INVESTIGATION INTO RISE TIME OF BUOYANT FIRE PLUME FRONTS

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ABSTRACT

Experiments were conducted to investigate the rise time of buoyant plumes induced above fire sources in a free space and in vertical shafts. Two other existing full scale experiments available for this purpose were also analyzed. It was found that the time for the front of a buoyant plume to reach a given height from a fire source was inversely proportional to the 1/3 power of the heat release rate and proportional to the 4/3 power of the height in a free space and the region near the fire source in shafts, while proportional to the 2/3 and to the 2 power of the height in the region far from the source depending on that the top of the shaft is open and closed, respectively. Results of the experiments in spaces with different scales were correlated by a non-dimensional time. Based on the experiments, formulas to predict rise time of fire plume fronts were proposed.

1. INTRODUCTION

Two layer zone fire models are now frequently used for various analyses on smoke behavior in buildings [1]. In such models, although entrainment of the buoyant plumes generated by fire sources and hot door jets are usually incorporated as a component process, the travel times that the hot gases take to reach the ceiling are disregarded. A means to predict the rise time of hot gases may be desired for future improvement of practical fire models such as two layer zone models, particularly when spaces with very high ceilings are involved.

Regarding the transient plume rise time from a point heat source in a free space, Zukoski presented an insight on the dependence of the rise time on height from fire source and heat release rate [2] and Turner, in an earlier paper, also presented a theory and data from salt water experiments [3]. But these were limited to plumes in a free space and no experimental data using a real fuel has been made available.

In this study, investigations were made into the fundamental nature of the rise time of transient fire plumes above fire sources. Heat release rate of the fire source and space geometry are considered to be the two important governing factors of the travel time. This study aims at finding the relationship between the vertical transient travel time of hot gases which are generated immediately after ignition of fire sources. The experiments were conducted in three types of spaces: (1) a free space, (2) an open shaft (i.e. a vertical space with no roof such as a void space) and (3) a closed shaft (i.e. a vertical space with a roof such as an atrium, a shaft). In the experiments, the buoyant plumes were purely driven by the heat released from methanol pool fires. No other sources which could accelerate the flow, such as stack effect and mechanical ventilation, were involved.

2. THEORETICAL CONSIDERATION

Since it is too complicated to theoretically deal with the transient rise of the head of a buoyant plume generated immediately after ignition of a fire source, an attempt is made here to presume the basic relationship to govern the rise time based on existing knowledge for steady state fire plumes [4-7].

Assuming that the effect of the heat transfer from a fire plume to surrounding walls is insignificant, we have the relationship between the temperature rise and the flow velocity of a plume and the heat release rate of the fire source as follows:

$$\dot{Q} \propto c_p \rho \Delta T A w \qquad (1)$$

where c_p is specific heat of air at constant pressure, ρ, ΔT, w and A are the characteristic density, the temperature rise, the velocity and the horizontal section area of the plume, respectively, and $\dot{Q}$ is the heat release rate of the fire source.

Since the plume flow velocity w is induced by buoyancy due to the difference in density, or temperature, between the plume and the ambient air, we have the relationship as follows:

$$w \propto \sqrt{g(\Delta\rho/\rho)z} = \sqrt{g(\Delta T/T_\infty)z} \tag{2}$$

where g is the acceleration due to gravity, Δρ is the characteristic density difference between the plume and the ambient air, z is the height above the source and T_∞ is the ambient temperature.

Substituting Eqn.(2) into Eqn.(1) yields the relationship as follows:

$$\frac{\Delta T}{T_\infty} \propto \left(\frac{\dot{Q}}{c_p \rho T_\infty \sqrt{g}}\right)^{2/3} \left(\frac{1}{A\sqrt{z}}\right)^{2/3} \tag{3}$$

Further, substituting Eqn.(3) into Eqn.(2), we obtain:

$$w \propto \sqrt{g}\left(\frac{\dot{Q}}{c_p \rho T_\infty \sqrt{g}}\right)^{1/3} \left(\frac{z}{A}\right)^{1/3} \tag{4}$$

or in terms of an alternative expression using the non-dimensional flow velocity $w/\sqrt{gD}$,

$$\begin{aligned}\frac{w}{\sqrt{gD}} &\propto \left(\frac{\dot{Q}}{c_p \rho T_\infty \sqrt{g} D^{5/2}}\right)^{1/3} \left(\frac{Dz}{A}\right)^{1/3} \\ &= \dot{Q}_D^{*1/3}\left(\frac{Dz}{A}\right)^{1/3}\end{aligned} \tag{5}$$

where D is the characteristic length of the space, for which the side length of the horizontal section of a space is chosen in this study, and $\dot{Q}_D^*$ is the non-dimensional heat release rate defined using the characteristic length D:

$$\dot{Q}_D^* \equiv \frac{\dot{Q}}{c_p \rho_\infty T_\infty \sqrt{g} D^{5/2}} \tag{6}$$

Note, however, in deriving Eqn.(5), it was regarded that the plume density ρ is not significantly different from the ambient air density ρ_∞, that is $\rho \approx \rho_\infty$.

