A CALCULATION METHOD OF FULLY DEVELOPED FIRE TEMPERATURE FOR MULTI-ROOM FIRE SPREAD SCENARIOS

K. Harada
Department of Architecture and Architectural Engineering, Kyoto University
Building C2-406, Kyoto University Katsura Campus, Nishigyo, Kyoto 615-8540, Japan

ABSTRACT

A model was proposed to calculate the severity of fully developed fires in a multi room spreading scenario. The model is intended for use in fire resistance design. The model consists of a heat balance of rooms, network ventilation for mass flow rates through openings and heat conduction in enclosure walls. The model was compared with a full-scale experiment. Even though the verification is not perfect, the model could calculate the corridor temperature properly. Using the model, the effect of burning in adjacent rooms is examined for a simple two-room building and a realistic building with corridor and office rooms.

KEYWORDS: Fully developed fires, Multi-room spread, Room heat conservation ventilation network

INTRODUCTION

In the practical fire resistance design based on performance, the severity and duration of a fully -developed fire is often calculated based on post flashover compartment fire models. For example, Japanese Building Standards Law adopts a calculation method[1] originally proposed by McCaffrey et al. The fundamental theory for prediction of fully-developed fire temperature was proposed by Sekine and Kawagoe in the 1660's[2]. Based on experimental data, McCaffrey et al. proposed a simple closed form formula for fuel-controlled fires[3]. Matsuyama et al. extended the formula to ventilation-controlled fires as well[4].

The model is principally focused on single compartment fires only. However, in real buildings, rooms are interconnected by door openings and lightweight walls that are not necessarily fire rated. Thus the applicability of single fire compartment model is limited. If fire spreads between multiple compartments, then the fire severity might be different from that calculated under the assumption of single fire compartment. To examine the effect of multi room fire spread, a computer model was developed in this paper.

CALCULATION METHOD OF FULLY DEVELOPED FIRE IN MULTIROOM BUILDINGS

As shown in Fig. 1, a building with multiple rooms is considered. Fire starts in one of the rooms. As fire grows to fully developed stage, spread to adjacent rooms may take place at some key event such as flashover and/or breaking of doors and so on. To calculate the fire spread scenario, heat and oxygen conservation of rooms, mass flow rate of gas between rooms and heat conduction through room enclosures are solved simultaneously.

1) Room Heat Conservation

Even in multi-room scenario, heat balance of a room could be described by a conventional way if we focus on one of the rooms,

$$Q_{c,i} = Q_{a,i} + Q_{l,i} + Q_{r,i} + Q_{w,i} \qquad [1]$$

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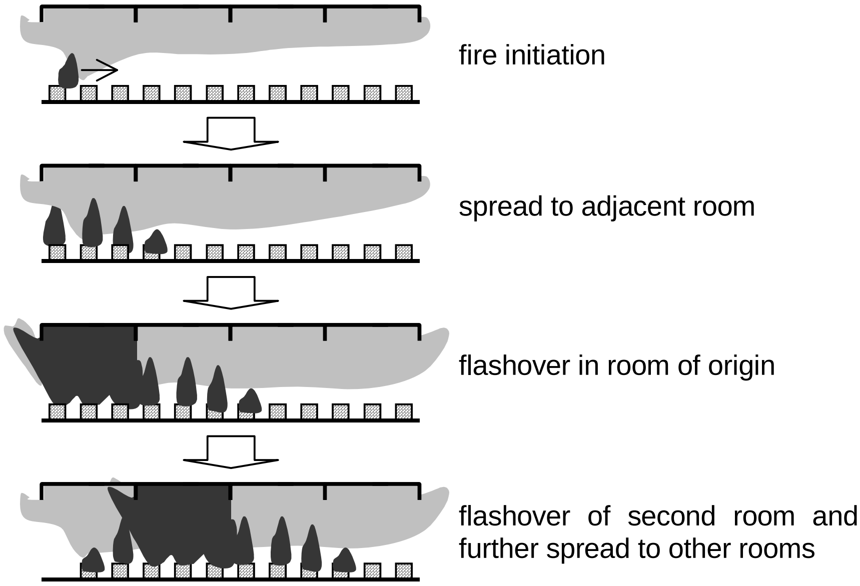

