Simple Formula for Ventilation Controlled Fire Temperatures

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ABSTRACT

Simple equations for predicting the fire temperatures of the room of origin and the connected corridor are proposed. These are obtained by applying the existing equation for predicting pre-flashover compartment fire temperature by Quintiere et al. to ventilation controlled fire. The results of the predictions using the simple equations are compared with the predictions by a more detailed computer fire model. The accuracy of the equations is as good as the computer model and deemed to be acceptable for many of such practical applications as structural fire safety designs of buildings.

1 INTRODUCTION

Fire resistance of structural elements and fire walls are being assessed under the heating conditions defined by a prescribed temperature-time curve in virtually every country. Sometimes, this curve is expressed in an analytical formula such as the famous ISO 834 curve given $T - T_O = log_{10}(8t - 1)$. Any of such temperature-time curves, however, cannot take into account the conditions of compartment boundary and openings, which definitely affect the fire temperature.

As a result, computer fire models, which often assumes ventilation controlled fire, are invoked when more rational assessment is desired for the compartment fire temperatures. However, it will be undoubtedly convenient for many practical applications if a simple analytical equation is available for fire room temperature. Also, it might be convenient if a simple formula is provided for the temperature of the spaces connected to the fire room in such a case as assessing the endurance of the fire doors installed at places somewhat remote from the fire room.

In this paper, the existing equation for pre-flashover room fire temperature developed by Quintiere et al. is extended to obtain simple equations for ventilation controlled fire temperatures of the room of origin and the corridor connected to the room.

2 COMPUTER FIRE MODEL

It is practically impossible to experimentally investigate compartment fire behavior under a variety of conditions. Hence, only possible way to validate the simple equations to be developed is to compare with the predictions by a more detailed computer model. A multi-room computer fire model in which all the physical properties are assumed as homogeneous is developed for this purpose. The schematic of the model is shown in Figure 1, and the outline of the mathematical formulation is as follows:

2.1 The Zone Equations

Considering the conservation of mass, oxygen and energy, and the state of ideal gas for each of the spaces involved in a fire, the following equations for the temperature, oxygen mass concentration and the room static pressures, which hold for any of the indoor spaces considered, are derived.

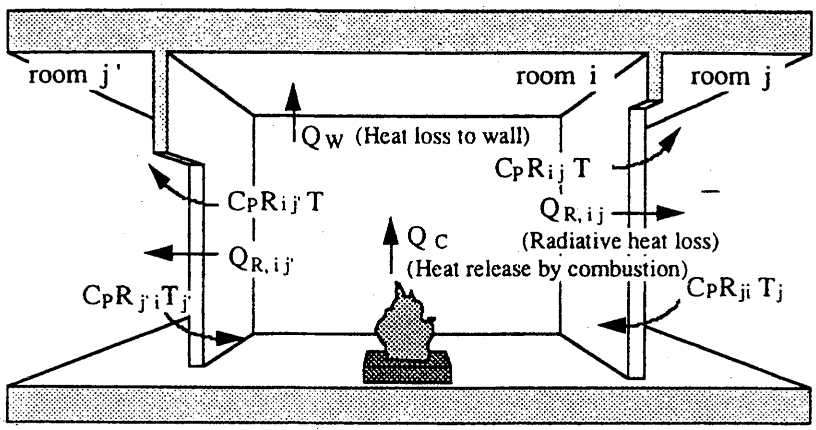


Figure 1: Schematic of the computer model

(a) Room temperature

$$\frac{dT}{dt} = \frac{T}{C_P V \rho_\infty T_\infty}\left(Q_C - Q_W - \sum_{j=0}^{n} Q_{R,ij}\right) - \frac{T}{V\rho_\infty T_\infty}\left\{\sum_{j=0}^{n} m_{ji}(T-T_j) + m_b(T-T_P)\right\} \quad (1)$$

(b) Oxygen mass concentration

$$\frac{dY_{O2}}{dt} = -\frac{T}{V\rho_\infty T_\infty}\left\{\sum_{j=0}^{n} m_{ji}\left(Y_{O2}-Y_{O2,j}\right) + m_b Y_{O2} + \frac{Q_C}{\Delta H_{O2}}\right\} \quad (2)$$

(c) Room static pressure

$$\frac{1}{C_P T}\left(Q_C - Q_W - \sum_{j=0}^{n} Q_{R,ij}\right) + \frac{1}{T}\sum_{j=0}^{n} m_{ji}T_j - \sum_{j=0}^{n} m_{ij} + \frac{T_P}{T} m_b = 0 \quad (3)$$

Note that subscript i, which denotes an arbitrary room, is omitted from every variable in the above equations for simplicity. Subscript j stands for a space connected with room i, and $j = 0$ specifically stands for the outdoor space. The summations in Eqns.(1) through (3) are taken for all the spaces connected with room i.

The ordinary differential equations (1) and (2) are numerically integrated using Runge-Kutta method. Each flow term of Eqn.(3) is formulated as a function of the room pressures and Eqn.(3) is solved for the pressures using Newton-Raphson method.

2.2 Transfer Terms

The terms for transfer of mass and energy included in Eqns. (1) through (3) are formulated as follows:

(1) Heat transfer to compartment boundary

Assuming the homogeneous temperature of the compartment boundary, the rate of heat transfer from the room gases to the boundary is calculated as

$$Q_W = \left\{\varepsilon_W \sigma\left(T^4 - T_W^4\right) + \alpha_W\left(T - T_W\right)\right\} A_T \quad (4)$$

where the convective heat transfer coefficient is assessed by

$$\alpha_W = \begin{cases} 5\times10^{-3} & (T_\alpha \le 300K) \\ (0.02T_\alpha - 1)\times10^{-3} & (300K < T_\alpha \le 800K) \\ 15\times10^{-3} & (800K < T_\alpha) \end{cases}$$

with T_α defined as

$$T_\alpha = (T + T_W)/2$$

The temperature of the boundary surface T_W, which is indispensable for the calculation of heat transfer to the boundary, is calculated by numerically solving the one-dimensional heat conduction equation using finite difference method. (2) Radiative heat exchange through openings

In this model, radiative heat transfer from a room to its adjacent rooms connected by opening of area $A_{D,ij}$ is taken into account by:

$$Q_{R,ij} = \sigma\left(T^4 - T_j^4\right) A_{D,ij} \tag{5}$$

(3) Mass flow rate through openings

The equations for the mass flow rates through the opening m_{ij} between room i and room j are provided as a function of the room static pressure P, room gas density ρ, and opening width B, soffit height H_u, and sill height H_l as shown in Table 1. The equations in Table 1 cover all the flow patterns conceivable in the multi-room fire model under the assumption of uniform temperature in every space.

