT FIRE PRODUCTS IN A CONCRETE FULL-SCALE CORRIDOR

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ABSTRACT

With regard to the horizontal motion of hot fire products from a growing fire source in a full scale concrete corridor, velocity and temperature were measured using newly designed smoke-wire systems and an array of thermocouples. Based on the photographic records of vertical profiles of velocity and together with those of temperature, the horizontal motion subject to the turning process can be divided into two regimes: A supercritical region with jump where both the Reynolds number and the ratio of Reynolds number to Richardson number exceeds 3×10^4 . Succeeding it is a subcritical region where slight mass extraction occurred through the free interface. It was found that the average velocity increased in proportion to the $1/3$ power of the burning rate and was dominated by the magnitude of heat conductivity of the ceiling material. Covering these two regimes, the consistency of the relationship between buoyancy and apparent circulation was confirmed instead of the buoyancy-momentum relationship, except in the earlier stage of combustion.

INTRODUCTION

The flow behavior of fire products is a matter of great concern in the area of fire safety as well as fire detection. Generally the flow of hot products from a fire source can be demarcated into three regimes: upward flow including flame and fire plume, turning region, and horizontal flow of hot products. The term "corridor" should be taken to include both tunnels and malls.

So far several reports have been made on the experiments which had been

carried out in buildings, shopping-malls, and vehicle tunnels.⁽¹⁾⁻⁽⁸⁾ These papers dealt primarily with the formation of a two-layer countercurrent with a free interface, located about half-height to the ceiling, and an exponential attenuation mode of temperature and velocity along the distance travelled when a fire reached its maximum burning. Maeda et al.⁽⁹⁾ examined a hot plume (Reynolds number of $1 \times 10^3 - 6 \times 10^3$) visualized by punk smoke in a scale-corridor with length of 5 m: and they discussed the stability of the free interface and mixing between the hot-smoky flow and the ambient air assuming the flow to be a gravity current. Tsujimoto⁽¹⁰⁾ discussed the attenuation modes of velocity and temperature as well as the variation of the flow depth along the distance with regard to the flow from an alcohol-pool fire, which was blown out through a slit using an electric fan with smoke generators. Quintier et al.⁽¹¹⁾ observed a formation of a four-layer smoke pattern in a scale corridor and found a little mixing between the layers. Handa et al.⁽¹²⁾ had also recognized a similar flow pattern in a full-scale corridor of about 8 m in length using a quasi-steady, burning, wood crib pile. Such a four-layer pattern was found when the flow was fully developed and the corridor had a narrow or L-shaped end. Generally, the studies thus far were concerned with the behavior of a quasi-steady flow from a pool fire or a gas burner.

Nevertheless, in respect for the fire detector and safety evacuation studies, it is not too much to say that the time-dependent, flow behavior of hot products in the early stage of combustion or from a growing fire source rather than those in the steady states should be satisfied accurately. In this respect, Handa et al.⁽¹³⁾⁻⁽¹⁷⁾ had carried out the measurement of velocity, temperature, gas concentration, and smoke concentration in the flow generation from the wood crib pile with a growing burning rate using a full scale corridor (about 70 m in length) with a plywood ceiling and walls. They discussed the attenuation modes of velocity, temperature and gas concentration on a reduced-time base, and it is convenient to presume, a feasible understanding of the flow behavior, that the horizontal flow regime begins after the jumping of a plume occurred on the ceiling. However they could not make out a clear pattern of the jumping phenomena in their former study. Alpert⁽¹⁸⁾ had studied the ceiling-jet

connecting the upward flow without concern for the jumping.

The objective of the present study is firstly, to clarify the horizontal flow behavior in the concrete, full-scale corridor and secondly, to clarify if the jump of a plume really does occur in the turning process. Especially, the accurate knowledge of the jumping of a plume on the ceiling may give us a valuable insight into the mechanism by which the depth and starting location of horizontal flow are determined in the field near a fire source.

EXPERIMENTAL

The facility used in this study was a full-scale corridor of 150 m in length, 3.3 m in width and 1.63 m in height with no interior lining and no windows.

A cross pile of wood was used as a growing fire source. The sticks used were Japanese cedar cut into two sizes; one was 3 cm x 2 cm (cross section) x 36 cm (in length), and the other was 180 cm in length with the same cross section. The moisture content of these sticks was 10 -11 %. The sticks of one layer were arranged at right angles to each preceding layer. The sticks were piled up to about 21 cm in thickness which consisted of 4 layers of 7 long sticks and 3 layers of short ones. The longitudinal axis of the pile was placed along the width direction of the corridor to make the flow a two dimensional scheme. Total mass of the crib was about 40 kg, and the pile was set on iron bed.