FIGURE 1. Schematic of fire spread scenario between rooms

As proposed by Sekine and Kawagoe, where Q_c is the heat release rate, Q_a is the rate of heat accumulation by room gas, Q_l is the rate of heat loss by ventilation, Q_r is the rate of heat loss by radiation, Q_w is the rate of heat absorption by room enclosure materials [kW]. Subscript *i* denotes the room number.

In single compartment models, the heat balance equation is approximated by closed form formula with the aid of empirical relationships using opening factor and thermal inertia. However, in case of multi-room scenarios, this type of simplification is not possible, but each term has to be calculated explicitly.

Rate of heat loss by radiation is expressed by using mass flow rate through openings between room *i* and adjacent rooms *j*.

$$Q_{l,i} = c_p \sum_j (m_{ij} T_i - m_{ji} T_j) \qquad [2]$$

where m_{ij} is the mass flow arte of gas from room *i* to room *j*, m_{ji} is the mass flow arte of gas from room *j* to room *i*, c_p is the specific heat of gas [J/kg·K], T_i is the temperature [K] of room *i*, and T_j is the temperature of adjacent room *j*. The summation denotes the sum of all the openings facing to room *i*.

Assuming that fire gas is approximated by black body gas, the rate of heat loss by radiation is:

$$Q_{r,i} = \sum_j A_{ij} \sigma (T_i^4 - T_j^4) \qquad [3]$$

where A_{ij} is opening area [m^2] between rooms *i* and *j*, and s is the Stefan-Boltzman constant (= 5.67 x 10^{-11} kW/m^2·K^4).

The rate of heat absorption by wall surfaces is calculated by:

$$Q_{w,i} = \sum_k A_{w,i,k} h_{i,k} (T_i - T_{w,i,k}) \qquad [4]$$

where A_w is wall area [m^2], *h* is overall heat transfer coefficient [kW/m^2·K] between fire gas and wall surface, and T_w is wall surface temperature. The summation over *k* denotes the sum over all the

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elements of construction of room *i*.

Summarizing above relationships, temperature in room *i* can be calculated by:

$$T_i = \frac{Q_i + (c_p \sum_j m_{ji} + \sum_j A_{ij} h_{r,ij}) T_j + \sum_k A_{w,i,k} h_{i,k} T_{w,i,k}}{c_p \sum_j m_{ij} + \sum_j A_{ij} h_{r,ij} + \sum_k A_{w,i,k} h_{i,k}} \qquad [5]$$

where $h_{r,ij}$ is radiative heat transfer coefficient between rooms *i* and *j*.

$$h_{r,ij} = \sigma (T_i^2 + T_j^2)(T_i + T_j)\,. \qquad [6]$$

After knowing heat release rate Q_i, mass flow rates m_{ij} and m_{ji}, wall surface temperature $T_{w,i,k}$, room temperature can be calculated by equation [5].