Considering the relationship given by Eqn.(4), the travel time of a fire plume front from the source to a given height z is expected to be:

$$t \propto \int_0^z \frac{dz}{w} \propto \dot{Q}^{-1/3} \int_0^z \left(\frac{A}{z}\right)^{1/3} dz \tag{7}$$

Or letting τ be the non-dimensional travel time defined by:

$$\tau \equiv \left(t\sqrt{\frac{g}{D}}\right)\dot{Q}_D^{*1/3} \tag{8}$$

a non-dimensional expression alternative to Eqn.(7) can be derived as:

$$\tau \propto \int_0^z \left(\frac{A}{Dz}\right)^{1/3} d\left(\frac{z}{D}\right) \tag{9}$$

where use was made of the following relationship:

$$t \propto \int \frac{dz}{w} = \sqrt{\frac{D}{g}} \int \left(\frac{w}{\sqrt{gD}}\right)^{-1} \frac{dz}{D}$$

2.1 Region without a Boundary Constraint

In case of a fire plume in a free space, it is well known that the radius of the horizontal section of the fire plume increases proportionally to the height from the source, hence the horizontal section area of a plume increases proportionally to square of the height. Note, however, that whether a space is free or confined is just the matter of relative scale of the space and the plume. Even in a confined space such as a shaft as well, the development of a plume is expected to be like in a free space in the region near the fire source, where the plume is not constrained by the boundary walls. Hence, in such circumstance, the relationship of the plume sectional area with height will be as:

$$A \propto z^2 \tag{10}$$

Substituting this into Eqn.(7) yields the relationship as follows:

$$t \propto \dot{Q}^{-1/3} z^{4/3} \tag{11}$$

that is, the rise time of the plume in the region with no boundary constraint is expected to be inversely proportional to 1/3 to heat release rate and proportional to 4/3 to height. Or substituting Eqn.(10) into Eqn.(9), we have the expression alternative to Eqn.(11) in terms of the non-dimensional time τ, heat release rate $\dot{Q}^*$ and height z/D as follows:

$$\tau \propto \int_0^{z/D} \xi^{1/3} d\xi = \left(\frac{z}{D}\right)^{4/3} \tag{12}$$

2.2 Region with a Boundary Constraint

In a shaft, the lateral development of a fire plume is considered to be constrained by the boundary walls in the region far from the source, so the plume horizontal sectional area is expected to be controlled by the horizontal sectional area of the space, that is:

$$A \propto D^2 \left(\propto z^0 \right) \tag{13}$$

Substituting this into Eqn.(7) yields the relationship for the travel time t as follows:

$$t \propto \dot{Q}^{-1/3} z^{2/3} \tag{14}$$

that is, the travel time of a fire plume is expected to be proportional to 2/3 to height in the region far from fire source. Or, alternative to Eqn.(14) we can have a non-dimensional form as:

$$\tau \propto \int_0^{z/D} \xi^{-1/3} d\xi = \left(\frac{z}{D} \right)^{2/3} \tag{15}$$

It should be born in mind, however, that the relationships derived in the above are all based on the consideration of steady state plumes. Needless to say, some pertinent experiments are indispensable to validate the adequacy of these presumptions.

3. MEASUREMENTS OF TRAVEL TIME OF FIRE PLUME FRONTS

3.1 Measurement Method

Several series of small scale and large scale experiments are conducted in this study. Fig. 1 illustrates the schematic of the experimental method employed in this study. Thermocouples were arrayed along the central axis of the fire source. The temperatures were continuously recorded at every 0.025 second by the data acquisition system which had been started from in advance of the ignition of the fire source. As illustrated in Fig. 1, the thermocouple located at a given height above the source demonstrates a sudden rise of the temperature at a certain time after ignition due to the contact of a rising plume. The time at which a thermocouple exhibited a sudden temperature rise was regarded as the time at which the plume front arrived at the height of the thermocouple. Multiple thermocouples may exhibit sudden temperature rise at the same acquisition time points if the plume front passed multiple thermocouple during 0.025 second of the acquisition interval. In this case, needless to say, the height of the thermocouple remotest from the source was regarded as the distance that the plume front made until the acquisition time.

3.2 Estimation of the Heat Release Rate

Methanol pools in trays with different diameters, ranging from 0.12m through 0.87m, were used as the fire sources in this series of experiments. The heat release rates of the fire sources were estimated based on the burning rates per unit pool surface area of methanol fires measured by Yamada in a free space [8,9], which are shown in Fig. 2. The plotted points denote the Yamada's measurements and the solid line indicates their average. The burning rates of the sources in this series of experiments were estimated based on the results.

In addition to the results of the experiments conducted by the authors themselves, the data from two other large scale experiments done by Fujita Corporation [10] and Tokyo Fire Department [11] were included in the analyses in this paper. The heat release rates used in dealing with the data from these experiments were based on the estimations by Fujita Corporation and Tokyo Fire Department, respectively.