(4) Mass burning rate

The mass burning rate in ventilation controlled compartment fire experimentally established by Kawagoe-Sekine is used in this model.

$$m_b = 0.1 A_W \sqrt{H_W} \tag{6}$$

where A_W and H_W are the area and the height of the opening, respectively. For the stability of the numerical computation, the burning rate is increased linearly up to this value in one minute.

(5) Heat release rate in the compartment

The theoretically maximum rate of the heat that can be released within a compartment under ventilation controlled fire is governed by the rate of oxygen supplied along with air entering into the compartment through the openings, i.e.:

$$Q_C = \Delta H_{O2} \sum_{j=0}^{n} m_{ji} Y_{O2,j} \tag{7}$$

Although the concentration of oxygen may not become to be completely zero even in fully developed stage, the heat release rate in this model is assumed as Q_C given by Eqn.(7).

condition		pressure difference	flow rate eqns.
$\rho_j = \rho_i$	$p_j \leq p_i$		$m_{ij} = \alpha B_W (H_u - H_l)\sqrt{2\rho_i \Delta P}$ $m_{ji} = 0$
	$p_j > p_i$		$m_{ij} = 0$ $m_{ji} = \alpha B_W (H_u - H_l)\sqrt{2\rho_j \Delta P}$
$\rho_j > \rho_i$	$Z_n \leq H_l$		$m_{ij} = 2/3 \alpha B_W \sqrt{2g\rho_i \Delta\rho}\left\{(H_u - Z_n)^{3/2} - (H_l - Z_n)^{3/2}\right\}$ $m_{ji} = 0$
	$H_l < Z_n < H_u$		$m_{ij} = 2/3 \alpha B_W \sqrt{2g\rho_i \Delta\rho}(H_u - Z_n)^{3/2}$ $m_{ji} = 2/3 \alpha B_W \sqrt{2g\rho_j \Delta\rho}(Z_n - H_l)^{3/2}$
	$H_u \leq Z_n$		$m_{ij} = 0$ $m_{ji} = 2/3 \alpha B_W \sqrt{2g\rho_j \Delta\rho}\left\{(Z_n - H_l)^{3/2} - (Z_n - H_u)^{3/2}\right\}$

where $\Delta P = |P_i - P_j|$ $\Delta\rho = |\rho_i - \rho_j|$ $Z_n = (P_i - P_j)/(\rho_i - \rho_j)g$

Table 1: Opening flow rate under various conditions

The burning rate given by Eqn.(6) causes ventilation controlled fire, but for a short period of starting up fire there is a fuel controlled stage as shown in Figure 2. The heat release rate in this stage is calculated by

$$Q_C = \Delta H_{wood} m_b \tag{8}$$

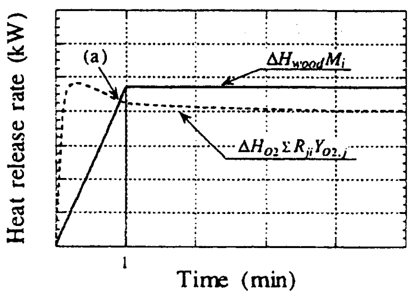


Figure 2: Transition of heat release rate

2.3 Prediction of Temperature by the Computer Fire Model

Sample calculations are made to investigate how the temperatures of the room of origin and the adjacent corridor are affected by the conditions of the spaces.

(1) Calculation conditions a) Space geometries

The room of origin and the connected corridor as shown by Figure 3 are employed as the object of the sample calculations. The dimensions of the spaces and the openings which are given a specific number in the figure are fixed at the value in all the calculations, and those whose dimensions are not specified in the figure are varied depending on the calculation condition.

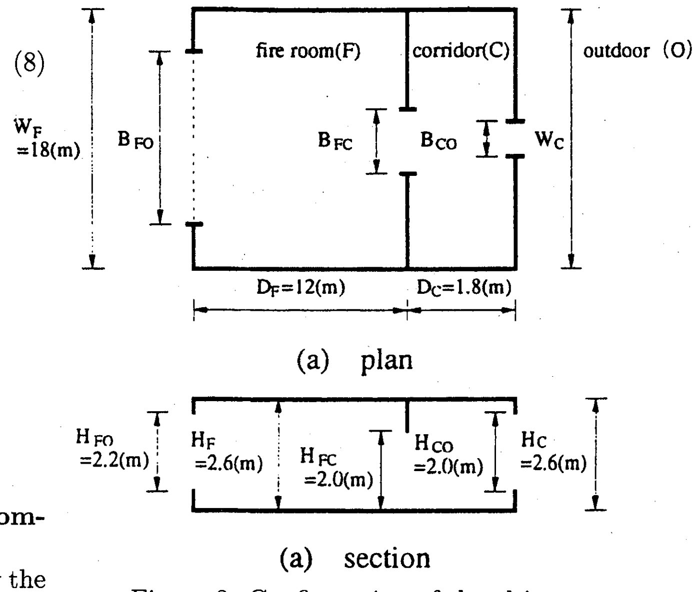


Figure 3: Configuration of the object space

b) Thermal properties of space boundaries

Normal concrete, light weight concrete and ALC are assumed as the boundary walls of the room of origin and the corridor. The thermal properties of each of the walls used in the calculations are shown in Table 2.