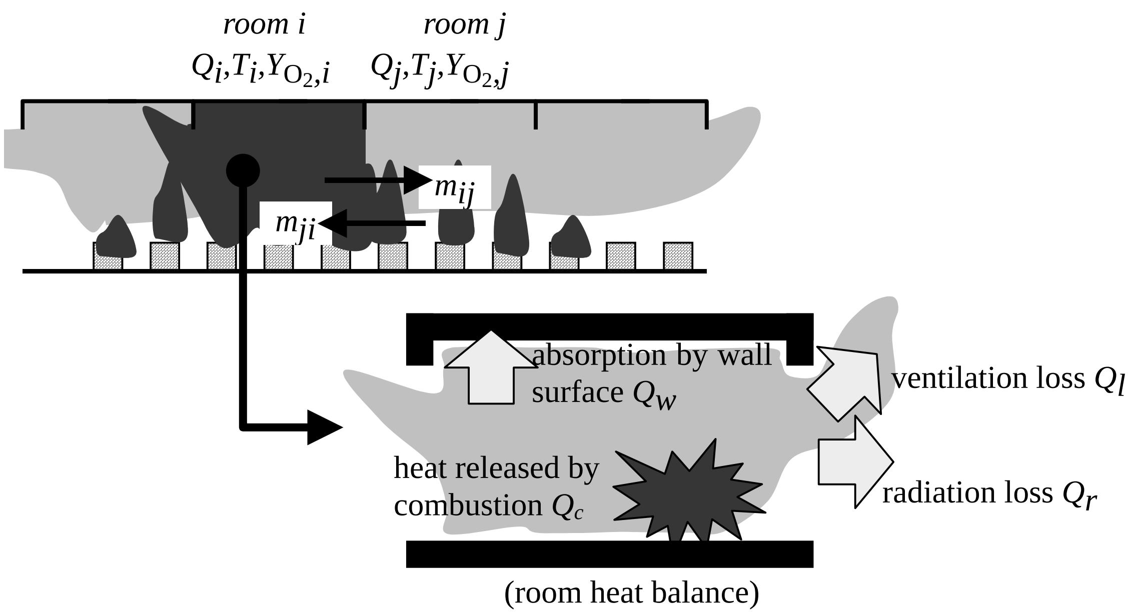

FIGURE 2. Heat conservation of fire room

2) Heat Release Rate

Heat release rate would be determined by the rate of decomposition of volatile materials and rate of incoming air to fire room. As is well known, heat release rate is proportional to fuel surface area if sufficient air is supplied (so-called fuel surface control). Under poor ventilation, heat release rate is limited by the rate of oxygen inflow (so-called ventilation control). Considering these two limiting states, heat release rate is given by using burning type index.

In case of single fire compartment, heat release rate is calculated by[5]:

$$Q = 16{,}000 A_{fuel} \times \begin{cases} 0.007 & (0.08 < \chi \le 0.1) \\ 0.12\chi \exp(-11\chi) + 0.003 & (0.1 < \chi) \end{cases} \qquad [7]$$

where χ is burning type index [$m^{1/2}$]

$$\chi = A\sqrt{H} / A_{fuel} \qquad [8]$$

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determined by the ratio of ventilation factor $A\sqrt{H}$ [$m^{5/2}$] and fuel surface area A_{fuel} [m^2].

In multi-room scenarios, description by ventilation factor is not valid but replaced with mass flow rate of oxygen incoming to fire room. In case of single opening where formula [7] has been developed, mass flow of air incoming to fire room is expressed by:

$$m_{air} = 0.52 A\sqrt{H} \quad [9]$$

Multiplying with oxygen concentration $Y_{O_2,0}$ [kg/kg], mass flow of air incoming to fire room is:

$$m_{O_2} = 0.52 A\sqrt{H}\ Y_{O_2,0} \quad [10]$$

Therefore, burning type index can be re-written by:

$$\chi = \frac{A\sqrt{H}}{A_{fuel}} = \frac{m_{O_2} / 0.52 Y_{O_2,0}}{A_{fuel}}. \quad [11]$$

In case of multiple openings, summation over all the opening should be introduced as:

$$\chi = \frac{\sum_j m_{ji} Y_{O_2,j} / 0.52 Y_{O_2,0}}{A_{fuel}} \quad [12]$$

where $Y_{O_2,j}$ is the oxygen concentration in adjacent rooms j.

3) Mass Flow Rates between Rooms

Mass flow rates were calculated by single-layered, ventilation network smoke transport model developed by Matsushita et al. [6]

4) Wall Surface Temperature

Wall surface temperature was calculated by finite difference method for one-dimensional heat conduction.

