A SIMPLE PREDICTIVE METHOD FOR ROOM FIRE BEHAVIOR

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ABSTRACT

Simple predictive equations for the room fire behavior were proposed. These were obtained by applying simple predictive method for pre-flashover compartment fire temperature proposed by McCaffrey et al. to ventilation controlled fire. These equations can easily predict the temperature inside the compartment, the rate of heat loss due to ventilation and the rate of heat loss to compartment boundary. These can be used when the room fire is ventilation controlled regime. The results of the prediction using the simple equations were compared with the results of a more detailed computer model. Through this comparison, it was confirmed that these simple predictive equations are practical useful to estimate ventilation controlled compartment fire behavior, even though there is a little error caused by neglecting heat loss by radiation through the openings.

1. INTRODUCTION

In fire resistance design of buildings, room fire behavior is usually assessed based on the predictions using a computer models which assume ventilation controlled fire. This may not be so inconvenient in this computer age, but obviously it would be much more beneficial for practical applications. If simple predictive formulae with moderate accuracy are available in place of the computer models. Room fire behavior is best represented by the temperature inside the compartment, but heat transfer through compartment boundaries relates to the structural stability, integrity of wall and the spread of fire by thermal conduction and outflow heat through openings affects various hazard encountered outside the compartment, such as hazards to evacuation. In

this paper, simple predictive formulae are proposed for fire behavior (fire room temperature, heat loss due to ventilation, and heat loss to component boundaries) in ventilation controlled room fire. The applicability of formulae are examined by comparing with the predictions of a computer model.

2. PREDICTION OF ROOM FIRE BEHAVIOR WITH A COMPUTER MODEL

This section describes the outline of a computer model and its calculation results, in preparation for comparison with the simple predictive formulae proposed later.

2.1 Concepts of the model

This model is designed for post-flashover

fire, and is based on the assumption that all the physical properties such as the temperature inside the compartment are uniform. Room fire, in general, is a complex phenomenon consisting of many coupling element processes. In this model, we formulate the room fire behavior into a mathematical models considering the physical law which hold for the behavior as follows;

(1) Mass conservation equation

In consideration of the mass conservation, the following equation hold for the in the post-flashover fire compartment.

$$\frac{d}{dt}(\rho_F V) = M + m_a - m_g \quad (2.1)$$

(2) Energy conservation equation

The energy conservation equation in the fire room is given by

$$\begin{aligned} \frac{d}{dt}\{c_p r_F (T_F - T_\infty) V\} &= Q_C - Q_W - Q_R - Q_V \\ &= Q_C - Q_W - Q_R - c_p m_g (T_F - T_\infty) \end{aligned} \quad (2.2)$$

(3) State equation

In this model, we shall ignore the trivial change of air density, which stems from a small pressure difference induced by the fire and gas composition variation due to combustion. Thus the state equation for ideal gas used as follows;

$$\rho_F T_F = \rho_\infty T_\infty \quad (2.3)$$

(4) Mass burning rate

From experimental results, Kawagoe and Sekine have derived the following semi-empirical relation for the mass burning rate [1].

$$M \approx 0.1A\sqrt{H} \quad (2.4)$$

This mass burning rate yields ventilation controlled fire, which produces unburnt gases. The burning rate in this model is set attain $0.1A\sqrt{H}$ (kg/s) after 5 minutes considering the stability in numerical calculation.

(5) Heat production

In this model, the heat produced by burning

combustibles is considered for two regimes; namely fuel controlled fire and the ventilation controlled fire, as follows.

• Fuel controlled fire ($Q_C = Q_{C1}$)

Assuming that the heat produced per unit mass of burning wood is 16,000 (kJ/kg), the following equation is given.

$$Q_{C1} = 16,000M \quad (2.5)$$

• Ventilation controlled fire ($Q_C = Q_{C2}$)

The heat generation per unit mass of air consumed in combustion is about 3,000 kJ/kg (air) [2][3] indifferent of fuel type. Consequently, based on the assumption that the inflow air is perfectly consumed in the ventilation controlled fire, the following equation is given.

$$Q_{C2} = 3,000m_a \quad (2.6)$$

This is the maximum rate of heat released inside a room fire.