Table 2: Wall thermal properties

	conductivity k ($kW/m/K$)	density ρ (kg/m)	specific heat c ($kJ/kg/K$)	$\tau(=t/k\rho c)$
normal concrete	0.00163	2,250	0.895	0.3t
light weight concrete	0.000523	1,350	1.39	1.02t
ALC	0.000151	600	1.09	10.13t

c) Fire load

The fire load density in the room of origin is fixed at $30kg/m^2$ for all the cases, and the total fire load is determined by multiplying this value by the floor area.

d) Combination of the conditions

The calculations are made for the combination of the conditions of the space dimensions and the thermal properties of the boundary shown in Table 3. The effect of the condition of a specific factor is investigated by changing the value of the factor while fixing the other factors to the reference values, which are shaded in Table 3.

denote reference value

fire room	dimensions $W \times D \times H(m)$	$18.0 \times 12.0 \times 2.6$			
	fire load density (kg/m^2)	30.0			
	window $H_W \times B_W(m)$	2.2×4.5	2.2×9.0	*2.2×13.5*	2.2×18.0
	doorway $H_W \times B_W(m)$	2.0×1.0	*2.0×2.0*	2.0×3.0	2.0×4.0
corridor	dimensions $W \times D \times H(m)$	$9.0 \times 1.8 \times 2.6$	*$18.0 \times 1.8 \times 2.6$*	$27.0 \times 1.8 \times 2.6$	$36.0 \times 1.8 \times 2.6$
	window $H_W \times B_W(m)$	2.0×0	*2.0×1.5*	2.0×4.5	2.0×13.5
wall	wall type	normal concrete	light weight concrete		ALC
	thickness (cm)	10.0			
outdoor(^{o}C)		20.0			

Table 3: Calculation conditions

(2) Results of the calculations

The predicted results in Figure 4 illustrates the effect of each factor on the temperatures of the room of origin and the corridor.

It is shown that the conditions of the external opening of the room of origin have a significant effect on the temperatures of the corridor as well as the room of origin. Also, the effect of thermal properties is significant on the temperatures both of the two spaces. The conditions of the openings of the corridor, external and internal, seem to primarily affect the corridor temperature.

3 SIMPLE EQUATIONS FOR FIRE TEMPERATURE

Simple equation for predicting pre-flashover room fire temperature was proposed by Quintiere et al. Here, the equation is extended to the room of origin under ventilation controlled fire and a connected corridor configuration.

3.1 Simple Equations

According to Quintiere et al., the temperature of fire compartment with the heat release rate Q can be reasonably predicted by

$$\frac{\Delta T}{T_\infty}\left(=\frac{T-T_\infty}{T_\infty}\right) = 1.6\left(\frac{Q}{\sqrt{g}C_P\rho_\infty T_\infty A_W\sqrt{H_W}}\right)^{2/3}\left(\frac{h_k A_T}{\sqrt{g}C_P\rho_\infty A_W\sqrt{H_W}}\right)^{-1/3} \quad (9)$$

with the effective heat transfer coefficient defined as

$$h_k = \left(\frac{k\rho c}{t}\right)^{1/2} \quad (10)$$

Substituting Eqn.(10) into Eqn.(9) and the concrete values of g , C_P, ρ_∞ and T_∞ yields

$$\frac{\Delta T}{T_\infty} = 0.023\left(\frac{Q}{A_W\sqrt{H_W}}\right)^{2/3}\left(\frac{A_W\sqrt{H_W}}{A_T}\right)^{1/3}\left(\frac{t}{k\rho c}\right)^{1/6} \quad (11)$$

(1) Temperature of the room of origin

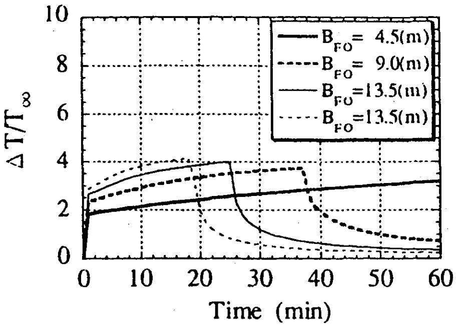
In ventilation controlled fire, the rate of heat released within the compartment Q is controlled by the rate of air supply through the opening. The air inflow rate through an opening in a fully developed fire m_a can be estimated as

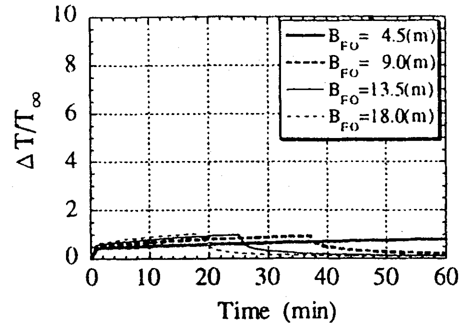
$$m_a = 0.5A_W\sqrt{H_W} \quad (12)$$

On the other hand, the heat release per unit mass of air consumed in combustion is $3{,}000kJ/kg - air$ regardless the kind of fuel, hence, Q becomes as

$$Q = 1{,}500A_W\sqrt{H_W} \quad (13)$$

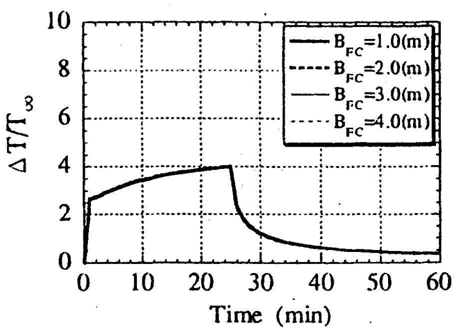
Most of the air available for the combustion in fire compartment is undoubtedly supplied through the opening directly open to the outdoor, but some the air can be supplied through the doorway open to the connected corridor. Figure 5 shows the oxygen concentrations predicted by the computer model described in the above. According to the results the oxygen concentration quickly becomes zero when the corridor has no opening to the outdoor, but the concentration stays at considerably high level even when the width is considerably small. Hence, we employ the following approximations as