A simple weighing system was adopted to easily obtain a continuous record of the crib weight during burning while shielding the effect of radiation. It consisted of an iron bed with three legs of about 54 cm in length which were each set on a strain gauge protected from radiation by a water-cooling jacket. The electrical output from the strain gauges was directly recorded to obtain any changes in the weight of the crib. The mass burning rate (R_b :g/sec) was obtained by differentiating the mass-time curves.

The ignition scheme consisted of burning a small amount of methylalcohol (about 100 ml) which was poured in an eaves through 1.0 cm below the crib. The through had a length of 182 cm and was set under the crib along its longitudinal direction. Thereby, methylalcohol as an ignitor was lit by a small pilot flame at the start of each run.

In order to visually know the flow patterns of the velocity profiles at several locations along the corridor, a newly designed smoke-wire system was employed, taking advantage of the fact that wood with the low moisture content of 10 - 11% produced very thin smoke except in its early stage of combustion. Heavy paraffin oil, which was coated on wire of 0.3 mm ϕ and 130 cm in length, instantly produced a white particle smoke on the application of electricity. In order to reduce the thermal interference caused from the heating of the wire, an adequate but not excess amount of paraffin was used to keep the amperage below a reasonable level. Photos of the paraffin smoke were taken with a time delay of 1 sec after application of the current. The time delay was exactly adjusted using an oscilloscope set prior to the experiment. After the smoke-wire system was set at each selected location, a photo with a 5 cm square grid was preliminarily taken to obtain good focus on the smoke pattern. The distance between the wire and the location of the smoke was measured on the photo and compared to the scale of grid. Velocity, therefore, was estimated by dividing that distance by time. At several measuring locations excluding the region in the field very near the plume, various features of velocity profiles were obtained. The tuft system was also employed simultaneously for the demonstration of profiles and the estimation of velocity. A 12 cm tuft of woollen yarn was set on a rake every 12 cm distance apart. An approximate value of velocity could be estimated from the tilt angle of the tuft.⁽¹³⁾

Temperature of the flow was simultaneously measured at the measuring locations using arrays of chromel-alumel thermocouples of 0.65 mm ϕ . To measure the heat loss, thermocouples were tightly placed on the ceiling surface and were also molded inside the concrete slabs of the ceiling with depths of 0.5, 1.5, and 3.0 cm respectively.

Since it was preliminarily known that the profiles of velocity and temperature for the width-direction were flat, excluding the narrow zone of about 5 cm close to the walls, the traverse of the smoke-wires and the rake of thermocouples were set at the midwidth axial of the corridor.

For the illustration of the flow pattern, a cartesian co-ordinate was adopted with the abscissa for the corridor direction taking $x = 0$ at a location

on the ceiling right above the center of fire source and with the ordinate for the downward vertical direction taking $y = 0$ at the surface of the ceiling.

RESULTS

The vertical temperature difference between the ceiling and the floor was about 5 K and the horizontal one between the two ends was about 1 K before each run. There was almost no indication of natural convection and ambient air flow in the facility before each run.

The propagation of the burning zone within the crib was induced along the vertical traverse, rather than the horizontal outward, for an initial period of 30 sec - 1 min. About 1 min after the ignition, the flame reached the top surface of the pile, and then rapid propagation occurred along the horizontal traverse outwardly to yield a pronounced increase in the total mass burning. Mass burning rate increased approximately with a square of time during a period of 1 - 5.5 min. The heat-release rate (Q_o) from the burning pile increased in proportion to R_b and is expressed as $Q_o = A \cdot R_b$, where A is the apparent heating value of wood, which was estimated to be 3600 - 3800 kcal/kg. At around 6 - 7 min, R_b reached a maximum burning rate of about 57 - 60 g/sec. Stationary combustion at the maximum burning rate continued for about 1 min, and then the R_b value showed an abrupt fall. About 27 - 30% of the initial mass of the pile was burned up in about 7 min. As a whole, R_b increased with a sigmoidal curve excluding the period when it reached stationary burning.

As a first approximation, the visual flame height increased with a square root of the increasing R_b value above the fire source. At around 4 min, the flame tip extended about 80 - 90 cm up from the pile and began to reach the ceiling. The flame tip impinged frequently on the ceiling and began to spread horizontally under the ceiling, and during the period of 5 - 7 min, the length of the horizontally elongated flame reached about 150 ± 50 cm.

The time history of the growth of velocity showed a typical sigmoidal one similar to that of R_b .

Photo 1-(a) displays a particular velocity profile on the vertical traverse at a location of $x = 9$ m and at $t = 4$ min. This photo shows that the flow developed into two countercurrent layers, an upper layer of hot fire products and

Photo 1 Photo of the artificial smoke pattern from a smoke-wire system at the location of 4 m and time of 4 min (a), and of 40 m at 5 min (b), respectively.

a lower layer of inflowing ambient air, the upper layer was demarcated into two regimes; main-flow and wake. The vertical velocity distribution of the main-flow looked like a half-gaussian profile bisected by the ceiling, whereas that of the wake showed a flat profile with a downward tail reaching the interface.