Figure 1. Transient change of the rates of heat releases

Figure. 1 illustrates the transient change of the rate of heat release for this model. Before point (a), at which the Q_{C1} curve crosses the Q_{C2} curve, the fire is a fuel controlled type so the rate of heat release is given by Q_{C1} . After point (a), the fire becomes a ventilation controlled type so the rate of heat release is expressed by Q_{C2} . Some unburnt gas is also produced in this state. Since ventilation controlled fire is assumed in this model, our primary interest lies in the state after point (a).

(6) Fire room temperature

The fire room temperature can be obtained by integrating Eq. (2.7), which is derived from Eqs. (2.1)-(2.3) to give T_F explicitly.

$$\frac{dT_F}{dt} = \frac{T_F}{c_p r_\infty T_\infty V} (Q_C - Q_W - Q_R) - \frac{T_F}{r_\infty T_\infty V} (m_a + M)(T_F - T_\infty) \quad (2.7)$$

(7) Heat loss through the compartment boundaries

Assuming that the surface temperatures of the inner compartment boundaries are uniform, the heat loss to the boundaries Q_W is given by the following equation, which is the sum of the heat loss by radiation and by convection to the boundaries.

$$Q_W = e_w s (T_F^4 - T_W^4) A_W + a_w (T_F - T_W) A_W \quad (2.8)$$

As shown by (2.8), Q_W is a function of the boundary surface temperature T_W . So T_W , which changes with the development of fire should be calculated simultaneously. In this model, T_W is obtained by numerically solving the following heat conduction Eq. (2.9) with the boundary condition given by Eq. (2.10),

① Heat condition equation

$$\frac{dT}{dt} = \frac{k}{c\rho} \left(\frac{d^2 T}{dX^2} \right) \quad (2.9)$$

② Boundary conditions

$$\begin{aligned} -k \left(\frac{dT}{dX} \right) \Big|_{x=0} &= q''_{in}(t) \\ -k \left(\frac{dT}{dX} \right) \Big|_{x=l} &= q''_{out}(t) \end{aligned} \quad (2.10)$$

where

$$q''_{in} = Q_W / A_W \quad (2.11)$$

and it is assumed in this paper $q''_{out}(t) = 0$.

In addition, the convection heat transfer coefficient α_w in Eq. (2.8) is assessed by [4]

$$\alpha_w = \begin{cases} 5 \times 10^{-3} & (Ta \leq 300K) \\ (0.02 T_\alpha - 1) \times 10^{-3} & (300K < Ta < 800K) \\ 15 \times 10^{-3} & (800K \leq Ta) \end{cases} \quad (2.12)$$

Where T_α defined by

$$T_\alpha = (T_F + T_W) / 2 \quad (2.13)$$

(8) Radiation heat loss through the openings

Assuming that the radiation emissivities of the fire gases and the ambient air are 1.0, the heat loss by radiation radiated through the opening Q_R is given by

$$Q_R = s (T_F^4 - T_\infty^4) A \quad (2.14)$$

(9) Ventilation rates

The in- and out-flow rates of gases can be expressed as Eq. (2.15) and (2.16) as a function of neutral plane height X_n . In this model, the mass conservation law is invoked to solve the neutral plane height X_n and mass flow rate.

$$m_a = \frac{2}{3} \alpha B (2g\rho_F |\Delta\rho|)^{1/2} (H_h - X_n)^{3/2} \quad (2.15)$$

$$m_g = \frac{2}{3} \alpha B (2g\rho_\infty |\Delta\rho|)^{1/2} (X_n - H_l)^{3/2} \quad (2.16)$$

Figure 2 shows the structure of the computer model designed on the basis of the above-mentioned assumptions and criteria.

2.2 Calculation conditions

The following describes the calculation conditions employed in this model to predict room fire behavior.