COMPARISON WITH EXPERIMENTAL DATA

Experimental Condition

To examine the accuracy of developed calculation method, a full-scale experiment was simulated[7]. As shown in Fig. 3, four rooms were involved with the experiment. Fire was put in room-3 where 4 tons of wood stacks were ignited. Part of the exterior windows was fitted with steel plates to reduce opening area in order to create ventilation control condition. The other part of window is fitted with ordinary float glass, which was broken down 10 minutes after ignition.

Room-2 (corridor) is connected to the fire room. The door to fire room was left open during experiments. At the end of the corridor, a water closet is located, where a small ventilation opening is equipped on an exterior wall. Room-4 was specially created for the purpose of observation during the experiment, separated from fire room by a concrete block wall and steel shutter.

Other walls and floors were made of concrete blocks. Ceiling is made of suspended lightweight board.

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The size of opening is listed in Table 1.

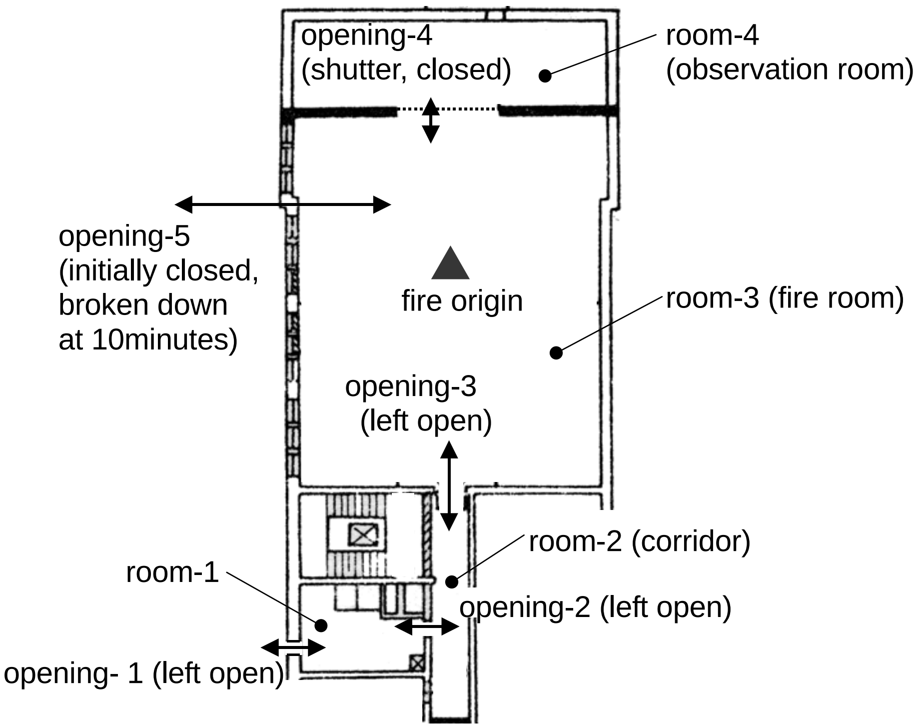

FIGURE 3. Arrangement of full-scale fire experiment

TABLE 1. Geometry of opening

Opening no.	Connecting rooms		Width [m]	Height		Remarks
				Sill [m]	Soffit [m]	-
1	WC	outside	1.6	1.5	2.2	-
2	corridor	WC	0.8	0	2.1	-
3	fire room	corridor	1.8	0	2.1	-
4	observation room	fire room	4.2	2.4	0	Only leakage area was considered.
5	fire room	outside	1.9	2.2	0.8	Initially closed, broken at 10 minutes

Calculation Results

The calculated results are shown in Fig. 4. Fire room temperature is increased for the first several minutes. Then the increase is stopped, and the temperature decreases because of the burning is quenched. After 10 minutes when the window glass is broken, burning is intensified and increases temperature. This tendency is common in both experiment and calculation results.