Similar velocity profiles to photo 1-(a) were also obtained at the measuring locations of $x = 4, 5, 6, 7.5, 9$, and 11 m.

Photo 1-(b) shows the typical normal velocity profile at a location of $x = 40$ m and at $t = 5$ min. This velocity profile showed a discrete pattern of two countercurrent layers, indicating an approximately half-gaussian velocity profile for the upper buoyant flow of fire products, and a flat profile for the lower reverse-flow of fresh air. These velocity profiles were observed covering the range of $20 - 50$ m.

The magnitudes of velocity at an arbitrary distance from the ceiling (U) were normalized by that of the maximum ($U_{\max}$) with regard to the same vertical traverse and time. Their vertical distribution profiles were demonstrated by plotting them against a normalized distance from the ceiling as shown in figure 1, where δ is the flow depth at each location. The normalized profiles of the

Figure 1 Normalized horizontal velocity versus normalized vertical distance at the location of 4 m (a) and at 20 m (b), respectively where δ is the flow depth, ∇ =1 min, $\blacktriangledown$ =2 min, $\circ$ =3 min, $\bullet$ =4 min, $\triangle$ =5 min, $\blacktriangle$ =6 min, $\square$ =7 min, and $\blacksquare$ =8 min.

Figure 2 Normalized temperature versus normalized vertical distance at the location of 4 m (a) and 30 m (b) (symbols are same as in Figure 1).

vertical velocity distribution at each location looked very similar covering a period of 1 - 8 min and thus were able to be superimposed on each other as the same profile, irrespective of time but disregarding a slight scatter of points around the standard plot.

The same normalization as conducted on the velocity data was carried out for the temperature data. Figure 2 shows the typical profile of the normalized temperature distribution covering a period of 1 - 8 min at the locations of $x = 4$ and 20 m, respectively. The vertical distance from the ceiling was also normalized by the flow depth (δ). Similarity was clearly recognized between

the normalized profiles of velocity and temperature at an arbitrary location. It is not too much to say that the upper layer of buoyant flow must consist of a main-flow and a wake as was shown in the vertical temperature profiles in the range of 4 - 11 m and also in the velocity profiles covering the same range of distance. Downstream beyond $x = 20$ m, the vertical temperature profiles looked flat with tails reaching the interface.

The flow depth (δ) was estimated by both pictures of the artificial smoke and those of the tilt angles in the tuft systems. The depth of the main-flow and wake was about 30 ± 5 cm and the variation of the total flow depth along the scatter of the depth values with time were not pronounced, irrespective of the increase in Rb . It was observed that the depth of the corridor smoke layer nearly coincided with the flow depth for the period of 1 - 8 min. The smoke near the interface with optical density of about 10^{-2} m^{-1} , showed a very slow, wavy movement. However, the shedding of smoke from the layer and the vortex-like mixing near the interface were not clearly recognized by visual observations.

Figure 3 shows the variations of average velocity ($\bar{U}$), average excess temperature (θ), and the flow depth δ along the corridor direction. Thereby, the total flow depth of about 60 cm for a period of 3 - 8 min remained independent of the distance in a first approximation.

In order to study the attenuation modes of $\bar{U}$ and θ for corridor direction, the logarithmic values of normalized velocity ($\bar{U}/\bar{U}_0$) and temperature (θ/θ_0) were plotted against the logarithmic values of dimensionless distance travelled (x/δ). $\bar{U}_0$ and θ_0 were the average velocity and excess temperature at $x = 5$ m, which was taken as a location for the start of horizontal flow in a first approximation. As the flame tip elongated beneath the ceiling with the increasing of Rb , a terrace appeared and extended downstream of the plots of U/U_0 and θ/θ_0 against x/δ .

Effluent fluxes of mass, momentum, and heat were estimated based on the profiles of velocities, densities and excess temperatures at the measuring locations. Therein, the variation of density of the flow coming from the co-presence of smoke particles was taken into account. Since the smoke from the com-

bustion of the wood was very thin, the contribution of smoke to the density of the flow was negligibly small. Therefore, the flow density was estimated as a function of temperature variation. Specific heat under constant pressure (C_p) was taken as 0.241 kcal/kg·deg C while neglecting the contribution from the smoke and temperature increase. Figure 4-(a) shows the variation of mass efflux along the corridor at 5 min. Total mass efflux decreased along the distance travelled especially in the near field near fire source (4 - 11 m); whereas the decrease in mass efflux was slight far from the source (20 - 50 m). Irrespective of the total extraction of mass in the field near the fire source, a slight increase was found for the mass efflux of the main-flow in the same region during a period of 3 - 8 min. This may be due to the air entrainment from the wake, based on the turbulent eddies occasionally observed as in photo 1-(a). The depth of the main-flow (δ_m), which was a distance from the ceiling to the location of the apparent internal interface between the main-flow and wake varied with distance travelled. Thereby, δ_m slightly increased with distance travelled in the field near the fire source (4 - 11 m). Downstream beyond 20 m, a slight mass extraction was observed for a period of 3 - 8 min when the flow was fully developed. In this situation, hot fire products could travel for a long distance with hardly any active mixing or any exchange with ambient air through the interface.