(1) Compartment conditions

In consideration of floor areas of typical office buildings we selected three conditions of compartment dimensions; i.e., ① 18W(m)-12D(m)-2.6H(m), ② 21W(m)-15D(m)-2.6H(m), and ③ 42W(m)-21D(m)-2.6H(m) for case study calculations.

(2) Materials of compartment boundaries

Calculations were performed for three types of concrete walls; i.e. normal concrete, light weight concrete, and ALC (autoclaved light weight concrete) walls. Table 1 shows the values of the heat conductivity k (kW/m/K), the specific heat c (kJ/kg/K) and the density ρ (kg/m³) of the materials used in this case

Figure 2. Calculation program structure

Table 1. Thermal properties of the compartment boundary materials

	conductivity k (kW/m/K)	density ρ (kg/m ³)	specific heat c (kJ/kg/K)
normal concrete	0.00163	2,250	0.895
light weight concrete	0.000523	1,350	1.39
ALC (autoclaved light weight concrete)	0.000151	600	1.09

studies.

(3) Temperature factor

The temperature factor F_0 is defined by $F_0 = A\sqrt{H} / A_T$, where A is the area of the opening, H the height of the opening, and A_T the total interior surface area of the room (including the opening area). The maximum of F_0 for realistic office rooms may be estimated by assuming that windows exist along full width of two of the four boundary walls. Since the maximum value of F_0 thus estimated is about 0.15, calculation was performed for several values of F_0 between 0 and 0.15, namely, 0.01, 0.025, 0.05, 0.075 and 0.15.

The calculations were performed for the combinations of the conditions shown in

Table 2, which consist of conditions (1), (2) and (3) in order to investigate the influence of each condition. The fire room temperature, the rate of heat loss due to ventilation, and the rate of heat loss to compartment boundary were calculated for every case.

2.3 Calculation results

(1) Effect of different compartment dimensions

Figures 3(a)-3(c) show the comparison among the results for different compartment conditions; i.e., different compartment dimensions, but the same boundary material (regular concrete) and the same fire load density (30 kg/m²).

A small difference is observed in fire dura-

Table 2. Calculation patterns

condition setting	(1) Effect of compartment dimensions	(2) Effect of boundary materials	(3) Effect of temperature factors
compartment dimensions (m) (W×D×H)	18-12-2.6 (m) 21-15-2.6 (m) 42-21-2.6 (m)	18-12-2.6 (m)	
boundary materials	normal concrete	normal concrete light weight concrete ALC	normal concrete
temperature factors	0.01, 0.025, 0.05, 0.075, 0.15		
fine load density	30 kg/m ²		

tion time, whereas for all temperature factors no difference is observed in fire room temperature, nor the rate of heat loss due to ventilation, nor the rate of heat loss to compartment boundaries. This shows that the ventilation controlled fire behavior is controlled only by the temperature factor and is independent of the compartment dimensions.

(2) Effect of boundary materials

Figures 4(a)-4(c) show the comparison among the results for different boundary conditions; i.e., different boundary materials, but the same compartment dimensions (18-12-2.6 (m)) and the same fire load density (30 (kg/m²)).

The heat conductivities k (kW/m/K) of the three materials are normal concrete ($k=0.00163$) > light concrete ($k=0.000523$) > ALC ($k=0.000151$). Since heat can be more easily conducted through a material for a higher k -value, relative fire room temperature rise and the rate of heat loss due to ventilation become in order of ALC > light concrete > normal concrete and the rate of heat loss to compartment boundaries is in reverse order.

Similar calculations as shown in Figs. (3) and (4) were performed for five temperature factors, but since the results for different temperature factors are very similar, the results only for $F_0=0.01$ are shown in the figures.

(3) Effect of temperature factors

Figures 5(a)-5(c) show the comparison among the results for different temperature conditions; i.e., different temperature factors, but

the same compartment dimensions (18-12-2.6 (m)), the same boundary material (normal concrete) and the same fire load density (30 (kg/m²)).