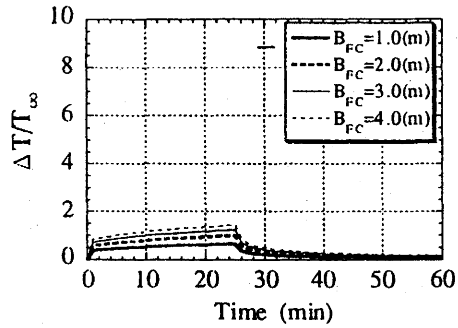




(a) fire room temperature (b) corridor temperature

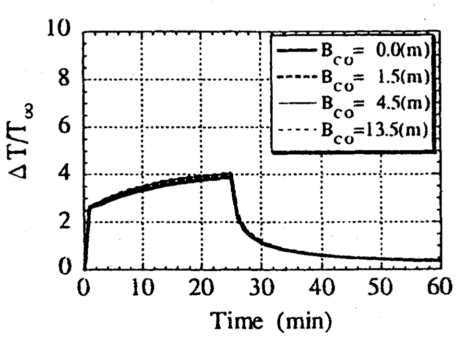
(1) Effects of fire room window size

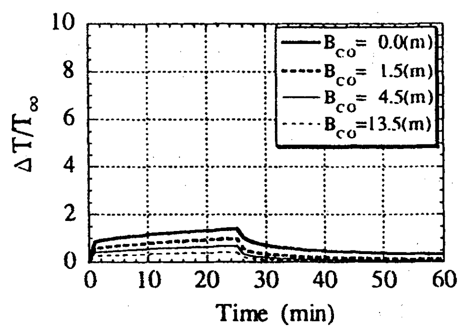




(a) fire room temperature (b) corridor temperature

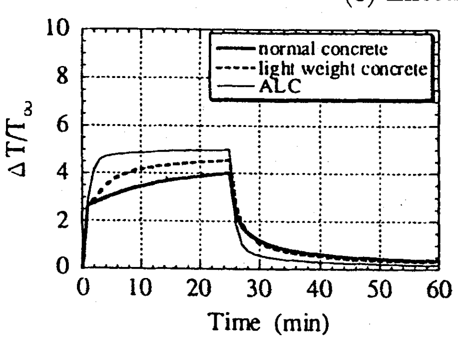
(2) Effects of doorway size

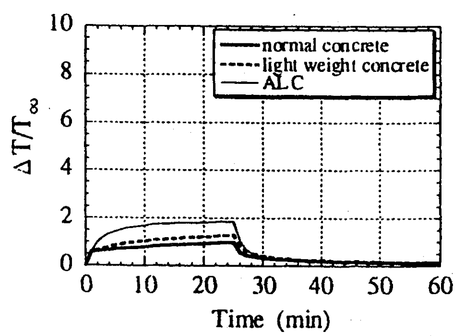




(a) fire room temperature (b) corridor temperature

(3) Effects of corridor window size





(a) fire room temperature (b) corridor temperature

(4) Effects of wall thermal properties

Figure 4: Effects of factors on fire temperature

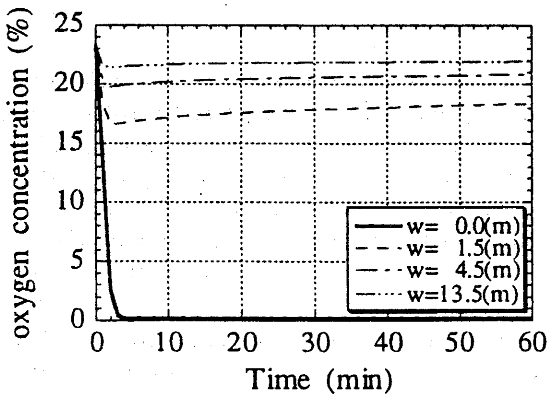


Figure 5: Oxygen concentration in the air through doorway (B_{CO} : doorway width)

a) When there is no opening between the corridor and the outdoor

$$Q = 1,500 A_{FO}\sqrt{H_{FO}} \tag{14-1}$$

b) When there is an opening between the corridor and the outdoor

$$Q = 1,500\left(A_{FO}\sqrt{H_{FO}} + A_{FC}\sqrt{H_{FC}}\right) \tag{14-2}$$

Substituting Eqns.(14-1) and (14-2) into Eqn.(11) yields the equations for the fire room temperatures for the cases:

a) When there is no opening between the corridor and the outdoor

$$\frac{\Delta T_F}{T_\infty} = 3.0\left(\frac{A_{FO}\sqrt{H_{FO}}}{A_{FO}\sqrt{H_{FO}} + A_{FC}\sqrt{H_{FC}}}\right)^{2/3} \left(\frac{A_{FO}\sqrt{H_{FO}} + A_{FC}\sqrt{H_{FC}}}{A_{T,F}}\right)^{1/3} \left(\frac{t}{k\rho c}\right)^{1/6} \tag{15-1}$$

b) When there is an opening between the corridor and the outdoor

$$\frac{\Delta T_F}{T_\infty} = 3.0\left(\frac{A_{FO}\sqrt{H_{FO}} + A_{FC}\sqrt{H_{FC}}}{A_{T,F}}\right)^{1/3} \left(\frac{t}{k\rho c}\right)^{1/6} \tag{15-2}$$

respectively, where $A_{T,F}$ is the total surface area of the fire room boundary.

Incidentally, both Eqn.(15-1) and (15-2) become as

$$\frac{\Delta T_F}{T_\infty} = 3.0\left(\frac{A_{FO}\sqrt{H_{FO}}}{A_{T,F}}\right)^{1/3} \left(\frac{t}{k\rho c}\right)^{1/6} \tag{16}$$

when there is no opening between the room of origin and the connected corridor. This can be used for predicting the temperature of single fire room.

(2) Temperature of the corridor

It is assumed that Eqn.(12) holds for the flow rate through the doorway between the fire room and the corridor, then the rate of heat convected to the corridor is given by

$$\begin{aligned} Q_C &= C_P m_{FC}(T_F - T_\infty) \\ &= 150 A_{FC}\sqrt{H_{FC}}\left(\frac{\Delta T_F}{T_\infty}\right) \end{aligned} \tag{17}$$

where $T_\infty = 300K$ is employed.

This Q_C can be considered as the rate of heat given to the corridor. Substituting Q_C into Q in Eqn.(11) and using Eqns.(15-1) and (15-2) yields:

a) When there is no opening between the corridor and the outdoor

$$\frac{\Delta T_C}{T_\infty} = 1.35\left(\frac{A_{FC}\sqrt{H_{FC}}}{A_{T,C}}\right)^{1/3} \left(\frac{A_{FO}\sqrt{H_{FO}}}{A_{FO}\sqrt{H_{FO}} + A_{FC}\sqrt{H_{FC}}}\right)^{4/9} \left(\frac{A_{FO}\sqrt{H_{FO}} + A_{FC}\sqrt{H_{FC}}}{A_{T,F}}\right)^{2/9} \left(\frac{t}{k\rho c}\right)^{5/18} \tag{18-1}$$

b) When there is an opening between the corridor and the outdoor

$$\frac{\Delta T_C}{T_\infty} = 1.35\left(\frac{A_{FC}\sqrt{H_{FC}} + A_{CO}\sqrt{H_{CO}}}{A_{T,C}}\right)^{1/3} \left(\frac{A_{FC}\sqrt{H_{FC}}}{A_{FC}\sqrt{H_{FC}} + A_{CO}\sqrt{H_{CO}}}\right)^{2/3} \left(\frac{A_{FO}\sqrt{H_{FO}} + A_{FC}\sqrt{H_{FC}}}{A_{T,F}}\right)^{2/9} \left(\frac{t}{k\rho c}\right)^{5/18} \tag{18-2}$$

respectively, where $A_{T,C}$ is the total surface area of the corridor boundary.