Figure 4-(b) and (c) show the variations of effluent momentum flux and effluent heat flux with distance travelled at $t = 5$ min. The scatters of plots in the near field (4 - 11 m) and in the distant field (40 - 50 m) of the fire source looked grater than the one in the middle range of 20 - 30 m. For the decrease of momentum and heat efflux, the effect of mass extraction through the interface must be small due to the reason that the decrement of mass efflux was found to be small enough, as shown in Figure 4-(a). Therefore, the decrease of momentum must be due to the frictional loss on the ceiling and wall surface as well as on the free interface. Figure 5 shows the heat loss conducted through the ceiling material plotted against the decrement of heat efflux of the flow during a passage time of the flow from one measuring location to the next one. The loss flux through the ceiling was accounted for on the basis of

Figure 3 Average velocity (a) excess temperature (b), and total flow depth (c), along the distance travelled at 5 min.

Figure 4 Effluent fluxes of mass(a), momentum (b), and heat(c), at 5 min after ignition.

Figure 5 Conducted heat loss through the ceiling concrete versus the deficiency of effluent heat flux at each span; $\circ$ =5 - 10 m, $\bullet$ =10 - 20 m, Δ =20 - 30 m, $\blacktriangle$ =30 - 40 m, and $\square$ =40 - 50 m.

the time-dependent variation of temperature profiles in the concrete slab, using the average density of $2.29 \times 10^3 \text{ kg/m}^3$, the specific heat of $0.21 \text{ kcal/kg} \cdot \text{deg C}$ and the thermal conductivity of $1.94 \times 10^{-4} \text{ kcal/sec} \cdot \text{m} \cdot \text{deg C}$. The slope of the linear plot in Figure 5 was about 0.85 indicating that 85 % of the heat was lost through ceiling during the flow travel. The total heat loss by conduction through the ceiling reached about 30 % of the generated heat (Q_0) at the fire source and the magnitude of that ratio was maintained during a period of 2 - 8 min. Thereby, it should be mentioned that the fire source used was small relative to the facility volume and therefore, the burning rate was not controlled by the rate of air supply to the fire. For such fires, the burning rate and hence the heat output, dependent on the amount of fuel and how it burnt.⁽¹⁹⁾ As about 5 - 10 % of substantial heat output was required to maintain the burning of the fire,⁽²⁰⁾ and remembering that about 25 - 30 % of heat output was lost by direct radiation in the field near the fire source,⁽¹⁹⁾ the remainder (30 - 40 %) of the heat output must have been consumed for the heating of the combustion products which were pushed out with high buoyancy in the corridor direction.

DISCUSSION

Presence of Internal Jump

Comparing the profiles of horizontal velocity and excess temperature at arbitrary locations and times, both thickness of δ_v and of δ_θ were almost coincident with each other, so that the ratio of δ_v/δ_θ was expected to be unity. Therefore, it was not so important to take the Prandtle number of the flow into consideration and hence it was disregarded in the further study.

The profiles of velocity as well as temperature could be differentiated into three types. The first, a flat profile with a tailing toward the free interface was observed downstream at 20 - 50 m through the whole burning period. This profile was approximately coincident with the ones which Handa et al.⁽¹³⁾ Hinkley⁽⁴⁾ and Tsujimoto⁽¹⁰⁾ had obtained. The second type, which was observed at locations of 30, 40, and 50 m at $t = 0$ and 30 sec, showed that air was moving in the whole vertical cross section of the facility at a velocity of several cm/sec. This kind of phenomena was also observed in the Glasgow tunnel test.⁽⁶⁾ This may be somehow due to some pressure change from the thermal expansion of the combustion gases in the field near the fire source before the stratification of flow, since it disappeared as the flow developed and the first-type profile came out. The third-type profile, which showed a very different feature from those of the first and the second types, was the one obtained in the field near (4 - 11 m) the fire source. The last type looked like a doubly piled-layers profile although the first-type profile appeared for an initial period of 1 - 3 min. The variation in every profile feature (from the first type to the last one) began at a time corresponding to the inflexion time in Rb-time history. Therefore, this can be regarded to occur due to the change in pressure balance and from the abrupt increase in the effluent volume flux. Figure 6 shows the equi-velocity contour at $t = 4$ min and the equi-temperature contour at $t = 5$ min. Such contour maps for a period of 3 - 8 min showed that the downward-projected features appeared at around $x = 7 - 11$ m and $y = 30$ cm. This implies that the jump occurred in that region. In confirming that possibility, the change in the densimetric Froude number (Fr) was evaluated by noting that $Fr = \bar{U}/\sqrt{g^* \cdot \delta}$. In the equation, g^* is $(\Delta\rho/\rho) \cdot g$ with $\Delta\rho = \rho_a - \rho$ and δ equal to the