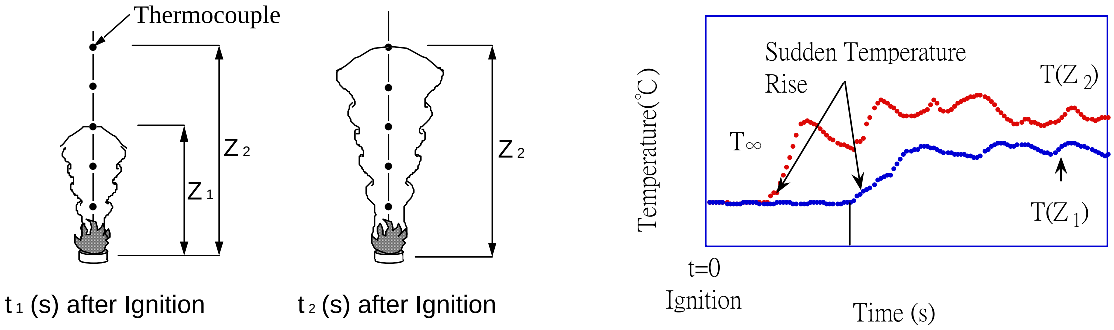


Fig. 1: Schematic of measurement method

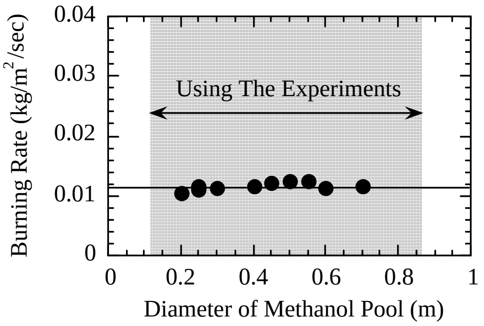


Fig. 2: Burning rate of methanol pool with different diameter [8,9]

3.3 Small Scale Experiments

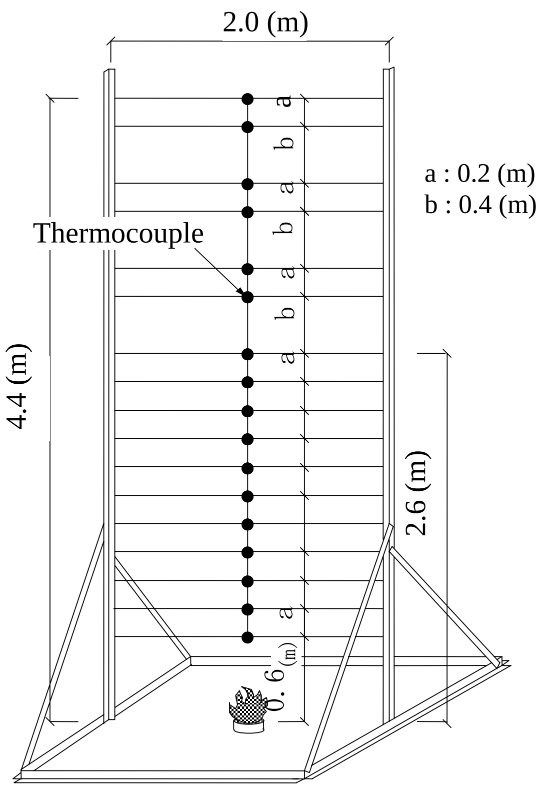
Several series of small scale experiments under different situations were conducted in this study. In each of the small scale experiments, the methanol fire source was burned for a while before the start of the test and put out once by covering the pool fire with a noncombustible board, then again ignited quickly after the start of the data acquisition. This procedure was employed to preheat the fire source so that the burning rate of the fire source would reach steady state as quickly as possible. The lowest thermocouple was arrayed at the height of 0.6 m above the source, so that its damage could be avoided. Every small scale experiment was repeated 30 times and the average of the measurements was used in the analyses.

3.3.1 Free space experiments

The experiments for measuring the rise time of plume in a free space were conducted for 7 pool fire sources with different diameters and the temperatures were measured by the thermocouples arrayed on the wires set up as shown in Fig. 3.

3.3.2 Open shaft experiments

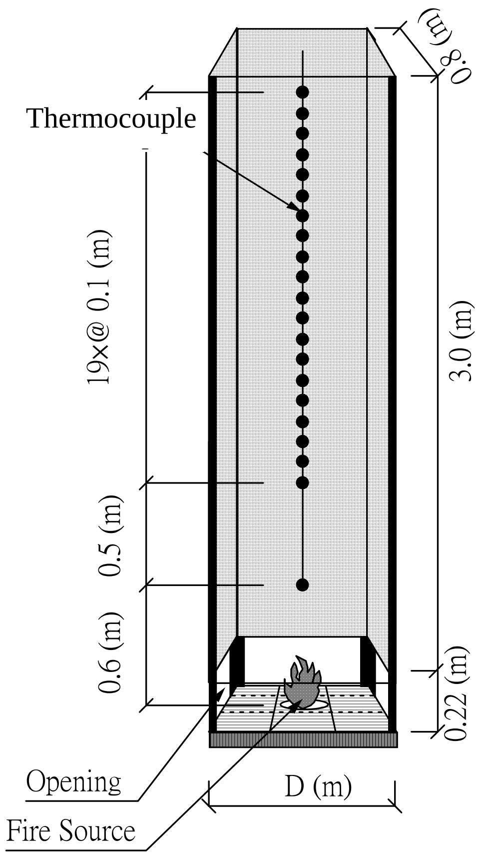
Here, ‘an open shaft’ is defined as a shaft which has no roof or which has an opening as large as the horizontal section area of the shaft. The experiments for the travel time in open shafts were conducted using the reduced scale shafts as shown in Fig. 4. The dimensions of the horizontal section of the shaft were changed as indicated also in Fig. 4 to investigate into the effect of the aspect ratio of shafts. The thermocouples were arrayed at 0.6 m and 1.1 m through 3.1 m with 0.1 m spacing. The fire sources were the same as the “3.3.1 Free space experiments” in the above.