Quantitatively, the calculated results are fairly close to experimental data. In case of fire room, the calculated temperature is a bit higher than the average of experimental values excluding the measurement close to fire source denoted by open circle. In case of other rooms, the temperature history is reproduced fairly well.

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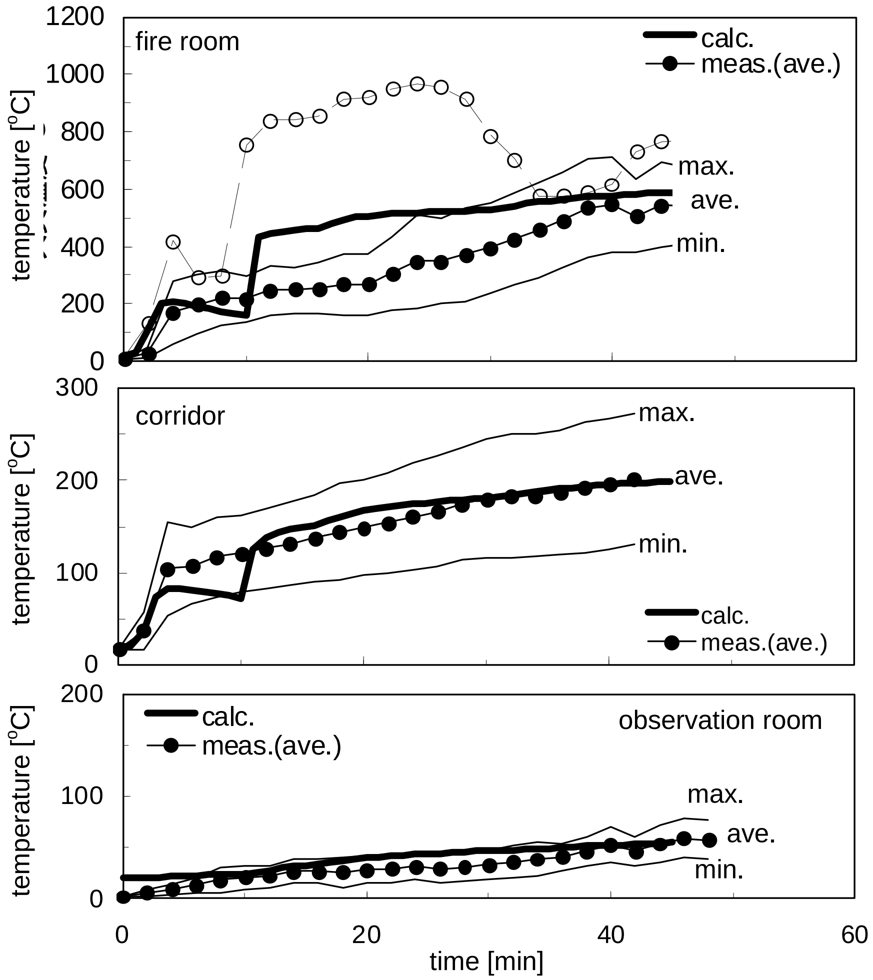

FIGURE 4. Comparison with experimental data

SIMULATION OF MULTIROOM SPREADING FIRE TEMPERATURE

Calculation Examples for Simple Geometry Building

In order to examine the effect of multi-room fire spread scenario, parametric study was carried out for a building with simple geometry. The building geometry is shown in Fig. 5. Office use is considered to have 560MJ/m^2 of fuel load density per floor area. Two rooms are the same size, 10 m (width) x 10 m (depth) x 4 m (height). Each room has one opening connecting outside. Another opening connects the two rooms. Fire starts in room 1. Heat release rate is given by:

$$Q = \alpha t^2 \quad [\mathrm{kW}], \qquad [13]$$

$$\alpha = (0.26 \times 10^{-6}) q_l^{5/3} = 0.100 \quad [\mathrm{kW/s^2}] \qquad [14]$$

during the initial stage of fire. If the heat release rate calculated by formula [13] exceeds the value for fully developed fire, formula [7] is adopted.