Figure 6 Equi-velocity contour map at 4 min (a) and equi-excess temperature contour map at 5 min (b). Arabic numerals are the velocity in units of m/s and the excess temperature is in unit of absolute temperature (K).

flow depth. Observations of the optical smoke density, contour maps in Figure 6, and photo 1, tacitly lead to an assumption that an internal interface must exist between the main-flow and the wake of the upper layer current in that region. It follows that the Fr should be estimated on the basis of the main-flow depth (δ_m) rather than the total flow depth (δ). However, a difficulty should exist in determining the exact thickness of δ_m , since the boundary between the main-flow and the wake was diffuse because they were miscible in each other. It is suggested that they must come from the same origin with almost the same composition ratio of combustion gases. Further, they were inherently turbulent with tailing profiles. Accordingly, these brought about an ambiguity in the estimation of Fr . It is more reasonable, therefore, to consider the occurrence of the jump on the basis of the gradient Richardson number (Ri) rather than Fr . This follows by noting that $Ri = -g \cdot (\partial \rho / \partial y) / \rho (\partial U / \partial y)^2$. In this equation, the density gradient was estimated based on the temperature gradient. When a jump occurred in the flow, this appeared as the change in values of Ri . Remembering the fire-induced flow was inherently a turbulent gravity current, it is instructive to take account of the balance between turbulence and buoyancy. The Reynolds number (Re) was invoked as an index of turbulence given by $Re = U \cdot \delta / \nu$ with ν the kinematic viscosity of the flow. The stability of the internal interface as well as the presence of jump can be evaluated by referring to the balance between buoyancy, inertia force and drag forces. The situation of balance among these forces may be expressed partly by Re and by Ri . Figure 7 shows the log-log plots of Re against Re/Ri at the measuring locations for a period of 1 - 8 min. The scatter can be regarded to be indebted to the difficulty in the estimation of the gradients of both velocity and temperature, as well as the exact flow depth. The experimental results shown in Figure 7 may support that the choice of Re and Re/Ri as the major governing parameters was satisfactory for the explanation of the phenomenon. The flow was characterized into two regimes bisected by the dotted lines of $Re = 3 \times 10^4$ and $Re/Ri = 3 \times 10^4$. Thereby, the cross-point of the lines corresponded to a state with a critical Richardson number of $Ri = 1$. The horizontal flow in the upper region which was subjected to the turning process, pos-

Figure 7 Logarithmic plot of the Reynolds number versus the ratio of the Reynolds number to the Richardson number for various locations and times: $\circ$ =5 m, $\times$ =10 m, Δ =15 m, $\square$ =20 m, for the main-flow; $\oplus$ =5 m, $\ominus$ =10 m, Δ =15 m, $\square$ =20 m for the wake; $\bullet$ =25 m, $\bullet$ =30 m, ∇ =35 m, $\blacksquare$ =40 m, $+$ =45 m, and $\diamond$ =50 m, for the subcritical horizontal flow.

sessed a high velocity, high temperature and low Ri . As for the main-flow, Ri was smaller than 1 for the period of 3 - 8 min, and therefore it must belong to a supercritical state. At around $x = 20$ m and beyond, the third type of velocity profile gradually changed into the first type and simultaneously Ri approached 1. The bottom of the flow near the internal interface was agitated depending on the viscosity and wavy motion. With regard to the change in Ri , this implies the decay of the flow with distance travelled from a supercritical to a subcritical state with the initial boundary becoming very wavy and causing breaks of the interface and mixing of fluids between the main-flow and the wake in the field near the fire source. Finally, the third-type velocity profile as well as the internal interface disappeared to form the first-type profile. Therefore, the state of Re/Ri greater than 3×10^4 is supposed to satisfy the quasi-stable condition of the initial interface. Therein, the quasi-stability showed an active-mixing process with a simultaneous jump of hot fluid.

