A MODEL OF SMOKE MOVEMENT IN STAIR SHAFTS

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Abstract

Full-scale experiments were carried out to measure temperature and smoke concentration distribution in order to develop prediction model for movement of smoke caused by fire in stair shaft. Smoke arrival time, transient changes of profiles and steady state profiles were determined by using measured data. In case of no opening above fire source, smoke rose up mainly at center part of shaft as mixing with air. While, in case of door opened above fire source, uni-directional upward flow was observed due to buoyancy forces.

Prediction model for smoke movement and temperature distribution was developed and compared with experimental results. In landing with fire source, two-layered approximation was applied. Upper part of shaft was approximated by a duct with ribs which increases flow resistance. In case with no opening above fire source, it was approximated that smoke rose up by mixing with upper air due to turbulent diffusion. Turbulent mass flux was expressed with density gradient and turbulent diffusion coefficient. In case of door opened above fire source, vertical temperature distribution was approximated by an exponential function derived from heat and mass balance, and smoke velocity was predicted by flow resistance of stair shaft. Calculation values of temperature and rising velocity agreed fairly well with experimental results.

KEYWARDS: stair shaft, full-scale experiment, turbulent diffusion, stack effect

INTRODUCTION

Stair shaft is a very important route for egress, fire fighting and rescue. Thus various provisions are made to protect from heat and smoke. However, such as in Shinjuku Myojo 56 Building fire in 2001, there is still a possibility of fire initiation in stair shaft and/or smoke spread through stair shaft. In such cases, efficient fire protection measures are necessary in order to protect evacuees waiting for rescue. Information on the state in a stair shaft is also necessary to discuss if fire

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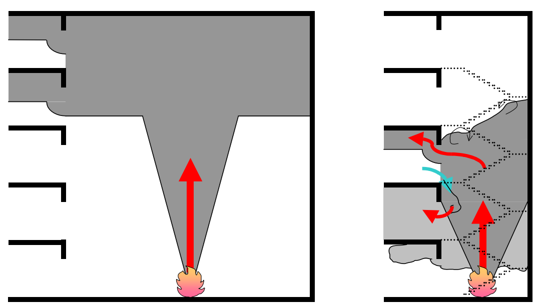
fighters can get in during rescue operation. For these proposes, smoke behavior in stair shaft shall have to be investigated.

In practical design of buildings, smoke behavior in a stair shaft is often predicted by two-layer zone models such as CFAST [1] and BRI2 [2]. Most two-layer zone models assume unconfined fires. It is approximated that smoke plume rises up to accumulate at upper part of enclosure as shown in figure 1. However, in stair shaft, smoke may be stagnant in the middle part of stair shaft or may flow downward because smoke loses buoyancy by contacting with cold wall and treadboards surface. Thus, the purpose of this study is to develop a model to predict smoke behavior in stair shaft quantitatively.

There are some studies on smoke behavior in stair shaft. For example, full-scale experiments were carried out by Tokyo Fire Department [3][4]. They measured vertical smoke temperature profile. In some of their experiments, smoke lost buoyancy during rising period to stay at middle of the shaft. *Suzuki* and *Yanai et al* [5] investigated combustion and smoke behavior in a short and narrow stair shaft. *He et al* [6] developed a network model based on CFAST and verified by full-scale experiments. In this network model, steady state smoke condition can be calculated by dividing a stair shaft and corridors into several enclosures in which one-zone model is applied. More detailed studies were carried out using model scale vertical shafts. *Ishino et al* [7] and *Tanaka et al* [8] were carried out model scale experiments in an atrium or in a courtyard. *Takahashi et al* [9] investigated temperature distribution in an atrium for wide range geometry of an atrium. However, there were no treadbords in shaft in these studies. *Mercier et al* [10] measured detailed temperature distribution in model scale atrium in case that smoke flew into bottom of side wall, but Reynolds number and Grashoff number were too small to apply to extend their results to actual fire conditions. *Cooper* [11] and *Cannon et al* [12] developed a model of rising process due to turbulent diffusion in slender plain shaft in case of no opening except the bottom of shaft.

This modeling method could be available for this study. As a result of review of previous studies, it is found that prediction models of smoke behavior in plain shaft were developed. Then, it would be available to predict smoke behavior in stair shaft by determining turbulent diffusion coefficients and flow resistance. Therefore, in this study, full-scale experiments were carried out, and prediction model of temperature distribution in stair shaft was developed based on experimental results.



a) Zone model approximation   b) Actual vertical shaft

FIGURE 1. Comparison between two-layer zone model and actual stair shaft

EXPERIMENTS

Experimental Setup

Full-scale experiments were carried out in actual stair shaft constructed by concrete. Stair shaft is 25.6 meters-high of seven stories whose bottom area is 2.83 meters-wide by 5.8 meters-deep as shown in figure 2. Story height is about 3.4 meters except 1st and 2nd stories. There are landings in the middle of each story. Tread, riser and balustrades are also made of concrete. At