(3) The parameters determining temperature

According to Eqns.(15-1), (15-2), (18-1) and (18-2), the temperatures of the room of origin and the corridor are determined by the following 5 parameters defined as:

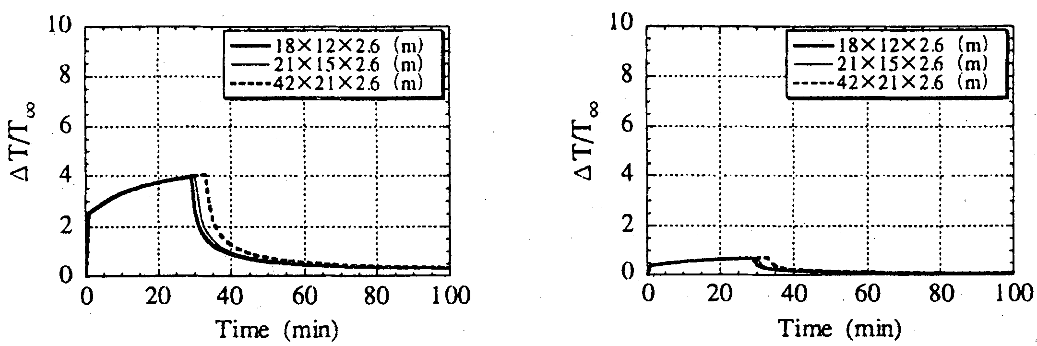
$$
\begin{aligned}
\tau &= \frac{t}{k\rho c} \\
K_F &= \frac{A_{FO}\sqrt{H_{FO}}}{A_{FO}\sqrt{H_{FO}}+A_{FC}\sqrt{H_{FC}}} \\
F_{O,F} &= \frac{A_{FO}\sqrt{H_{FO}}+A_{FC}\sqrt{H_{FC}}}{A_{T,F}} \\
K_C &= \frac{A_{FC}\sqrt{H_{FC}}}{A_{FC}\sqrt{H_{FC}}+A_{CO}\sqrt{H_{CO}}} \\
F_{O,C} &= \frac{A_{FC}\sqrt{H_{FC}}+A_{CO}\sqrt{H_{CO}}}{A_{T,C}}
\end{aligned}
\tag{19}
$$

In fact, as can be seen in Figure 6, which demonstrates some examples of the predictions using the above computer model for the different conditions having the same values of the parameters, the temperatures become the same except for the difference due to the duration of fire.

3.2 Comparison between the Predictions by the Computer Model and the Simple Model

The applicability of the simple model is studied by comparing the predictions by the simple model and the computer model for the cases already shown in Table 3. Some examples of the predictions of the temperatures of the fire room and the corridor are shown in Figure 7.

For the cases of concrete boundary, the predictions by the simple model show a fair agreement with the predictions by computer model, and for the cases of light weight concrete boundary, somewhat worse but still acceptable for the period of less than an hour. On the other hand, the discrepancies are huge from very early stage for the case of ALC, whose thermal inertia is remarkably smaller than the others.



(a) fire room temperature

(b) corridor temperature

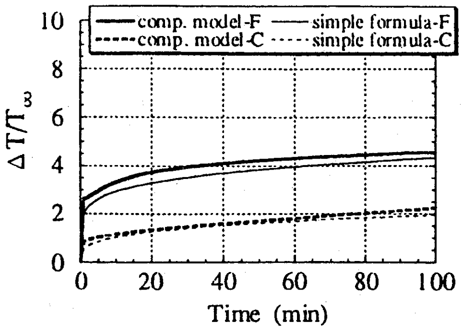
Figure 6: Temperatures for the same parameter

4 REFINED SIMPLE EQUATIONS

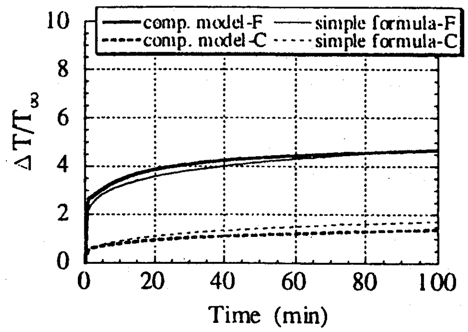
4.1 Wall Thermal Properties and Transient Change of Fire Temperature

According to the results shown in Figure 7, in which the temperature predicted by the simple equations and the computer model are compared for real time$t$, the accuracy of the simple equation seem to become lower as the space boundary wall becomes more thermally insulative. However, the difference between the simple equation and the computer model becomes the same regardless the difference of the boundary wall if we compare the predictions for the parameter t shown in Eqn.(19). In fact, as is demonstrated by the sample calculations shown in Figure 8, the temperatures change along the same curve for any of the three kinds of wall materials as long as the dimensions of the spaces and the openings are the same.

The reason why the gap develops between the predictions by the simple equations and the computer model as t becomes large is considered to be partly because the radiative heat loss from the external opening is not taken into account and partly because the heat transfer model is somewhat crude in the simple equations.