As the magnitude of the total loss due to jump and the frictional drag on the internal interface had not been directly measured, it must be estimated by the equation of motion:

$$\frac{d}{dt} \int_0^\delta \rho B \cdot U \cdot dy + \frac{d}{dx} \int_0^\delta \rho \cdot U^2 \cdot B dy + \frac{d}{dx} \int_0^\delta g \cdot B \cdot (\rho_a - \rho) + \tau_{total} = 0, \quad (1)$$

where B is the width of the corridor and τ_{total} is the sum of τ_f and τ_j . τ_f is the frictional loss on the perimeter of the ceiling and walls and τ_j is the loss induced by the jump, including that from the shearing stress imposed on the internal interface. τ_f was estimated based on C_f and the effluent momentum flux, where C_f is the shearing stress coefficient and is a function of Re as shown in a previous paper.⁽¹⁴⁾ Thus, τ_j was estimated by subtracting τ_f from τ_{total} . Meanwhile, the loss coefficient (C_j) must depend on how the jump occurred and is defined as $C_j = \tau_j / \frac{1}{2} \cdot \rho \cdot (U_{main} - U_{wake})^2 \cdot B$. In terms of this equation, C_j was evaluated as a function of Re/Ri on a log-log plotting, and could be expressed by $C_j = 10^3 (Re/Ri)^{-1}$ in the field ($x = 5 - 10$ m) near the fire source.

Effect of Cooling

As shown in Figure 3, the average excess temperature and the average velocity decreased with distance travelled although the change in total depth of the flow was slight enough to be regarded as approximately horizontally flat. Hence, it follows that the effluent heat flux (Q) decreased with distance due to loss to the surroundings. The heat balance equation is given:

$$\frac{\partial Q}{\partial t} - \frac{\partial Q}{\partial x} = h_w \cdot (\theta_m - \theta_w) \cdot B + h_s \cdot (\theta_m - \theta_s) \cdot B + \rho \cdot C_p \cdot V \cdot \theta \cdot B, \quad (2)$$

where h_w and h_s are the heat transfer coefficients for the ceiling and for the free interface respectively. θ_m , θ_w , and θ_s are the maximum excess temperature of each profile, the excess temperature on the ceiling surface and the excess temperature at the free interface, respectively; and v is the vertical velocity based on the overall mass extraction. Tsujimoto⁽¹⁰⁾ presented an entrainment from ambient air to the flow being superficially opposed to his results that the mass efflux did not increase with distance. According to previous papers⁽¹³⁾ -⁽¹⁵⁾ and also to the present one, the mass efflux of gases (CO and CO_2) was not

conserved between the locations of $x = 4, 7.5$, and 11 m. This leads to the implication that the actual mass exchange was induced through the free interface, besides that the mass extraction was greater than the entrainment and, as an overall result, the extraction proceeded with distance. Consequently, the mass extraction velocity (v) was defined by $v \equiv (\partial \int_0^\delta B \cdot \rho \cdot U \cdot dy / \partial x) / B \cdot \rho |_{x=x, t=t}$ and was evaluated. The ratio of v/U was on the order of 10^{-3} - 10^{-4} and it follows that the last term of the right-hand side of equation (2) was negligibly small. Comparing the order of the terms in equation (2) with each other, the first term of the left-hand side was also negligibly small. Hence, equation (2) can be rewritten into

$$\frac{\partial Q}{\partial x} = -h_w \cdot (\theta_m - \theta_w) \cdot B \cdot \left(1 + \frac{h_s (\theta_m - \theta_s)}{h_w (\theta_m - \theta_w)} \right).$$

For the heat transfer from an element of the flow to the surface of the ceiling.

$$h_w \cdot (\theta_m - \theta_w) = -k \cdot (\partial \theta / \partial y^*),$$

where k is the thermal conductivity of the concrete ceiling, and $(\partial \theta / \partial y^*)_w$ is the surface temperature gradient, and y^* is the distance into the ceiling measured from the surface. Remembering the ratio of heat loss from the interface (Q_s) to that from the ceiling and walls (Q_w) remained about 0.08 all through the corridor and the average excess temperature of the flow θ was defined by

$$\theta = Q / \rho \cdot C_p \cdot U \cdot \delta \cdot B,$$

equation (2) can be finally rewritten into equation (3), where

$$\frac{1}{Q} \cdot \frac{\partial Q}{\partial x} = St \cdot \frac{(\theta_m - \theta_w)}{\theta} \cdot \frac{1}{\delta} \quad (3)$$

St is the Stanton number and is noted as $h_w / \rho \cdot C_p \cdot U$. Provided the term of $(\theta_m - \theta_w) / \theta$ expressed by $\phi(\theta)$ is a kind of memory function for the delay in thermal conductivity, $\phi(\theta)$ must be a function of distance and the delay time, $\phi(\theta) = \phi(x, t)$ as Kennedy and Taylor,⁽²¹⁾ and Handa et al.^(14, 15) had presented.