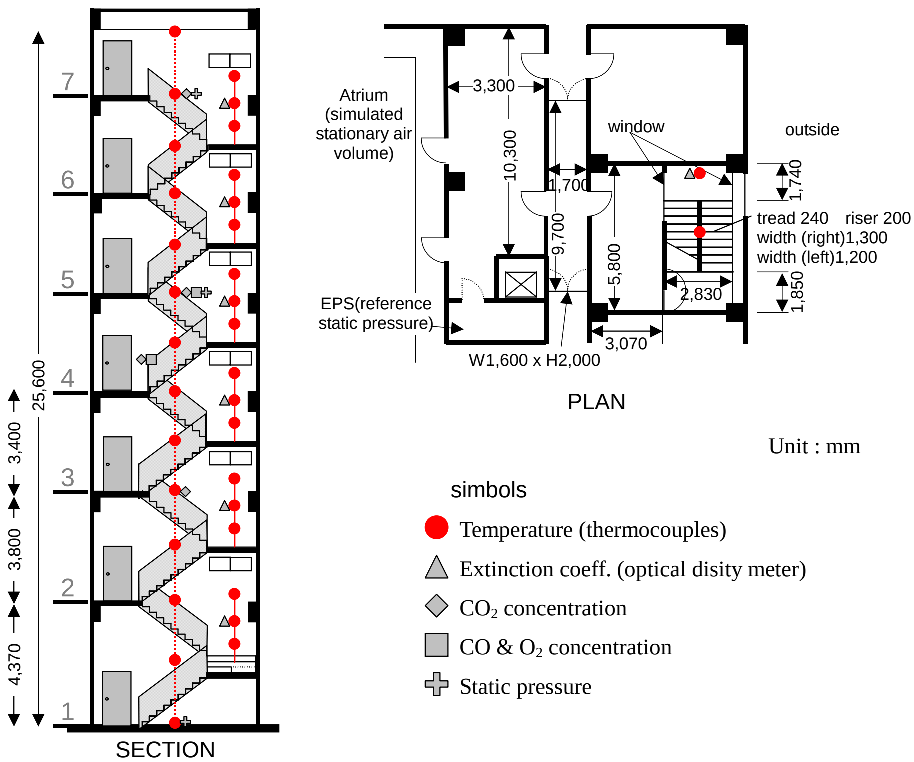


FIGURE 2. Sketch of experimental facility and instrumentation layout

each story, stair shaft is connected to atrium through vestibule, corridor and a room by doors whose size is 0.8 by 2 meters. Atrium was regarded as stationary air by sealing all windows and doors in order to eliminate the influence of outside wind flow.

Fire was simulated by burning six liters of methanol in 45 cm square pan located on the floor of either 1st, 4th or 7th story. In order to visualize smoke flow and to measure smoke density optically, white small particles were added to hot plume above fire source.

In figure 2, positions of all sensors are also shown. Thermocouples were equipped at centerline of stair shaft and at 0.5, 1.5 and 2.3 m above landing of each story. At 1.5 m above landing of each story, optical smoke density was measured by laser equipment. Carbon dioxide concentration was measured at floor levels of 3rd, 5th and 7th stories and at 1.5 m above 4th floor. Carbon monoxide concentration and oxygen concentration were measured at 5th floor level and 1.5m above 4th floor level. Static pressure was measured at 1st, 5th and 7th floor level, and hot-wire anemometers were equipped at 0.5, 1.0 and 1.5 m above floor of bottom opening to obtain smoke flow rate.

Experimental Condition

For nine combinations of positions of fire source and door opening, experiments were carried out. Heat release rate was approximately 80 kW and burning duration was about 20 minutes. Either one or two doors between stair shaft and vestibule of 1st, 4th or 7th story were opened. Summery of experimental conditions are shown in table 1.

Experimental Results

Case of no Opening above Fire Source

Figure 3 shows the distribution of temperature, carbon dioxide concentration

TABLE 1. Summery of experimental conditions

Exp. No.	Fire source	Ambient temp.	Door opening	Exp. No.	Fire source	Ambient temp.	Door opening
1	1F (79.3kW)	13.5 °C	1F	5	4F (83.2kW)	10.9 °C	1F, 7F
2	1F (83.2kW)	14.5 °C	1F, 7F(10min. after ignition)	6	4F (75.6kW)	10.5 °C	4F
				7	4F (71.8kW)	10.8 °C	4F, 7F
3	1F (75.6kW)	15.1 °C	1F, 7F	8	7F (83.2kW)	8.5 °C	1F
4	4F (79.4kW)	10.4 °C	1F	9	7F (83.2kW)	9.4 °C	4F