As shown in the figures, the fire room temperature and the rate of heat loss due to ventilation increase with the temperature factor, whereas the rate of heat loss to compartment boundaries decreases with the temperature factor. This tendency may be explained as follows: The ventilation controlled fire is assumed in this model, so when the opening area increases, the rate of air flowing into the compartment increases, which in turn increases the heat release rate in the compartment.

The fire duration decreases as temperature factor increases. This is because the calculations were performed for the same fire load and the same compartment dimensions, namely for the same total fire load, so the fire duration is inversely proportioned to the mass burning rate, which is proportional to the ventilation factor $A\sqrt{H}$, while temperature factor $A\sqrt{H}/A_T$ is only a function of $A\sqrt{H}$ when A_T is constant.

3. SIMPLE PREDICTIVE METHOD FOR ROOM FIRE BEHAVIOR

3.1 Simple predictive formulae

In the present study, simple formulae are proposed to calculate fire room temperature, the rate of heat loss due to ventilation, and the rate of

Figure 3. Calculation results of the computer model (for different compartment dimensions)

Figure 4. Calculation results of the computer model (for different boundary walls)

Figure 5. Calculation results of the computer model (for different temperature factors)

heat loss to compartment boundaries for ventilation controlled fire, on the basis of the simple prediction method for the fire room temperature of pre-flashover fire proposed by McCaffrey et al.

Considering the mass balance of the smoke layer and that the flow rate of gases through opening m_g is a function of the opening factor $A\sqrt{H}$ and the temperature, McCaffrey et al. deduced the following equation for the fire room temperature by regression analysis of many experimental results [5].

$$\frac{DT}{T_\infty} \left(= \frac{T_F - T_\infty}{T_\infty} \right) = \quad (3.1)$$

$$1.6 \left(\frac{Q}{\sqrt{g c_p r_\infty T_\infty A \sqrt{H}}} \right)^{2/3} \left(\frac{h_k A_T}{\sqrt{g c_p r_\infty A \sqrt{H}}} \right)^{-1/3}$$

where

$$h_k = \left(\frac{k \rho c}{t} \right)^{1/2} \quad (3.2)$$

(1) Fire room temperature $\Delta T / T_\infty$

It is known that for ventilation controlled fire the mass of air flowing into the fire room m_a can be approximated by [2]

$$m_a \approx 0.5 A \sqrt{H} \quad (3.3)$$

Since the heat generation per unit mass of air used for combustion is independent of the kind of fuel and approximately constant and equal to 3,000 (kW), the rate of heat release inside the fire room Q can be given as

$$Q \approx 1,500 A \sqrt{H} \quad (3.4)$$

From Eqs.(3.1) and (3.2), the equation

$$\begin{aligned} \frac{\Delta T}{T_\infty} &\propto \left(\frac{1,500 A \sqrt{H}}{\sqrt{g c_p r_\infty T_\infty A \sqrt{H}}} \right)^{2/3} \left(\frac{h_k A_T}{\sqrt{g c_p r_\infty A \sqrt{H}}} \right)^{-1/3} \\ &\propto \left(\frac{A \sqrt{H}}{A_T} \right)^{1/3} \left(\frac{1}{h_k} \right)^{1/3} \end{aligned} \quad (3.5)$$

is deduced. Substituting Eq.(3.2) into this equation, the following equation is obtained.

$$\frac{\Delta T}{T_\infty} = C_1 \left(\frac{A \sqrt{H}}{A_T} \right)^{1/3} \left(\frac{t}{k \rho c} \right)^{1/6} \quad (3.6)$$

where C_1 is a constant.

(2) The rate of heat loss due to ventilation Q_v / Q
The heat loss due to ventilation Q_v is given by

$$Q_v = c_p m_g \Delta T \quad (3.7)$$

In Eq. (3.7) $m_g \propto A \sqrt{H}$ and the rate of heat release Q is proportional to $A \sqrt{H}$, named by

Figure 6. Interior of a room in which a pre-flashover fire occurs

$Q \propto A\sqrt{H}$ as shown in Eq. (3.4), so it follows that Q_v / Q is proportional to ΔT , hence the following equation is deduced.

$$\frac{Q_v}{Q} = C_2 \left(\frac{A\sqrt{H}}{A_r} \right)^{1/3} \left(\frac{t}{k\rho c} \right)^{1/6} \quad (3.8)$$

where C_2 is a constant.