Fire source condition

Methanol Pool Diameter (m)	Heat Release Rate (kW)
0.12	2.6
0.15	4.1
0.18	5.9
0.20	7.2
0.24	10.4
0.27	13.2
0.30	16.3

Fig. 3: Thermocouple array and fire source conditions in reduced scale free space tests



D : 0.8 m (model 1)
0.4 m (model 2)

Shaft dimension

		model 1	model 2
Model Size (m)	Width	0.8	0.4
	Depth	0.8	0.4
	Height	3.22	3.22
H / D (-)	Height / Side	4.0	8.1

Fire source condition

Methanol Pool Diameter (m)	Heat Release Rate (kW)
0.12	2.6
0.15	4.1
0.18	5.9
0.20	7.2
0.24	10.4
0.27	13.2
0.30	16.3

Fig. 4: Setup and geometrical conditions of reduced scale shaft

3.3.3 Closed shaft experiments

Here, 'a closed shaft' is defined as a shaft which is covered by a roof at the top. The experiments for the travel time in closed shafts were conducted using the same configurations and the same conditions as in the "3.3.2 Open shaft experiments" except the condition of the openings at the top.

3.4 Large Scale Experiments

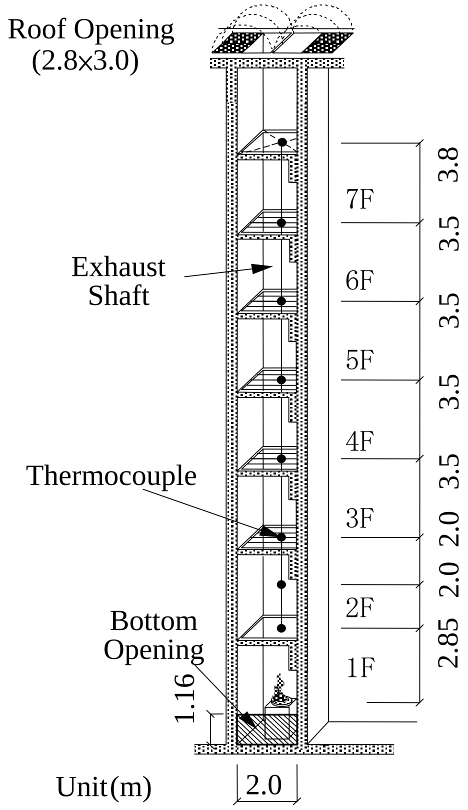
The large scale experiments were conducted using the smoke exhaustion shaft in the BRI Full Scale Fire Test Laboratory. The dimensions of the shaft, the locations of the thermocouples and the fire source conditions are shown in Fig. 5. The tests were conducted both in open and closed shaft conditions. In the former, the size of the opening at the top of the shaft was 2.8m x 3.0m, which was the same as the horizontal section of the shaft. The preheating of the fire source was not done since the fire sources were too large to be covered by a board.

3.5 Other Large Scale Experiments

The data from two other large scale experiments, conducted for different purposes, were also used in this study to check if the results from the small scale experiments could be applied to real scale situations.

3.5.1 Smoke filling experiment in a large space

Smoke filling experiments were conducted by Fujita Corporation in a large space as shown in Fig. 6, whose floor area and height were about 1,625 m^2 and 28m, respectively. The fire sizes in the experiments were changed as shown by the number of unit square trays of 0.5m x 0.5m put together [10]. Temperature measurements were made by a number of thermocouples distributed in the space, but only the data from the 9 thermocouples arrayed above the fire source were used for the analyses in this paper. The heights of the thermocouples above the source are shown in Fig. 6. The data acquisition interval was one second.



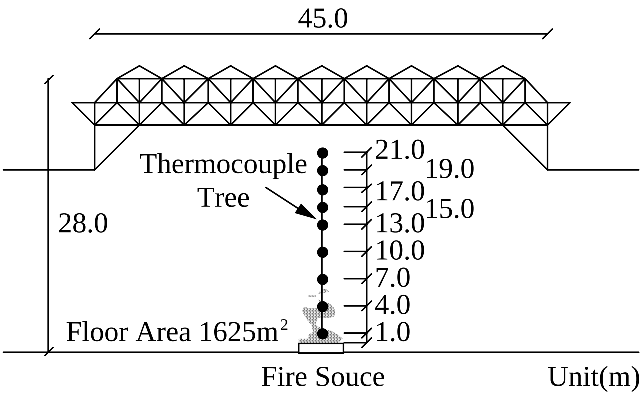
Shaft dimension

Model Size (m)	Width	2.8
	Depth	3.0
	Height	30.3
H / D (-)	Height / Side	10.1

Fire source condition

Methanol Pool Diameter (m)	Heat Release Rate (kW)
0.5	45
0.7	89
0.87	137

Fig. 5: Geometrical condition, fire source conditions and thermocouple array of full scale tests in BRI smoke shaft