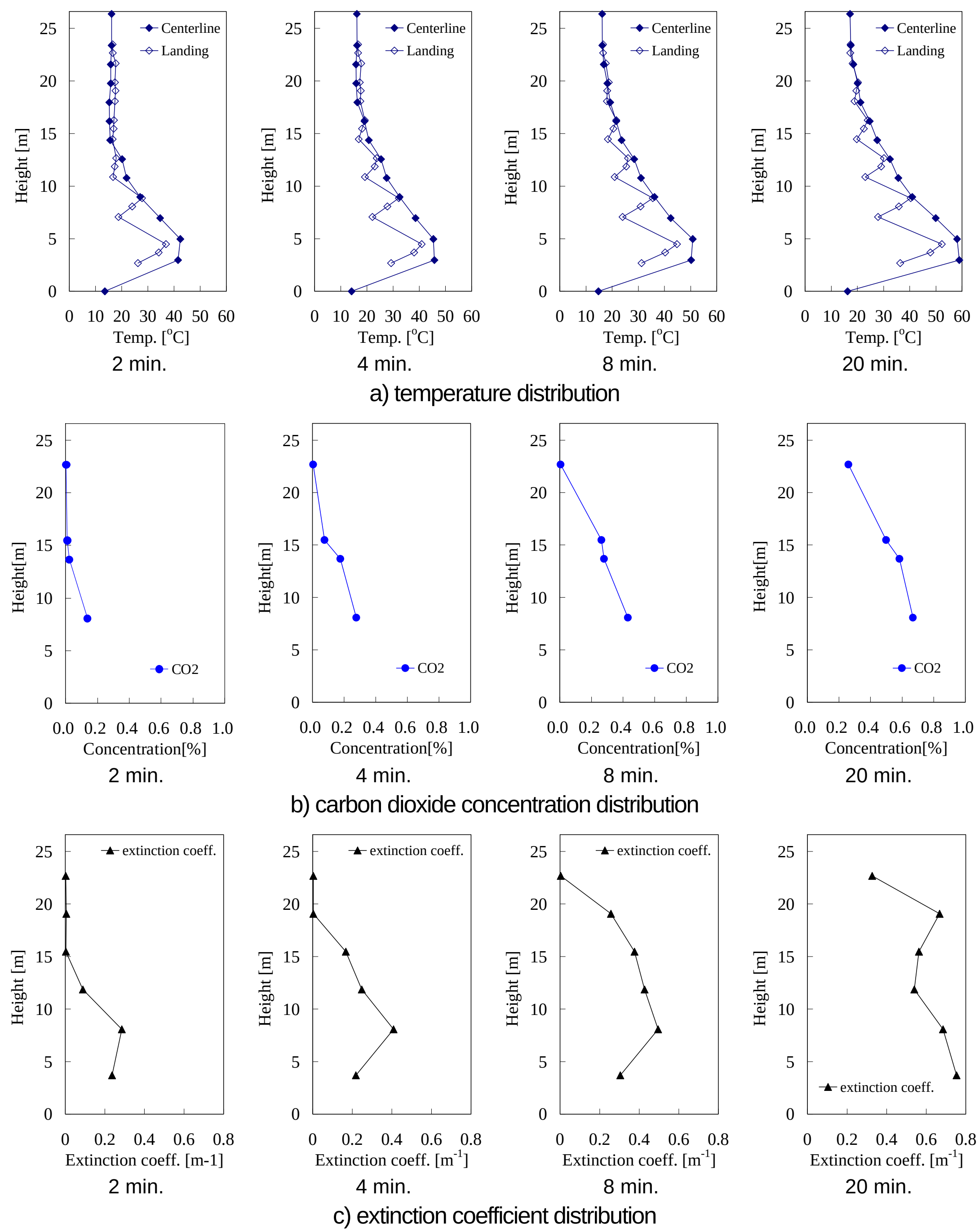


FIGURE 3. Vertical distribution in case of no-opening above fire source (Exp. No. 1) and extinction coefficient in case of no opening above fire source (Exp. No. 1). Carbon monoxide concentration was also measured, however, the concentration was quite small. At two minutes after ignition, temperature at upper part of 3rd floor (12.6 m) began to increase. Maximum temperature was observed just below ceiling of 1st story (4.97 m) as shown in figure 3a). At landing of 1st and 2nd story, vertical temperature difference existed distinctly, which indicates that two-layer environment was formed. Later, temperature at upper part of stair shaft was increased. Smoke arrived at 7th floor level (23.4 m) at eight minutes. Judging from landing temperature, it is found that two-layer stratification was maintained at each story below 5th story and that smoke was well mixed with air at upper stories than 5th floor. At twenty minutes after ignition, maximum temperature in the shaft was more increased than at eight minutes, but temperature at the top of stair shaft still remained close to ambient temperature.

Carbon dioxide concentration at floor level of 3rd story was also increased at two minutes when temperature at the same height began to increase. Profile of carbon dioxide concentration was almost linear at eight minutes after ignition although profiles of temperature looks like exponential function. Even at twenty minutes, carbon dioxide concentration was linear, but the values at every height were 0.3 % larger than at eight minutes. Therefore, it is found that carbon dioxide rose up gradually and accumulated in stair shaft although heat was absorbed to wall and treadboards.

Figure 3c) shows measured results of extinction coefficient. The profiles are similar to carbon dioxide concentration profiles measured at center of shaft.

Figure 4 illustrates smoke rising process presumed by measurement results in case of no opening above fire source. Just after ignition, smoke flew upward along back of tread at lower stories of stair shaft and bi-directional flow of smoke and air was formed. As mixing with air, stories in the middle of stair shaft were filled by low concentration smoke. After that, smoke rose up due to turbulent diffusion. Smoke concentration was gradually increased after smoke front arrived at the top of stair shaft.