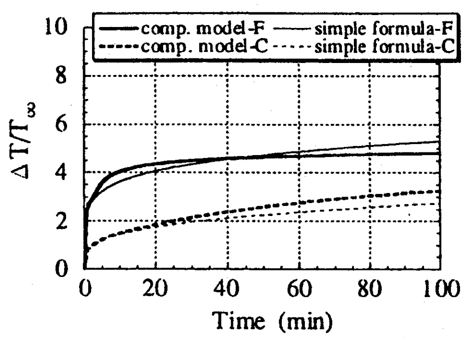


(a) without corridor window

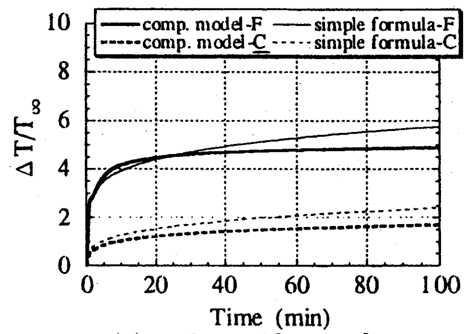


(b) with corridor window

(1) Normal concrete

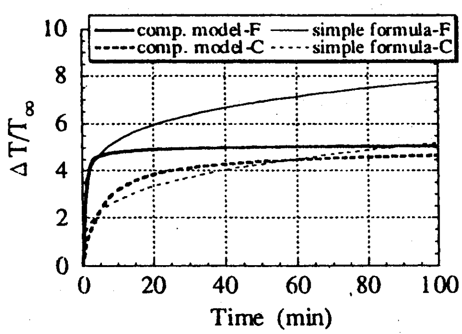


(a) without corridor window

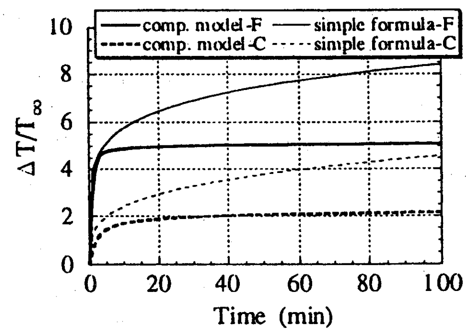


(b) with corridor window

(2) Light weight concrete



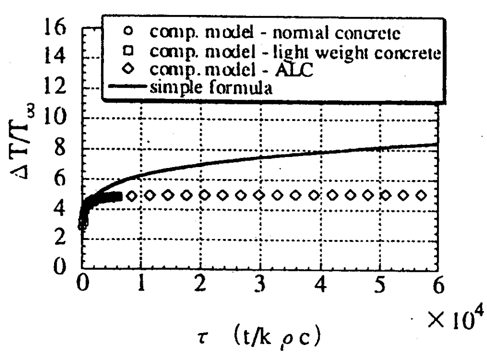
(a) without corridor window



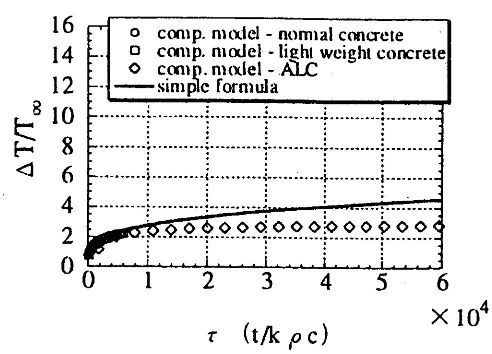
(b) with corridor window

(3) ALC

Figure 7: Comparison between the simple formulas and computer model



(a) fire room temperature



(b) corridor temperature

Figure 8: Predicted temperature v.s. τ

4.2 Refinement of The Simple Equations

(1) Fire room temperature

Firstly, the parameter $\beta_{F,1}$ and $\beta_{F,2}$ are defined as

$$\begin{aligned} \beta_{F,1} &= K_F^{2/3} \cdot F_{O,F}^{1/3} \cdot \tau^{1/6} \\ \beta_{F,2} &= F_{O,F}^{1/3} \cdot \tau^{1/6} \end{aligned} \tag{20}$$

respectively. Note that Eqn.(15); the simple equation for the fire room temperature; may be expressed using these parameters as

$$\frac{\Delta T_F}{T_\infty} = \begin{cases} 3.0\beta_{F,1} & \begin{pmatrix} \text{without external} \\ \text{opening in corridor} \end{pmatrix} \\ 3.0\beta_{F,2} & \begin{pmatrix} \text{with external} \\ \text{opening in corridor} \end{pmatrix} \end{cases} \tag{21}$$

Next, let's consider the ratio of the fire room temperature predicted by the computer model to the parameters defined by Eqn.(20) as follows:

$$\begin{aligned} \gamma_{F,1} &= \left(\frac{\Delta T_F}{T_\infty}\right) \Big/ \beta_{F,1} \\ \gamma_{F,2} &= \left(\frac{\Delta T_F}{T_\infty}\right) \Big/ \beta_{F,2} \end{aligned} \tag{22}$$

Figure 9 shows the ratios $\gamma_{F,1}$ and $\gamma_{F,2}$ Plotted for $\beta_{F,1}$ and $\beta_{F,2}$, respectively. The relationship in Figure 9 may be expressed by the following regression formulas which hold regardless the wall thermal properties as

a) When there is no opening between the corridor and the outdoor

$$\gamma_{F,1} = \begin{cases} 3.50 + (\beta_{F,1} - 1.00) & (\beta_{F,1} \leq 1.00) \\ 3.50 - (\beta_{F,1} - 1.00) & (\beta_{F,1} > 1.00) \end{cases} \tag{23-1}$$

b) When there is an opening between the corridor and the outdoor

$$\gamma_{F,2} = \begin{cases} 3.25 + (\beta_{F,2} - 1.25) & (\beta_{F,2} \leq 1.25) \\ 3.25 - (\beta_{F,2} - 1.25) & (\beta_{F,2} > 1.25) \end{cases} \tag{23-2}$$

Substituting Eqns.(23-1) and (23-2) into Eqn.(22) yields the refined formulas for fire room temperature which better agree with the predictions by computer model as follows:

a) When there is no opening between the corridor and the outdoor

$$\frac{\Delta T_F}{T_\infty} = \begin{cases} \beta_{F,1}(2.50 + \beta_{F,1}) & (\beta_{F,1} \leq 1.00) \\ \beta_{F,1}(4.50 - \beta_{F,1}) & (\beta_{F,1} > 1.00) \end{cases} \tag{24-1}$$