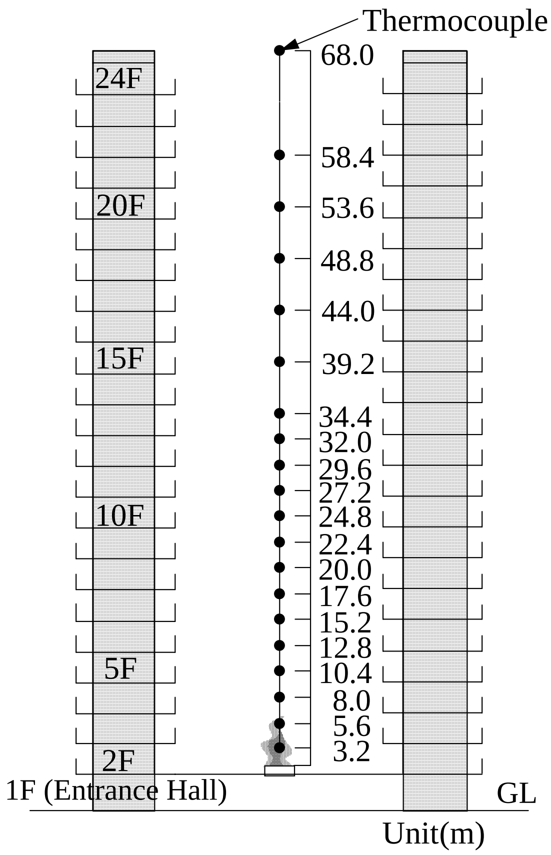
Fire source condition

	test1	test2
Size of Fire Source (m)	1.0 ? 1.0	2.5 ? 2.5
Heat Release Rate (kW)	400	2500

Fig. 6: Conditions in Fujita tests in a large scale space

3.5.2 Smoke behavior experiment in a real void space [11]

Tokyo Fire Department conducted full scale experiments to investigate the hazard due to smoke from fire in buildings having void spaces, using a void space in a real high-rise apartment building. They were assisted by technical institutes of building industries and The Science University of Tokyo. The plan of the void space was rectangular and the dimensions were as shown in Fig. 7. Methanol in 10 square trays, each 0.5 m x 0.5 m, were used as the fire source. The heat release rate of this fire source was reported as 1 MW. Fig. 7 shows the locations of the thermocouples arrayed above the fire source. The data acquisition interval of the temperatures in the experiments was 5 seconds.



Void space dimension

Space Dimension (m)	Width	8.0
	Depth	13.6
	Height	68.4
H / D (-)	Height / Width	8.6
	Height / Depth	5.0

Fire source condition

Size of Fire Source	10 × @ 0.5 ^{m}×0.5 ^{m}
Heat Release Rate	1 MW

Fig. 7: Real apartment building having a void space and thermocouple array used for Tokyo fire department tests

4. RESULTS AND ANALYSES OF EXPERIMENTS

4.1 Dependence of Travel Time on Heat Release Rate

The time *t*' at which a fire plume front arrived at a given height *z* is plotted versus the heat release rate $\dot{Q}$ on logarithmic coordinates in Fig. 8. While a certain degree of scattering is observed for a couple of the data, the travel times of transient fire plume fronts seem to be about proportional to the 1/3 power of heat release rate in any space as already presumed by the theoretical consideration for steady state fire plumes.

4.2 Dependence of Travel Time on Height

The travel time *t*' of a fire plume front to a given height *z* in a small scale test ($\dot{Q} = 7.2$ kW) is plotted in Fig. 9, where *t*' in this case is the time after the thermocouple at the height of 0.6m recorded temperature rise. Let β be the factor in the relationship assumed as $t' \propto z^{\beta}$. From the data in Fig. 9, β tends to be almost 4/3, but the data deviate from the correlation where the height from the source *z* is small. Note, however, *t*' in the coordinate of Fig. 9 is not exactly the time after ignition but the time after temperature rise was recorded by the thermocouples at the height of 0.6 m, while the origin of height *z* was the height of the source. The deviation of the plots in the area of small z is considered to be attributed to this inconsistency of the origins. So the travel time from the ignition *t* is estimated by the method as follows:

Letting t_0 be the travel time from the source to the height of the thermocouple located at 0.6 m above the source, the relationship between *t* and *t*' can be given as follows:

$$t = t' + t_0 \tag{16}$$

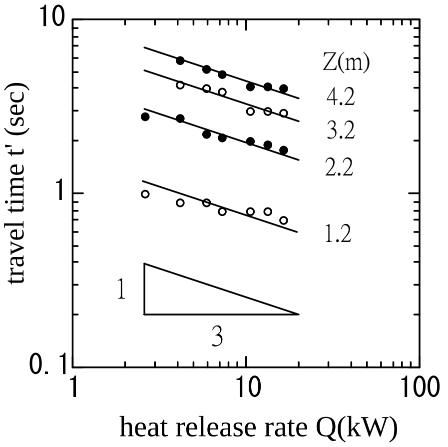
Based on the results of Figs. 8 and 9, assuming that