By integrating equation (3), we have

$$\ln(Q/Q_0) = \int_{x_0}^{x_u} St \cdot \phi(\theta) \cdot \frac{1}{\delta} \cdot dx. \quad (4)$$

where Q_0 is the effluent heat flux at the starting position of $x = x_0$. The

integration of the right-hand-side term to a general form of analytical function can not be theoretically attained because of the complexity of the memory function of $\phi(\theta)$. Figure 8 shows the semi-logarithmic plot of Q / Q_0 against

Figure 8 Semi-logarithmic plot of the normalized effluent heat flux versus the distance travelled: o=2 min, x=4 min, Δ =6 min, and $\square$ =8 min, respectively.

distance travelled (x). Figure 8 revealed the break with time by the appearance of a terrace in the field near the fire source indicating the progression with time of the actual effluent point ($x=x_0$) of horizontal flow toward the distant field. The variation of $\phi(\theta)$ with time at several locations is shown in Figure 9. Figure 10 shows the logarithmic plot of Q against the average velocity $\bar{U}$ at various times and places. The ratio of $Q / \bar{U} \sim 32$ was conserved, irrespective of time and location. The value of the ratio agreed approximately with the one which had been obtained in the full scale corridor with a plywood ceiling and walls.⁽¹⁴⁾ Therefore, substituting the term Q / Q_0 by $(U / U_0)^3$ yields

$$\ln(U/U_0) = -\frac{1}{3} \cdot \int_{x_0}^x St \cdot \phi(\theta) \cdot \frac{1}{\delta} \cdot dx. \quad (5)$$

When the fire had almost grown up to its maximum burning rate and the flow had

Figure 9 Memory function fore the delay in thermal conductivity versus distance travelled: o=2 min, x=4 min, Δ=6 min, and □=8 min.

Figure 10 Logarithmic plot of effluent heat flux versus average horizontal velocity: o=5 m, x=10 m, Δ=15 m, □=20 m, ●=24 m, +=30 m, ▽=40 m, and ◇=50 m.

become fully developed, both St and $\phi(\theta)$ reached their quasi-steady values which were approximately given as $St \sim 3 \times 10^{-2}$ and $\phi(\theta) \sim 1$, irrespective of place (except the jumping region).

Nevertheless, the determination of the true effluent point (x) of the horizontal flow, if it exists at all, is still a matter of discussion. To pursue this problem, two locations (for example $x = 5$ m and $x = 20$ m) were taken temporarily as effluent positions of the horizontal flow, although the former position was located in the range of jump.

Figure 11 shows the error in fitting the observed and the calculated values of velocity in terms of equation (5) at a time of 6 min, when $\phi(\theta)$ converged approximately to its asymptotic value of 1.

For $x_0 = 5$ m, an obvious error was found on the upstream side and for $x_0 = 20$ m, the deviation occurred on the downstream side.

Therefore, it is suggested that the true effluent point will exist in between and the progression of the effluent point with time may occur downstream in real fires. Remembering that the situation of doubly-stratified flow changed from supercritical to a subcritical state at around $x = 15$ m for the main-flow and at around $x = 10$ m for the wake, it is highly probable that the true effluent

Figure 11 Variation of the average horizontal velocities obtained by the present experiment and the calculated ones: Δ for $x_0 = 20$ m and $\square$ for $x_0 = 5$ m.

point must exist in between at $t = 6 - 7$ min, and correspond to a location where the condition of $Ri = 1$ is satisfied irrespective of time. As reported in previous papers, (14, 15) the attenuation of velocity and temperature on the reduced time ($t^* = t - 4x/U$) bases can be given as follows,

$$U = U_0 \cdot \exp \left(- \frac{C_f}{1 + Ar} \cdot \frac{1}{\delta} \right) \quad (6)$$

and

$$\theta = \theta_0 \cdot \exp \left(- St \cdot \phi(t^*) \cdot \frac{x}{\delta} \right) \quad (7)$$

where $\phi(t^*)$ is a function of the delay time for the heat conduction to the ceiling which converges asymptotically to a constant value with time. $\phi(t^*)$ at a quasi-steady state was given as about 0.27 for plywood ceiling and walls. Thereby, irrespective of time, the ratio of the attenuation coefficient $C_f/(1+Ar)$ to $St \cdot \phi(t^*)$ was experimentally given as 2, resulting in the conservation of the Froude number. Hence, the following relation was established among the hydraulic numbers concerned:

$$St = 2 \cdot C_f / \phi(t^*) \cdot (1 + Ar) \quad \text{with } t^* \rightarrow \infty$$

Therefore, in so far the Froude number - Ranking's relation $U/\sqrt{\theta \cdot \delta} = \text{constant}$

is conserved, a similarity can exist between U and θ with regard to the attenuation in the motion of hot fire products along a corridor and tunnel. Thereby, the logarithmic attenuations of velocity as well as temperature are governed by $St \cdot \phi(\theta)$ in a quasi-steady approximation where $\phi(\theta)$ is a constant, depending on the material of the ceiling and walls. In conclusion, the motion of hot fire products either in an upward or a horizontal direction obeys Bernoulli's equation overall, except in the difference in loss terms including that of the turning process due to jump. Thereby, the magnitude of thermal conductivity, the surface condition of the ceiling, the scale of the fire relative to space, as well as the pressure gradients, must all play significant roles in how fast and how far the fire-induced can move.