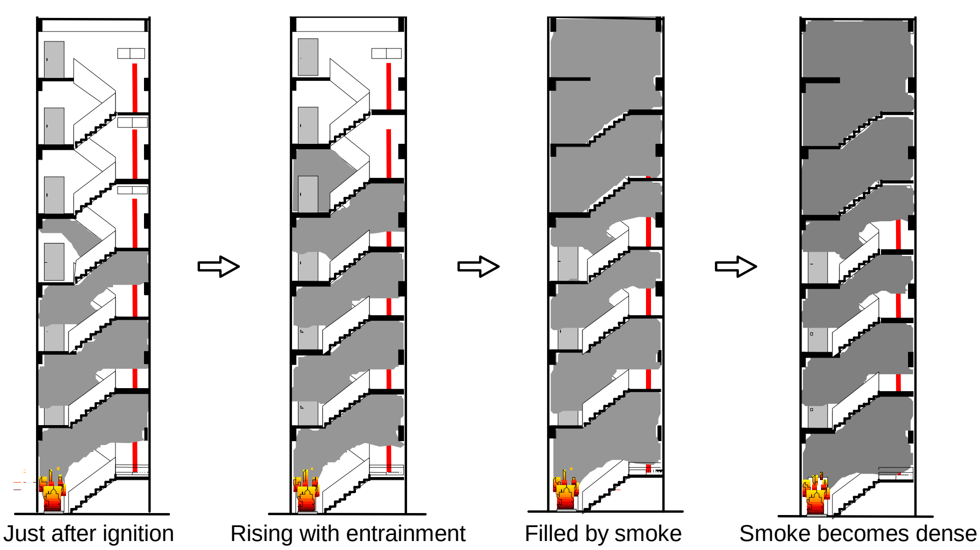
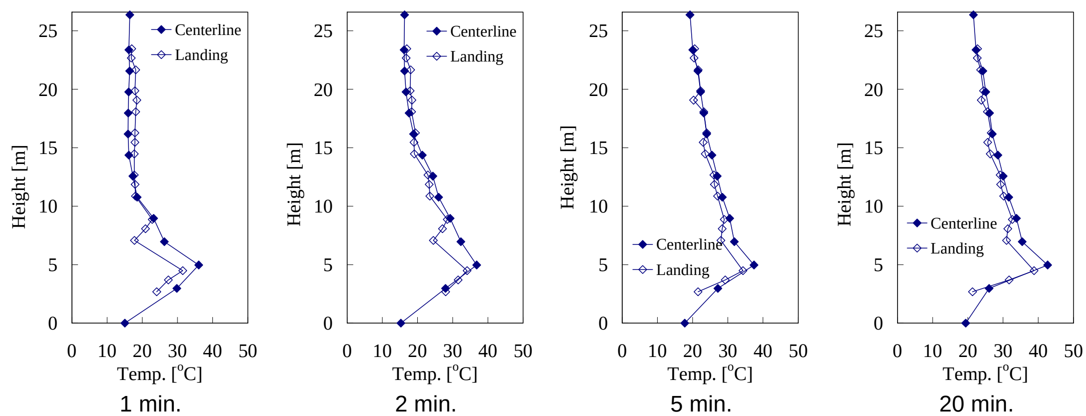


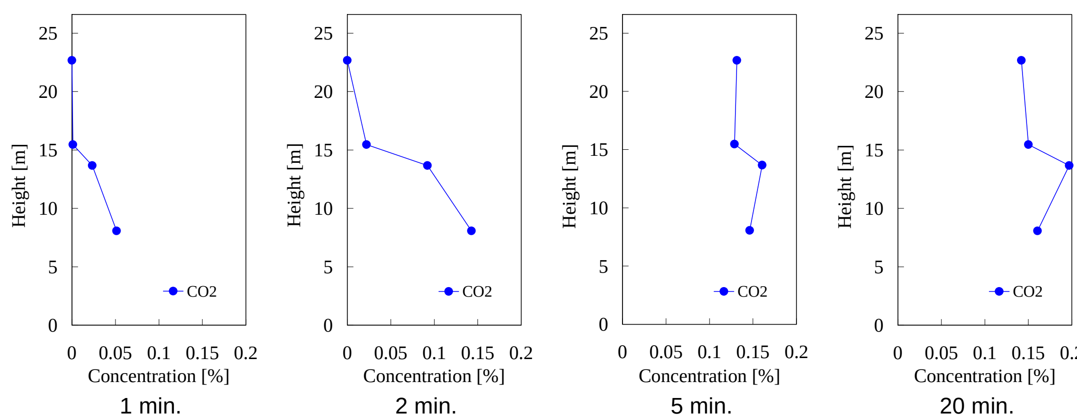
FIGURE 4. Schematics of smoke rising in case of no opening above fire source