$$t = C_1 \dot{Q}^{-1/3} z^{4/3} \tag{17}$$

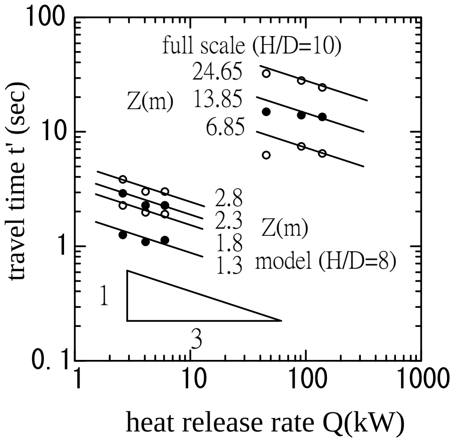
and using *z* = 0.6 when *t*' = 0, namely *t* = t_0 , in Eqn.(17), we have

$$t'(=t-t_0)=C_1\dot{Q}^{-1/3}\left(z^{4/3}-0.6^{4/3}\right) \qquad (18)$$

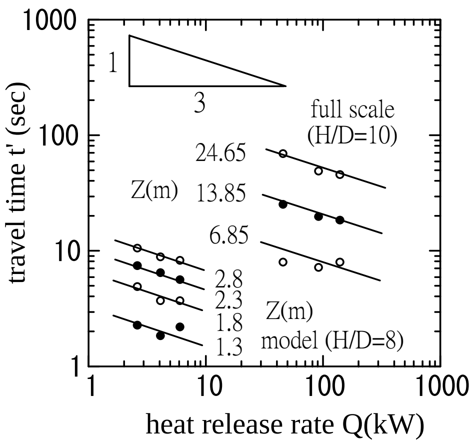
Coefficient C_1 can be obtained as the slope of t' plotted versus $\dot{Q}^{-1/3}\left(z^{4/3}-0.6^{4/3}\right)$ as illustrated by Fig. 10. The average value of C_1 thus obtained for small scale tests in free spaces was $C_1=1.7$. This value was regarded to remain to be the same in case of near source region in shaft space too since it is not considered that the plume lateral development is significantly affected by boundary wall in this region, so the plume behavior is considered to be the same as in free space. Fig. 11 shows the plots of the travel time $t(=t'+t_0)$ versus z for the same case as Fig. 9. The data seem to collapse to a line with slope of 4/3 excellently.



(a) Free space



(b) Open shafts



(c) Closed shafts

Fig. 8: Relationship between travel time and heat release rate

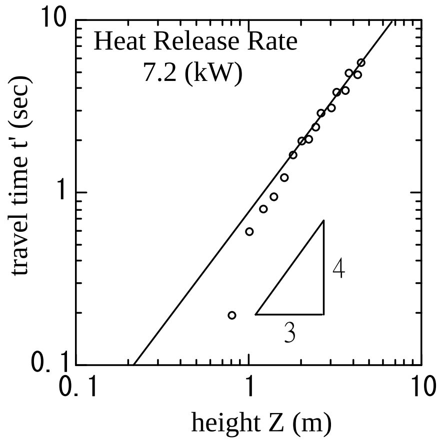


Fig. 9: Travel time from the lowest thermocouple in a reduced scale free space test

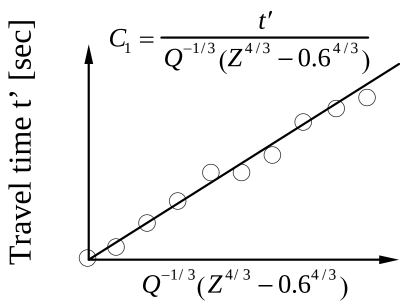


Fig. 10: Modified travel time and experimental coefficient

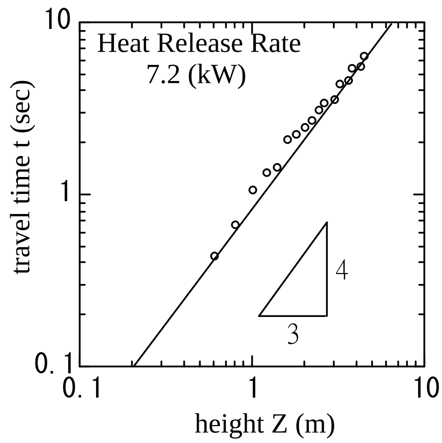


Fig. 11: Travel time versus height from fire source

4.3 Scaling of Travel Time of Fire Plume Fronts

The generic relationship for travel time of fire plume fronts that are successfully applicable to spaces having arbitrary scale can be established by translating the results of the experiments in this study into the relationship between relevant non-dimensional parameters.