- (3) The rate of heat loss to compartment boundaries Q_w / Q

Assuming the heat loss to compartment boundaries Q_w is given by

$$Q_w = h_k \Delta T A_r \quad (3.9)$$

the following equation for Q_w / Q is deduced by using Eq. (3.4), in a manner similar to the above deduction for Q_v / Q .

$$\frac{Q_w}{Q} = C_3 \left(\frac{A\sqrt{H}}{A_r} \right)^{-2/3} \left(\frac{t}{k\rho c} \right)^{-1/3} \quad (3.10)$$

where C_3 is a constant.

3.2 Results of regression analysis applied to the simple prediction formulae

Regression analysis of the computer model calculation results applied to Eq. (3.6), (3.7) and (3.10) to obtain the values of the constants C_1 , C_2 and C_3 yielded the following formulae.

$$\frac{\Delta T}{T_\infty} = 3.0 \left(\frac{A\sqrt{H}}{A_r} \right)^{1/3} \left(\frac{t}{k\rho c} \right)^{1/6} \quad (3.11)$$

$$\frac{Q_v}{Q} = 0.4 \left(\frac{A\sqrt{H}}{A_r} \right)^{1/3} \left(\frac{t}{k\rho c} \right)^{1/6} \quad (3.12)$$

$$\frac{Q_{v2}}{Q} = 0.45 \left(\frac{A\sqrt{H}}{A_r} \right)^{1/3} \left(\frac{t}{k\rho c} \right)^{1/6} \quad (3.13)$$

$$\frac{Q_w}{Q} = 0.45 \left(\frac{A\sqrt{H}}{A_r} \right)^{-2/3} \left(\frac{t}{k\rho c} \right)^{-1/3} \quad (3.14)$$

In the above equations, Q_v / Q and Q_{v2} / Q are the rate of heat loss through opening not

including and including the radiation heat loss, respectively. However the rate of heat loss to compartment boundaries Q_w / Q given by Eq. (3.4) exceeds 1 at early stage of times t and the prediction results are not in good agreement with the computer model calculation results, we propose the following equation derived from the relation $Q_w + Q_{v2} = Q$ in stead of Eq. (3.14).

$$\frac{Q_w}{Q} = 1 - 0.45 \left(\frac{A\sqrt{H}}{A_r} \right)^{1/3} \left(\frac{t}{k\rho c} \right)^{1/6} \quad (3.15)$$

Incidentally, the factor 3.0 in Eq. (3.11) can be is also obtained by substituting appropriate values into c_p , g , T_∞ and ρ_∞ .

3.3 Comparison between the model simulation results and the simple prediction formula and discussions

Figures 7 and 8 show the comparison between the results of the computer model calculation and the simple formulae, i.e. Eq.(3.11) for (a) the fire room temperature, Eq.(3.12) for (b) the ratio of heat loss due to ventilation and Eq.(3.15) for (c) the rate of heat loss to compartment boundaries, in the cases of normal concrete and light weight concrete, respectively. The temperature factor F_0 is assumed to be 0.025.

The results of computer model calculation for the fire room temperature $\Delta T / T_\infty$ and the ratio of heat loss due to ventilation Q_v / Q are in close agreement with the simple prediction results for all the temperature factors $F_0 = A\sqrt{H} / A_r$ in the cases of regular and light weight concrete. For large temperature factors, however, a discrepancy is observed in the ratio of heat loss Q_w / Q for light weight concrete boundaries. This discrepancy is considered to be attributed that the computer calculation includes the heat loss by radiation, while the simple predictive formulae do not; While in simple formulae, the heat loss due to ventilation is expressed by $Q_v = c_p m_g \Delta T$ not considering of radiation loss, Q_w / Q_v by Eq. (3.15) is calculated from the heat conservation law $Q_w + Q_{v2} = Q$, and Q_{v2} / Q values obtained by

Figure 7. Comparison between the model calculation results and the simple formulae (for normal concrete)

Figure 8. Comparison between the model calculation results and the simple formulae (for light weight concrete)

applying regression analysis to the computer model calculation results assuming the simple predictive formulae. Light weight concrete possesses a low heat conductivity, so when the opening area increases, the fire room temperature rises thereby increasing the heat loss due to radiation. In the simple prediction, however, the radiation heat loss is under estimated, which causes the discrepancy.