Case of door opened above Fire Source

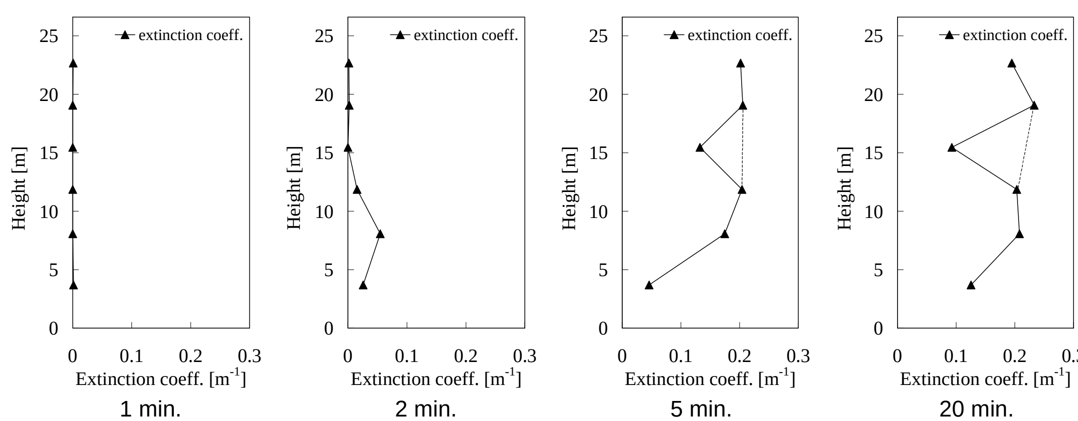
Figure 5 shows distribution of temperature, carbon dioxide concentration and extinction coefficient in case of door opened above fire source (Exp. No. 3). At one minute after ignition, temperature at floor level of 3rd story was increased as shown in figure 5a). Temperature at floor level of 6th story was also increased within one minute. At five minutes after ignition, temperature at shaft top started to increase. As the flow was



a) temperature distribution



b) carbon dioxide concentration distribution



c) extinction coefficient distribution

FIGURE 5. Vertical distribution in case with an opening above fire source (Exp. No. 3) caused by stack effect, smoke rose up much faster than the case of no opening above fire source. Maximum temperature just below ceiling of 1st story did not change throughout experiment. Even at twenty minutes after ignition, temperature distribution was almost same as five minutes. Only at landing of 1st story, vertical temperature difference existed throughout experiment. In case of 2nd floor landing, vertical temperature difference existed only in the early stage of experiment. Afterwards, temperature difference ceased because of mixing with smoke in central part.

Carbon dioxide concentration distribution was similar to temperature distribution until two minutes after ignition as shown in figure 5b). At five minutes, concentration in stair shaft was almost uniform. After that, uniform distribution was maintained even though there was still temperature difference between top and bottom of shaft because of heat loss to wall surface.

Figure 5c) shows the distribution of extinction coefficient. At one minute, extinction coefficient was almost zero at every point. As the measurements were carried out at the edge of landing at the middle height of each story, smoke has not arrived yet. After five minutes, extinction coefficient profile was close to uniform except the lowest point where plume from fire source did not hit directly, but contained in eddy region developed around fire source.

Figure 6 illustrates schematics of smoke flow in case of door opened above fire source. In the early stage after ignition, smoke rose up along back of treadbords and entrained air on the way of rising upward. As a result, smoke was well mixed also in horizontal direction.

Comparison of smoke arrival time

Time to begin to increase temperature and carbon dioxide concentration is shown in figure 7. In case of no opening above fire source (Exp. No. 1, 4 and 6), smoke arrival time is not in proportion with height, but the plot is shifted towards right side as shown in figure 7a). This implies that smoke velocity decreases as it travels upward. This tendency is clear at the height far from fire source shaft. Regardless of height above fire source, arrival time does not change significantly.

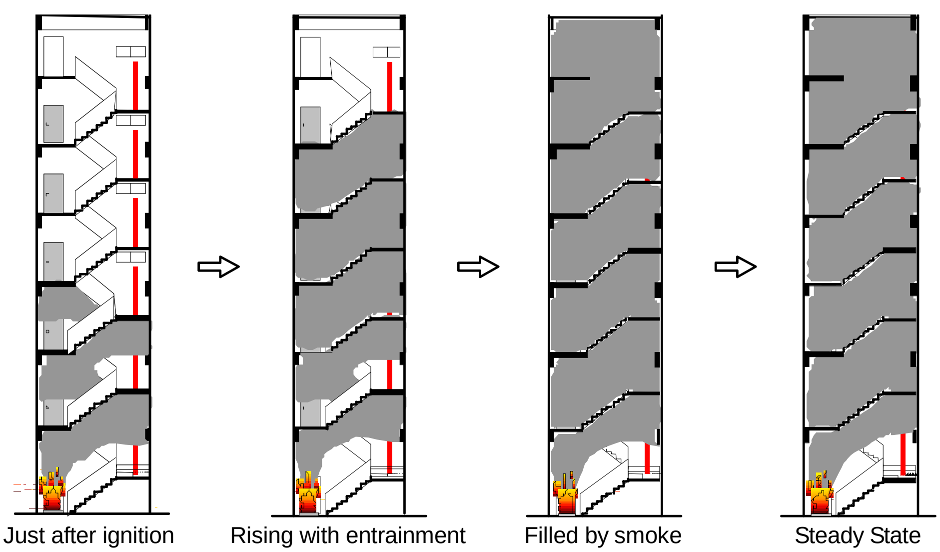
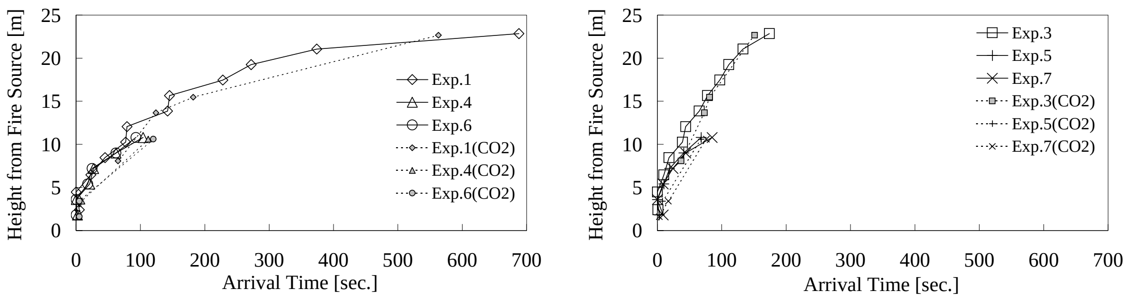