4.3.1 The travel time in free space

In case of free spaces, no obvious characteristic length exists, a dimensional formula can be generically applicable and may be more convenient than a non-dimensional formula for practical use. The formula which best fit the experimental data in this study may be given as:

$$t = 1.7\dot{Q}^{-1/3} z^{4/3} \tag{19}$$

However, non-dimensional formulas alternative to Eqn.(19) could be sought letting the characteristic length be fire source diameter *d*, or l that is defined by [12]:

$$l = \left(\frac{\dot{Q}}{c_p \rho_\infty T_\infty \sqrt{g}} \right)^{2/5} \tag{20}$$

The non-dimensional travel times corresponding to the characteristic lengths d and l become $\tau_d \equiv \left(t\sqrt{g/d}\right)\dot{Q}_d^{*1/3}$ and $\tau_l \equiv t\sqrt{g/l}$, respectively. These non-dimensional travel times are plotted in Figs. 12 and 13 versus the corresponding non-dimensional heights, i.e. z/d and z/l, respectively. It can be seen in Figs. 12 and 13 that all the data from the small scale experiments collapse to a single line fairly well regardless the difference in heat release rates. The data from the large scale experiments also merge to the same line in the region where the non-dimensional height is large. The poor agreement can be recognized in some of the large scale data in the region near fire source. This is attributed partly to that the large fire sources in the large scale experiments needed some time until the heat release rates has reached their steady state values, and partly to that the data acquisition intervals, which were one second and five second in Fujita and Tokyo Fire Department experiments, respectively as stated in the above, were not small enough to accurately measure the travel times.

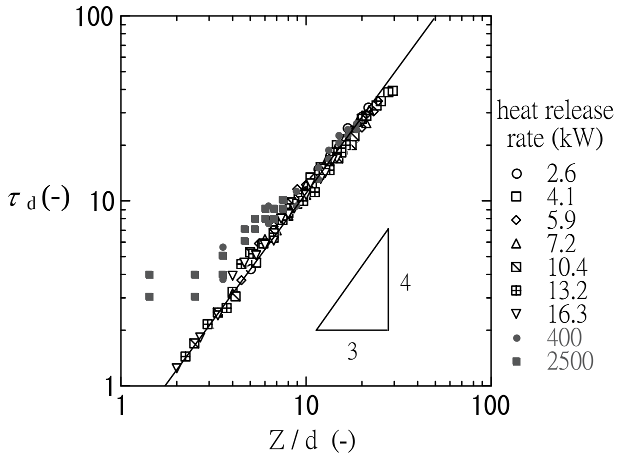


Fig. 12: Non-dimensional travel time τ_d in free spaces (characteristic length d)

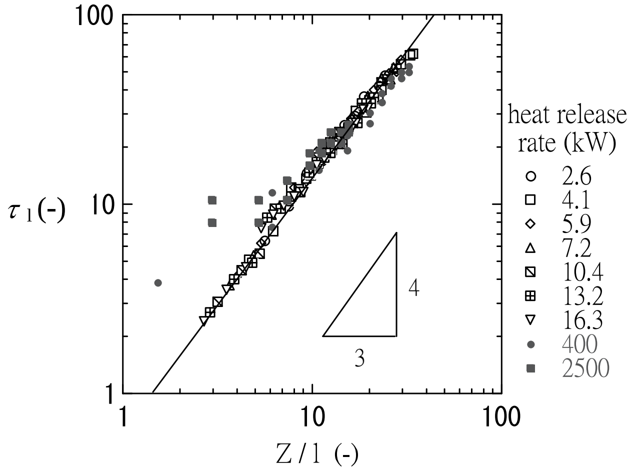


Fig. 13: Non-dimensional travel time τ_l in free spaces (characteristic length l)

In terms of formulas, the best fit regression lines in Figs. 12 and 13 may be expressed as:

$$\tau_d \left(\equiv t\sqrt{\frac{g}{d}} \right) = 0.56 \left(\frac{z}{d} \right)^{4/3} \tag{21a}$$

and

$$\tau_l \left(\equiv t\sqrt{\frac{g}{l}} \right) = 0.56 \left(\frac{z}{l} \right)^{4/3}, \tag{21b}$$

respectively.

In summary, the presumption made in '2. THEORETICAL CONSIDERATION' seems to hold for the plume front travel time in free spaces.

Zukoski derived an identical formula to Eqn.(21a) based on the model which assumed that the top of the plume rises to accommodate the air entrained at the same rate as that given for the steady state point heat source plume model [2]. According to his theoretical prediction the value of the constant be between 1/6 and 1/3 in stead of 0.56 obtained in this study. In an earlier paper, Turner investigated the rising plume in a free space using a model combining a buoyant plume and a vortex at the top and obtained a formula also identical to Eqn.(21a)[3]. The value of the constant based on his measurements made in salt water experiments was about 1/3.5 or 0.3.

4.3.2 The travel time in shafts

The non-dimensional travel time τ is defined here as $\tau \equiv \left(t\sqrt{g/D}\right)\dot{Q}_D^{*1/3}$ letting the characteristic length D be the side length of the horizontal section of a shaft. The data of the non-dimensional time which were reduced from the experiments in the open and the closed shafts are plotted versus non-dimensional height z/D in Figs. 14 and 15, respectively. Convergence of the data is satisfactory, although the data from the large scale experiments tend to show a certain deviation. This is thought to be caused by lack of accuracy for the large scale tests.