Relationship Between Buoyance and Shear

The functional relationship of average horizontal velocity and average excess temperature with distance travelled was not as straight-forward as it was in the results in previous paper^(14, 16, 17) provided that the region of jump is induced. In reality, the scatter came from the jumping phenomena. When a volume of hot, viscous fluid is forcibly driven into a uniform atmosphere, an eddy must be formed along the interface between the light fluid and the environmental air. Considering the actual mass exchange through the free interface, it must be related to the vertical component of velocity which supposedly originates from an eddy-motion around the free interface. This apparent circulation, defined as $\Gamma = \delta^{*2} \cdot (\partial v / \partial x - \partial U / \partial y)$, was estimated utilizing the gradients of v for horizontal and U for vertical direction; besides that, v was estimated based on the mass extraction as aforementioned. In the equation, δ^* is the apparent mixing length and was estimated by referring to the tailing part of the depth. Correspondingly, the modified buoyancy (F), as defined by $F = g^* \cdot vol$ with vol meaning the effluent volume flux, was evaluated at each cross section. Figure 12 shows the logarithmic plot of the modified buoyancy against the apparent circulation at selected locations and time (1 - 8 min). The consideration of the relationship of F and Γ empirically led to the overall representation of the flow characteristics as $F/\Gamma^2 = \text{constant}$ in a dimensionless form. As shown in Figure 11, each plot shows a remarkable tendency to cluster along the

Figure 12 Logarithmic plot of the modified buoyant force versus the apparent circulation of the horizontal flow: $\circ=5$ m, $\times=10$ m, $\Delta=15$ m, $\square=20$ m, for the main-flow: $\circ=5$ m, $\bullet=10$ m, $\Delta=15$ m, $\blacktriangle=20$ m, for the wake: $\bullet=25$ m, $\bullet=30$ m, $\nabla=35$ m, $\blacksquare=40$ m, $+=45$ m, and $\diamond=50$ m for the subcritical flow.

rigid line of $F = 1 \times 10^{-2} \Gamma^2$, excluding the wake region which is represented by the broken line of $F = 1.5 \times 10^{-1} \Gamma^2$. The transitional scatter of plots from the former line to the latter one may depend on the nature of the wake where some ambiguousness occurs in both the estimation of the volume efflux and the average density in the earlier stage of combustion. The flow cooled off with distance travelled on a real time basis during the growth of a fire source. However, when the mass burning rate approached that in the quasi-steady combustion producing the fully developed flow, each plot obviously tended to cluster around each line. Hence, it is not too much to say that the buoyancy-momentum relationship can be replaced by the buoyancy-eddy relationship, just as the former had been replaced by the latter for the upward motion.⁽¹⁹⁾ In con-

clusion, it can be said that the buoyancy-eddy relationship will characterize the overall motion of hot fire products, except in differences in constants due to the mode of energy loss.

SUMMARY and CONCLUSION

Smoke wires, woolen-yarn tufts and thermocouples have been used to determine the characteristic of the horizontal flow induced from a model fire source in a full-scale, concrete corridor. The utility of the smoke-wire system for velocity measurement of the flow with jump phenomena was verified and the location of the free interface was also determined by the system.

Both the ratio of heat efflux to kinematic energy efflux and heat efflux to momentum efflux were presented in their reduced form of $U/Q^{1/3}$ and $Q/\theta^{1/2}$, respectively. The consistencies of their value were found as $U/Q^{1/3} \sim 0.26$ and as $U/\theta^{1/2} \sim 0.1$, irrespective of measuring locations and time for the period of 3 - 8 min (excluding the region of jump). These values are located close to the ones of $U/Q^{1/3} \sim 0.32$ and $U/\theta^{1/2} \sim 0.08$, which had been obtained in the corridor with a plywood ceiling and walls.

Finally, the results of equi-contour maps of velocity and excess temperature brought out the dimensionless relationship of Re and Re/Ri and demarcated the flow into jump and subcritical flow regimes. The dominant role played by buoyancy and drag based on eddy viscosity is shown by the consistency of the F/r^2 relationship throughout the jumping and horizontal flow regimes of the main-flow.

ACKNOWLEDGEMENT

Sincere thanks are due to Nohmi Bosai Kogyo Co., Ltd., for their cooperation in the experiment and financial aid, and thanks are also due to members of the Fire Research Group in the Handa Laboratory of Science University of Tokyo, and to Mr. K. Sawai for his kind help of typing.

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Received, July 10, 1981