FIGURE 6. Schematics of smoke rising in case of door opened above fire source



a) case of no opening above fire souce b) case of door opened above fire souce

FIGURE 7. Arrival time of smoke

Figure 7b) shows smoke arrival time in case of door opened above fire source (Exp. No. 3, 5 and 7). Smoke rises up rapidly compared with the case of no opening above fire source. In contrast with the cases of no-opening, smoke arrival time is fairly in proportion with height. When distance from fire source to upper opening is large, smoke arrival time is slightly small. Therefore, the increase of pressure difference due to stack effect is more effective than the increase of flow resistance in stair shaft if the shaft length is increased.

In both cases, smoke arrival time obtained by carbon dioxide concentration is almost same as time by temperature.

THEORETICAL MODEL

Concept of Prediction Model

Prediction models for vertical temperature distribution in stair shaft are developed in both cases of no opening above fire source and of door opened above fire source. Because maximum temperature was obtained just below ceiling of the story with fire source in all experiments, prediction model is divided into two parts in both cases. First part is the story of fire source, where maximum temperature in stair shaft is calculated by two-layer zone model. The other part is upper shaft space, where upper part of shaft was approximated by a longitudinal duct with ribs which increase flow resistance. Based on experimental results, it is assumed in shaft that smoke rises up due to turbulent diffusion in case of no opening above fire source (figure 8) and that smoke flow is regarded as piston flow due to buoyancy in case of door opened above fire source (figure 10).

Case of no Opening above Fire Source

Formulation

Figure 8 shows schematics of prediction model for case of no opening above fire source. Mass and heat balance in stair shaft can be described as followings,

Mass balance:

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial (v\rho_s)}{\partial z} = 0 \qquad (1)$$

Heat balance:

$$\rho_s c_p \left(\frac{\partial T_s}{\partial t} + v \frac{\partial T_s}{\partial z} \right) = \frac{\partial}{\partial z}\left(k \frac{\partial T_s}{\partial z} \right) + \frac{(A_w/H)\alpha_c (T_w - T_s)}{A_{st}} \qquad (2)$$

According to *Cooper* [11], equation of state is substituted to Eq. 1, Eq. 2, and variables are averaged over characteristic time (Reynolds average). The final result is

$$\frac{\partial \overline{T}_s}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial \overline{T}_s}{\partial z} \right) + \frac{(A_w/H)\alpha_c (T_w - \overline{T}_s)}{c_p \rho_s A_{st}} \qquad (3)$$

This is differential equation for vertical temperature distribution. The first term in right hand side means mixture due to turbulent diffusion, and second term means heat loss to wall. Here, *D* in Eq. 3 is turbulent

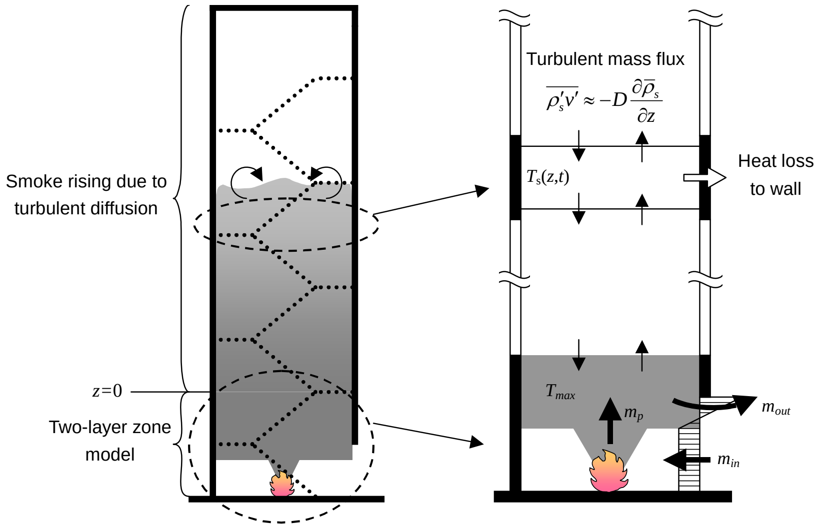


FIGURE 8. Schematics of prediction model in case of no opening above fire source

diffusion coefficient. *Cooper* [11] showed that this coefficient is significant when density gradient is positive toward upward direction as

$$D = \begin{cases} 0 & \left[\frac{\partial \overline{\rho}_s}{\partial z} \leq 0 \right] \\ K A_{st} \left\{ \frac{g}{T_s} \left(-\frac{\partial \overline{T}_s}{\partial z} \right) \right\}^{1/2} & \left[\frac{\partial \overline{\rho}_s}{\partial z} > 0 \right] \end{cases} \quad (4)$$

where coefficient K is determined by experimental results. For plain shaft, the value of K = 0.44 was proposed by *Cooper*.