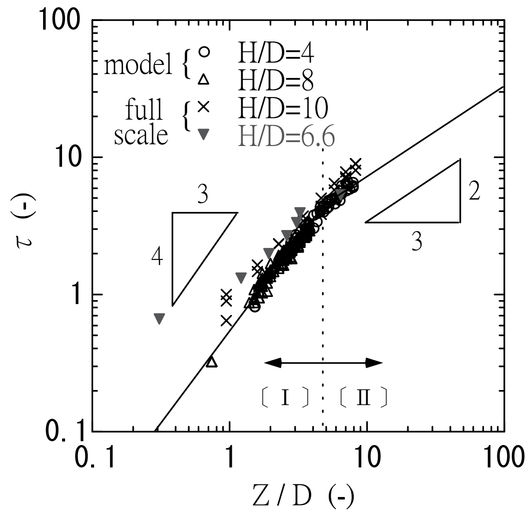


Fig. 14: Non-dimensional travel time τ in open shafts

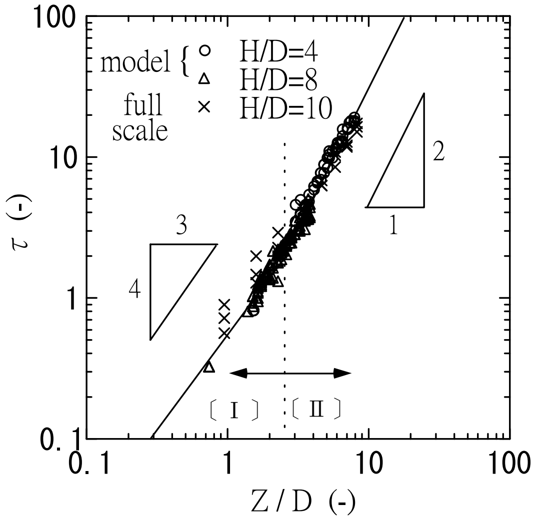


Fig. 15: Non-dimensional travel time τ in closed shafts

In the case of open shafts, the non-dimensional travel time τ is almost proportional to $(z/D)^{4/3}$ in the region $z/D \le 5$ and $(z/D)^{2/3}$ in the region $z/D > 5$ as was previously presumed. In the case of closed shafts, however, while τ is still proportional to $(z/D)^{4/3}$ where $z/D \le 2.5$, it becomes proportional to $(z/D)^2$ rather than $(z/D)^{2/3}$ in the case of open shafts where $z/D > 2.5$ contrary to the presumption. This considerable slow down of the travel time for $z/D > 2.5$ in closed shafts is suspected to be caused by that the air that initially occupies the upper part of the shaft. It cannot readily be replaced with the hot gases of rising plumes.

The best fit regression lines for the travel times in open and closed shaft spaces may be expressed in terms of formulas as follows:

(1) In open shafts

$$\tau = \begin{cases} 0.56\left(\frac{z}{D}\right)^{4/3} & \left(\frac{z}{D} \le 5\right) \\ 1.64\left(\frac{z}{D}\right)^{2/3} & \left(\frac{z}{D} > 5\right) \end{cases} \qquad (22)$$

(2) In closed shafts

$$\tau = \begin{cases} 0.56\left(\frac{z}{D}\right)^{4/3} & \left(\frac{z}{D} \le 2.5\right) \\ 0.30\left(\frac{z}{D}\right)^{2} & \left(\frac{z}{D} > 2.5\right) \end{cases} \qquad (23)$$

where τ is the non-dimensional time defined as:

$$\tau = \left(t\sqrt{\frac{g}{D}} \right) \dot{Q}_D^{*1/3}$$

letting D be the side length of horizontal section of a shaft.

5. CONCLUDING REMARKS

Experiments were conducted to investigate into rise time of the fronts of buoyant plumes induced above fire sources in free space and in vertical shafts. The data from two other existing full scale experiments available for this purpose were also used in the analyses. Based on the results of these experiments, it was found that the travel time of a fire plume front is:

(1) inversely proportional to the 1/3 power of the heat release rate of source,

(2) proportional to the 4/3 power of the height from the source in free spaces or in the region near fire source in shaft spaces as predicted based on the steady state fire plume model,

(3) proportional to the 2/3 and the 2 power of the height from the source in the region far from fire source in open and closed shafts, respectively, and

(4) well correlated as the relationship between the non-dimensional travel time defined by Eqn.(8) and the non-dimensional height.

The formula for the plume rise in a free space given by Eqn.(21a) is identical to the results obtained in the earlier works by Turner and Zukoski, but the coefficient in this study is somewhat different from the experimental value by Turner [3] and the theoretical prediction by Zukoski [2].

The travel time of plume fronts in closed shafts is not well explained by the simple model in this paper. The effect of opening conditions on plume rise time is still not clear. More investigations will be necessary in these aspects.

NOMENCLATURE

A characteristic horizontal section area of a plume (m^2)
c_p specific heat of air at constant pressure (kJ/kgK)
D characteristic length (m)
d fire source diameter (m)
g acceleration due to gravity (m/s^2)
l characteristic length defined by Eqn.(20) (m)
$\dot{Q}$ heat release rate (kW)
T_∞ ambient temperature (K)
ΔT characteristic temperature elevation of a plume (K)
t travel time from a fire source (s)
t' travel time from the lowest thermocouple located 0.6m above a fire source (s)
$\dot{Q}_x^*$ non-dimensional heat release rate defined using characteristic length x
w characteristic plume velocity (m/s)
z height from a fire source (m)
ρ characteristic plume density (kg/m^3)
ρ_∞ ambient air density (kg/m^3)
τ non-dimensional time defined by Eqn.(8)

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