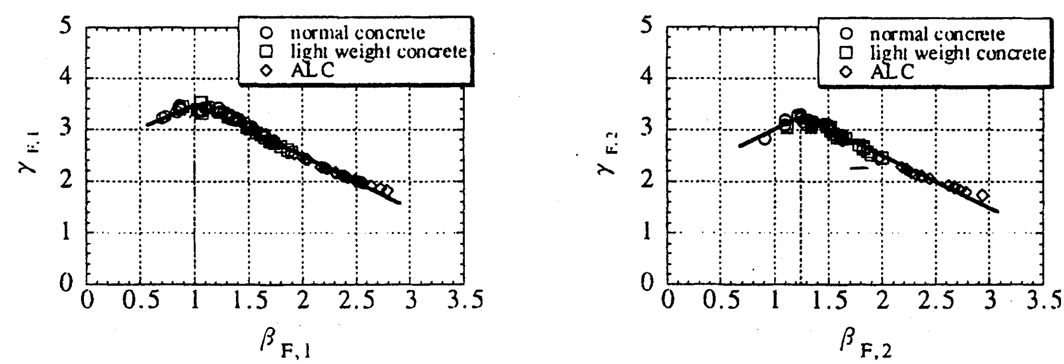
b) When there is an opening between the corridor and the outdoor

$$\frac{\Delta T_F}{T_\infty} = \begin{cases} \beta_{F,2}(2.00 + \beta_{F,2}) & (\beta_{F,2} \leq 1.25) \\ \beta_{F,2}(4.50 - \beta_{F,2}) & (\beta_{F,2} > 1.25) \end{cases} \tag{24-2}$$

(2) Corridor temperature

Similarly with fire room temperature, the parameters for corridor temperature $\beta_{C,1}$ and $\beta_{C,2}$ are defined as follows:

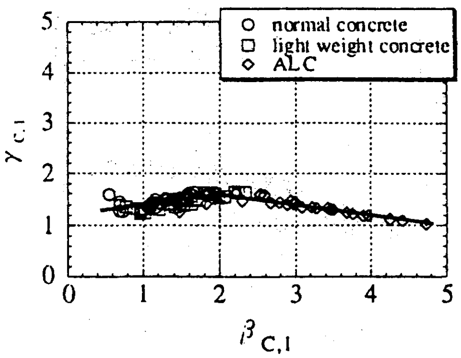
$$\begin{aligned} \beta_{C,1} &= K_F^{4/9} \cdot F_{O,C}^{1/3} \cdot F_{O,F}^{2/9} \cdot \tau^{5/18} \\ \beta_{C,2} &= K_C^{2/3} \cdot F_{O,C}^{1/3} \cdot F_{O,F}^{2/9} \cdot \tau^{5/18} \end{aligned} \tag{25}$$



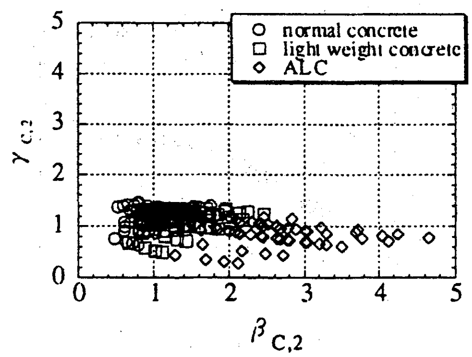
(a) without corridor window

(b) with corridor window

Figure 9: Ration of computed fire room temperatures to β_F



(a) without corridor window



(b) with corridor window

Figure 10: Ration of computed corridor temperatures to β_C

respectively. Note that Eqn.(18); the simple equation for corridor temperature; may be expressed using these parameters as

$$\frac{\Delta T_C}{T_\infty} = \begin{cases} 1.35\beta_{C,1} & \begin{pmatrix} \text{without external} \\ \text{opening in corridor} \end{pmatrix} \\ 1.35\beta_{C,2} & \begin{pmatrix} \text{with external} \\ \text{opening in corridor} \end{pmatrix} \end{cases} \tag{26}$$

Next, Let's consider the ratio of the corridor temperature predicted by the computer model to the parameters defined by Eqn.(25) as follows:

$$\begin{aligned} \gamma_{C,1} &= \left(\frac{\Delta T_C}{T_\infty}\right) \Big/ \beta_{C,1} \\ \gamma_{C,2} &= \left(\frac{\Delta T_C}{T_\infty}\right) \Big/ \beta_{C,2} \end{aligned} \tag{27}$$

Figure 10 shows the ratios $\gamma_{C,1}$ and $\gamma_{C,2}$ plotted for $\beta_{C,1}$ and $\beta_{C,2}$ respectively.

a) When there is no opening between the corridor and the outdoor

As can be seen in Figure 10(a), when there is no opening between the corridor and the outdoor the ratio $\gamma_{C,1}$ converge reasonably well with the use of parameter $\beta_{C,1}$ regardless the wall type. The regression line may be expressed as

$$\gamma_{C,1} = \begin{cases} 1.60 + 0.20(\beta_{C,1} - 2.00) & (\beta_{C,1} \leq 2.00) \\ 1.60 - 0.20(\beta_{C,1} - 2.00) & (\beta_{C,1} > 2.00) \end{cases} \tag{28}$$

Substituting Eqn.(28) into Eqn.(27) yields the equation which agree better with the computer prediction than Eqn.(18-1) as follows:

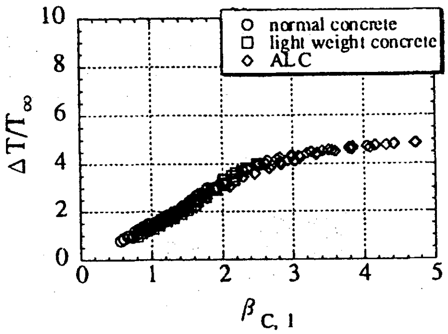
$$\frac{\Delta T_C}{T_\infty} = \begin{cases} \beta_{C,1}(1.20 + 0.20\beta_{C,1}) & (\beta_{C,1} \leq 2.00) \\ \beta_{C,1}(2.00 - 0.20\beta_{C,1}) & (\beta_{C,1} > 2.00) \end{cases} \tag{29}$$

b)When there is an opening between the corridor and the outdoor

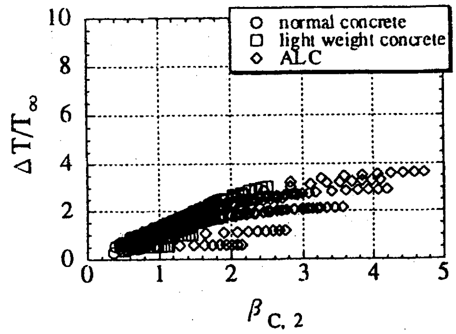
On the other hand, when there is an opening between the corridor and the outdoor, the conversion of the data is poor. In Figure 11(a) and (b), the temperatures predicted by the computer model are plotted versus $\beta_{C,1}$, for the cases without opening, and $\beta_{C,2}$, for the cases with an opening, respectively. As can be seen, while the temperatures for the cases without opening contract to the same line, those for the cases with an opening spread to asymptotically reach at different values as $\beta_{C,2}$ increases. We have not succeeded to find the parameter which brings nice conversion, however, Eqn.(18-2) may be used for many practical cases where the boundary wall is not extremely insulative.