Calculation Conditions

When Eq. 3 is solved by implicit scheme numerically. The boundary conditions for upper shaft are given by

$$\left. \overline{T}_s \right|_{z=0} = T_{max} \, , \qquad \left. \partial \overline{T}_s / \partial z \right|_{z=H} = 0 \quad (5)$$

Maximum temperature in the bottom of stair shaft is predicted by two-layer zone model as shown in figure 8. In calculation, mass balance and heat loss at the top of smoke layer were considered. Parameters used in calculation are shown in table 2.

Calculation Results

By searching for best-fit with experimental measurements, it was found that K = 0.1 is most appropriate. This value is approximately 1/4 of K-value for plain shaft proposed by *Cooper* [11]. The difference would be caused by treadboards and landings. Comparison between calculation and experimental value of centerline temperature is shown in figure 9. At two minutes after ignition, temperature is slightly over-estimated and predicted smoke arrival height

TABLE 2. Calculation parameters for the calculation to simulate Exp. No. 1

parameter	denotation	value	unit	parameter	denotation	value	unit
Bottom area of stair shaft	A_{st}	17.29	m^2	Wall surface area	A_w	817.46	m^2
Width of door	B_d	0.8	m	Heat release rate	Q	79.3	kW
Height of door	H_d	2.0	m	Ambient temperature	T_0	13.56	^oC
Discharge coefficient of door	C_d	0.68	-	Wall surface temperature	T_w	13.56 (= T_0)	^oC
Height of stair shaft	H	25.6	m	Convective heat transfer coefficient	α_c	0.0136	kW/m^2K

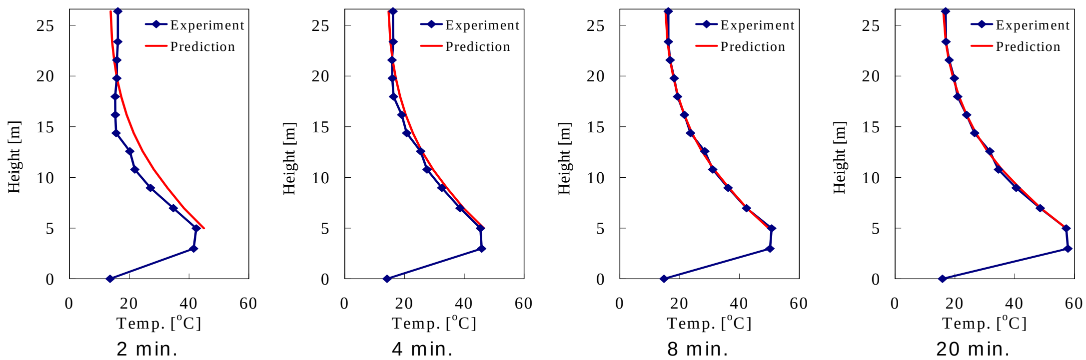


FIGURE 9. Comparison of calculation and experimental value in Exp. No. 1

is larger than measurement results. However, after four minutes, both of temperature distribution and smoke arrival height agree with experimental value.

Case of door Opened above Fire Source

Formulation

Schematics of prediction model in case of door opened above fire source is shown in figure 10. Vertical temperature distribution can be derived from heat balance as

$$\frac{\partial T_s}{\partial t} = -v_s \frac{\partial T_s}{\partial z} + \frac{\eta (A_w/H)\alpha_c (T_w - T_s)}{c_p \rho_s A_{st}} \qquad (6)$$

Assuming that wall surface temperature is equal to ambient temperature and neglecting term of time differentiation to simplify formula, vertical temperature distribution is expressed with exponential function as following

$$\frac{T_s(z) - T_0}{T_{max} - T_0} = e^{-\frac{\eta (A_w/H)\alpha_c z}{c_p \rho_s A_{st} v_s}} \qquad (7)$$

where maximum temperature T_{max} is calculated by two-layer zone model similar to previous section. Location of smoke front is assumed first. Then movement of smoke front is calculated by using velocity of smoke v_s. The velocity v_s is calculated in conventional way by using static pressure head due to temperature difference and pressure loss coefficient in stair shaft.