The discussion in the above shows that conservative prediction can be given for fire room temperature and the ratio of heat loss due to ventilation in the initial state of fire. For the rate of heat loss to compartment boundaries, however, a problem still remains in estimation of the heat loss due to radiation, and it was revealed that the temperature factor and the boundary material significantly affect the simple prediction of room fire behavior.

4. CONCLUSION

From the discussion of ventilation controlled fire behavior using computer model, the following conclusions are obtained:

- Fire behavior is determined by the temperature factor regardless the compartment dimensions.
- The compartment boundary material drastically affects the fire behavior.

The simple predictive formulae are derived by extending McCaffrey's formulae for pre-flashover fire to ventilation controlled fire. Although problem still remains regarding the radiation heat loss, the simple predictive formulae are useful for practical application in which the temperature factor is small or the heat conductivity is large. To improve the practicality of the formulae, the following problems should be solved.

- Derivation of simple predictive formulae with radiation heat loss
- Derivation of simple predictive formulae for plural compartments configuration

SYMBOL LIST

A : area of opening (m^2)	V : volume (m^3)
A_T : total surface area of a compartment (m^2)	X : depth from a boundary wall surface (m)
A_w : area of a boundary wall surface (m^2)	X_n : height of a neutral zone (m)
B : width of opening (m)	α : flow coefficient
c : specific heat of boundary material ($kJ/kg/K$)	α_w : convection heat transfer coefficient ($kW/m^2/K$)
c_p : specific heat of gas at a constant pressure ($kJ/kg/K$)	ε_w : emissivity of a boundary surface
F_0 : temperature factor ($A\sqrt{H}/A_T$)	ρ : density of boundary material (kg/m^3)
g : gravitational acceleration (m/s^2)	ρ_F : density of fire room gases (kg/m^3)
H : height of compartment opening (m)	ρ_∞ : density of ambient air (kg/m^3)
H_h : upper edge height of opening (m)	$\Delta\rho$: density difference between fire room gases and ambient air ($=\rho_\infty - \rho_F$) (kg/m^3)
H_l : lower edge height of opening (m)	σ : Stefan-Boltzmann constant [$= 5.67051 \times 10^{-11}$ ($kW/m^2/K^4$)]
h_k : effective heat transfer coefficient ($kW/m^2/K$)	
k : heat conductivity of boundary material ($kW/m/K$)	
l : thickness of boundary (m)	
M : mass burning rate (kg/s)	
m_a : mass inflow rate air through the opening (kg/s)	
m_g : mass outflow rate of hot gas through the opening (kg/s)	
m_p : mass plume flow rate entering into hot gas layer (kg/s)	
Q : rate of heat release (kW)	
Q_C : combustion heat release rate (kW)	
Q_R : radiation heat through window (kW)	
Q_V : heat loss due to ejecting flame (kW)	
	heat loss due to ventilation (kW)
Q_{V2} : heat loss due to ventilation including radiation loss (kW)	
Q_w : heat loss to compartment boundaries (kW)	
q''_{in} : incident heat to exposed (kW/m^2)	
q''_{out} : heat loss flux from non-exposed surface (kW/m^2)	
T : temperature (K)	
T_F : fire room temperature (K)	
T_w : boundary surface temperature (K)	
T_∞ : temperature of the atmosphere (ambient temperature) (K)	
ΔT : elevations of fire room temperature ($=T_F - T_\infty$) (K)	
t : time (s)	

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