4.3 Comparison of the Predictions by the Computer Model and the Simple Formulas

Figure 12 compares the predictions by the computer model and the refined simple equations for fire room temperature, i.e. Eqns.(24-1) and (24-2), and for corridor temperature for the cases without opening, i.e. (29). The conditions of the calculations are the same as those in Figure 6. It may be said that an excellent agreement has been attained by the refinement.

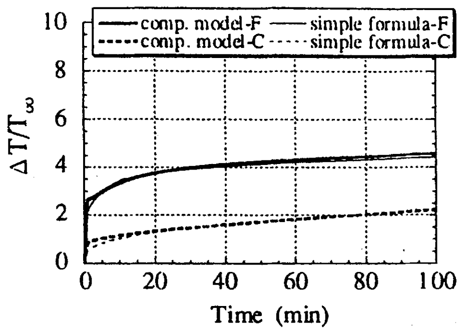


(a) without corridor window

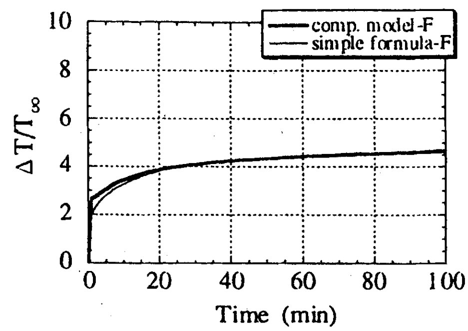


(b) with corridor window

Figure 11: Computed corridor temperatures v.s. β_C

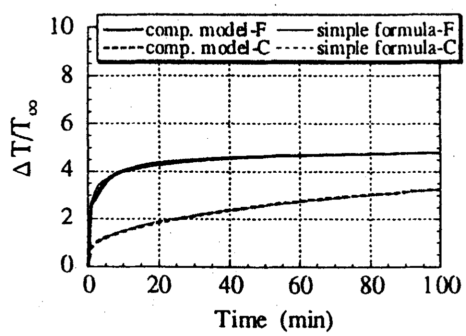


(a) without corridor window

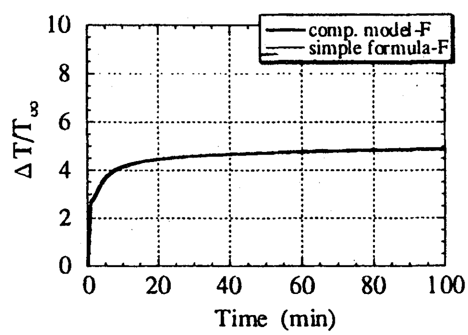


(b) with corridor window

(1) Normal concrete

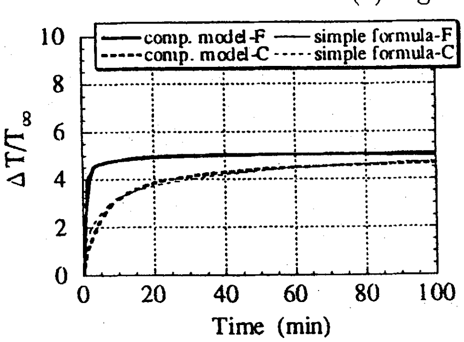


(a) without corridor window

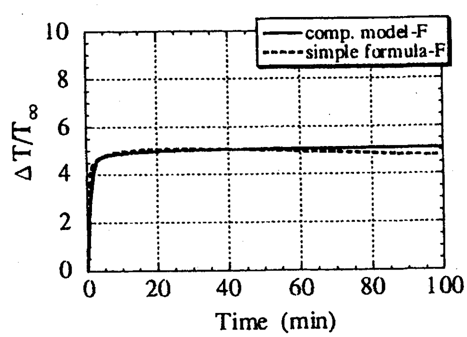


(b) with corridor window

(2) Light weight concrete



(a) without corridor window



(b) with corridor window

(3) ALC

Figure 12: Comparison of the predictions by the computer model and the refined simple formulas

5 CONCLUSION

Simple formulas for predicting the temperatures of ventilation controlled fire room and the connecting corridor were developed. By the use of the formulas, the fire room temperature can be predicted as accurately as by the use of the computer model regardless the wall type. The temperature of the corridor connected to the fire room can be predicted as well when there is no opening between the corridor and the outdoor. The formulas are more advantageous than the computer model in that the parameters affecting the temperature are explicitly known by the user in addition to the accessibility.

NOMENCLATURE

A :Area (m^2)
B :Opening width (m)
c :Specific heat of wall (kJ/kgK)
C_P :Specific heat of gas at constant pressure (kJ/kgK)
D :Depth of room (m)
g :Acceleration due to gravity (m/s^2)
H :Height (m)
ΔH_{O2} :Heat of combustion per unit mass of oxygen consumed (kJ/kg)
ΔH_{wood}:Heat of combustion of wood (kJ/kg)
h_k :Effective heat transfer coefficient (kW/m^2K)
k :Thermal conductivity of wall(kW/mK)
M :Mass burning rate (kg/s)
m :Mass opening flow rate (kg/s)
n :Number of rooms
P :Relative pressure (Pa)
Q :Heat release rate (kW)
Q_C :Combustion heat release rate (kW)
Q_R :Radiative heat loss through opening (kW)
Q_w :Heat loss to wall (kW)
T :Temperature (K)
ΔT :Temperature difference (K)
t :time (s)
V :Room volume (m^3)
W :Room width (m)
Y_{O2} :Mass fraction of oxygen
Z_n :Height of neutral plane (m)
α :Opening flow coefficient
ε :Emissivity
ρ :Density (kg/m^3)
σ :Stefan-Boltzmann constant (kW/m^2K^4)

Subscript

C :Corridor
D :Door
F :Fire room
O :Outdoor
T :Total
i :Arbitrary room
j :Room connected to room i
ij :From room i to room j, Between room i and j

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