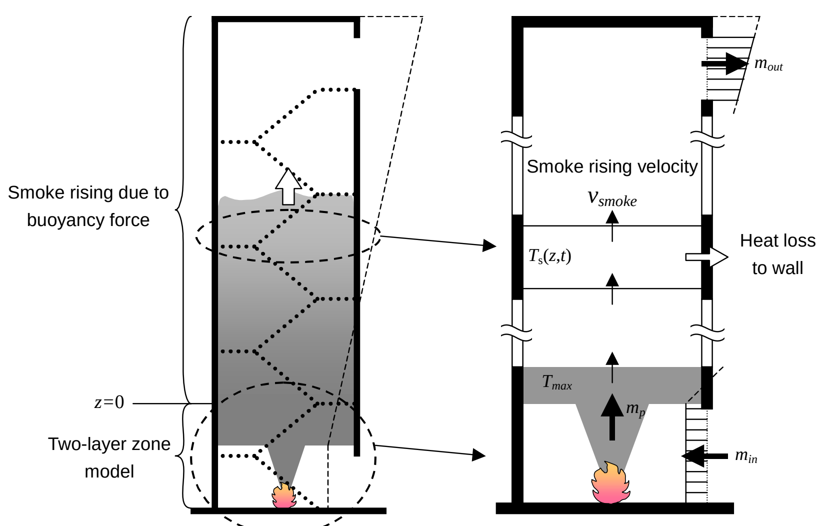


FIGURE 10. Schematics of prediction model in case of door opened above fire source

TABLE 3. Calculation parameters for the calculation to simulate Exp. No. 3

parameter	denotation	value	unit	parameter	denotation	value	unit
Bottom area of stair shaft	A_{st}	17.29	m^2	Wall surface area	A_w	817.46	m^2
Ambient temperature	T_0	15.1	^oC	Heat release rate	Q	75.1	kW
Discharge coefficient of door	C_d	0.68	-	Fraction of contact wall surface area	η	0.8	-
Height of top story floor	H_{top}	22.3	m	Flow resistance coefficient of air	ζ_a	24.0	m^{-1}
Width of door	B_d	0.8	m	Flow resistance coefficient of smoke	ζ_s	7.47	m^{-1}
Height of door	H_d	2.0	m				

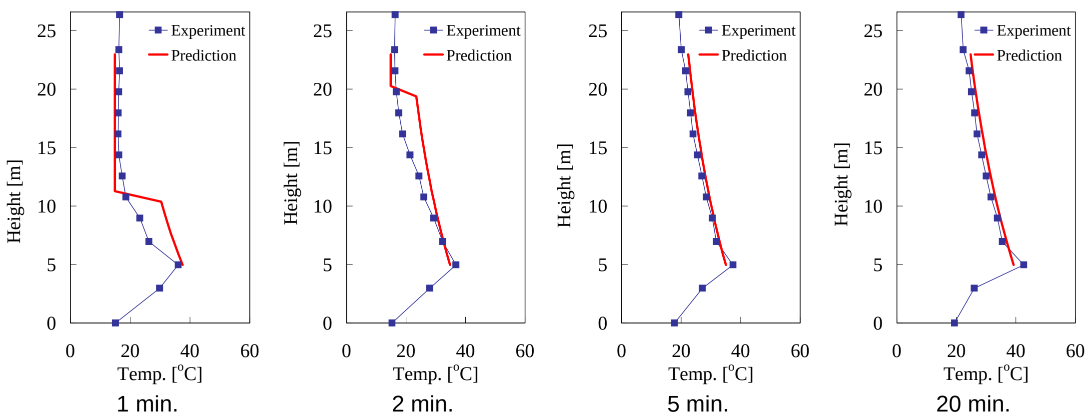


FIGURE 11. Comparison of calculation and experimental value in Exp. No. 3

Calculation Conditions

The values of input parameters used in calculation are shown in table 3.

Calculation Results

Figure 11 shows comparison between calculation and experiment No. 3. Such as at one or two minutes after ignition, temperature is overestimated until smoke arrives at the top of stair shaft although smoke arrival height agrees fairly well with experiment. After five minutes when smoke arrives at the top of stair shaft, calculation value of temperature distribution is in good agreement with experiment.

CONCLUSION

Full-scale experiments were carried out in order to develop prediction model of vertical temperature distribution in stair shaft. As a result, followings are clarified.

1) Regardless to conditions of opening, maximum temperature is presented just under ceiling of the story with fire source because fire plume was interfered by wall and treadbords. Temperature is decreased by heat loss to wall as smoke flows upward. Smoke rising process is greatly different according to conditions of opening.
2) In case of no opening above fire source, smoke rises up relatively slowly due to turbulent diffusion. Turbulent diffusion coefficient is expressed by density gradient and amount of turbulent mixing is reduced to approximately 1/4 compared with plain shaft because of resistance of treadboards.
3) In case of door opened above fire source, smoke rises upward due to buoyancy.

Considering pressure difference due to stack effect and flow resistance in stair shaft, vertical temperature distribution can be expressed as exponential function.

NOMENCLATURE

Alphabets

A area [m^2]
B width [m]
C_d discharge coefficient [-]
c_p heat capacity of air [kJ/kgK]
D turbulent diffusion coefficient [m^2/s]
g gravity acceleration [m/s^2]
H height [m]
k heat conductivity [kW/mK]
K coefficient in D [-]
Q heat release rate [kW]
t time [sec.]
T temperature [^{o}C]
v velocity [m/s]
z Height above ceiling of the story with fire source [m]

Greek letters

α_c convective heat transfer coefficient [kW/m^{2}K]
ρ density [kg/m^3]
η fraction of contact surface area to total wall surface area [-]
ζ coefficient of flow resistance [-]

Subscripts

a	air	d	door
max	maximum	s	smoke
st	stair shaft	top	top story
w	wall	0	ambient

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