As to the fire spread conditions, uncertain factors are to be considered for sophisticated analysis. However, in this calculation, fire spread would take place when the temperature in room 2 is increased by 140^{o}C above initial temperature. After fire spread, same method was applied to room 2 to calculate heat release rate.

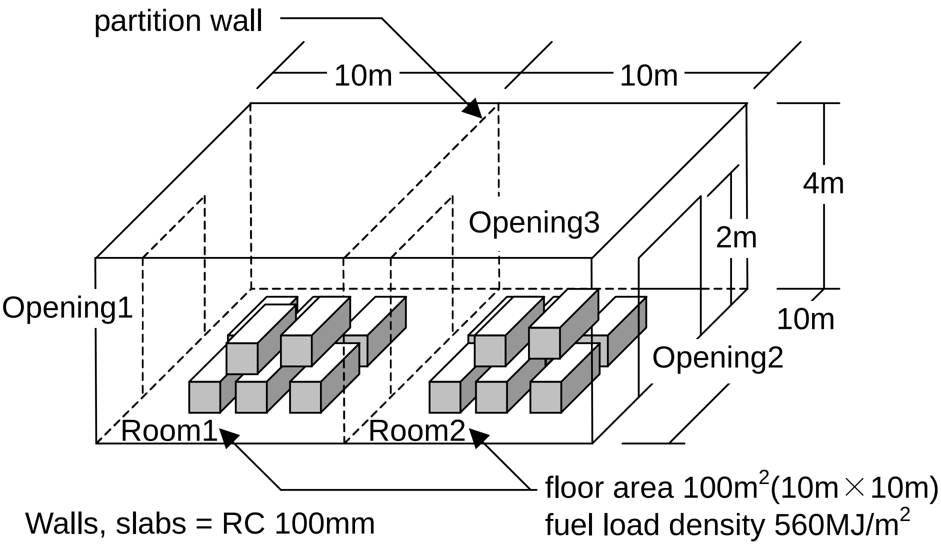

FIGURE 5. Two-rooms configuration

Calculation results are shown in Fig. 6. As shown in upper graph, only room 1 is burning up to 4 minutes. Maximum heat release rate is achieved during this period because burning in room 1 is supported by the air entering from opening 1 as well as from opening 2 via opening 3. After fire spread to room 2, heat release rate in room 1 is decreased because the air from opening 2 cannot be consumed in room 1. The heat release rate in each room agrees exactly with ventilation limit

$$Q = 1{,}500 A\sqrt{H} = 1{,}500 \times (5 \times 2)\sqrt{2} = 21{,}200\text{kW} \qquad [15]$$

because the building geometry is symmetric along partition wall.

The temperature history is shown in lower part of Fig. 6. The temperature in both rooms is quite similar. The distinct difference is the time gap for fire spread. However, the maximum temperature in room 2 is slightly higher than that of room 1. This is because of the preheating effect. During the first four minutes, heat from room 1 flows into room 2. Then the wall surfaces are heated in prior to fire spread to room 2.

In another scenario, size of opening was changed. Opening 2 was closed, while the size of opening 1 was doubled. The results are shown in Fig. 7. As shown in upper graph, maximum heat release rate is less than the ventilation limit (42.4 MW). Thus the fire is fuel controlled. On the other hand, heat release rate in room 2 is very small up to 65 minutes. After the combustion in room 1 is finished, sufficient air is supplied to room 2 through openings 1 and 3.

As shown in the lower graph, fire temperature in room 1 is mild. Maximum temperature is about 600^{o}C. On the other hand, temperature in room 2 is quite severe. During the first half, temperature is about 400^{o}C. In this period, room enclosure is pre-heated. Thus the temperature rise during the last half is significant. As is demonstrated, burning in one room may affect the severity of fire in other rooms.

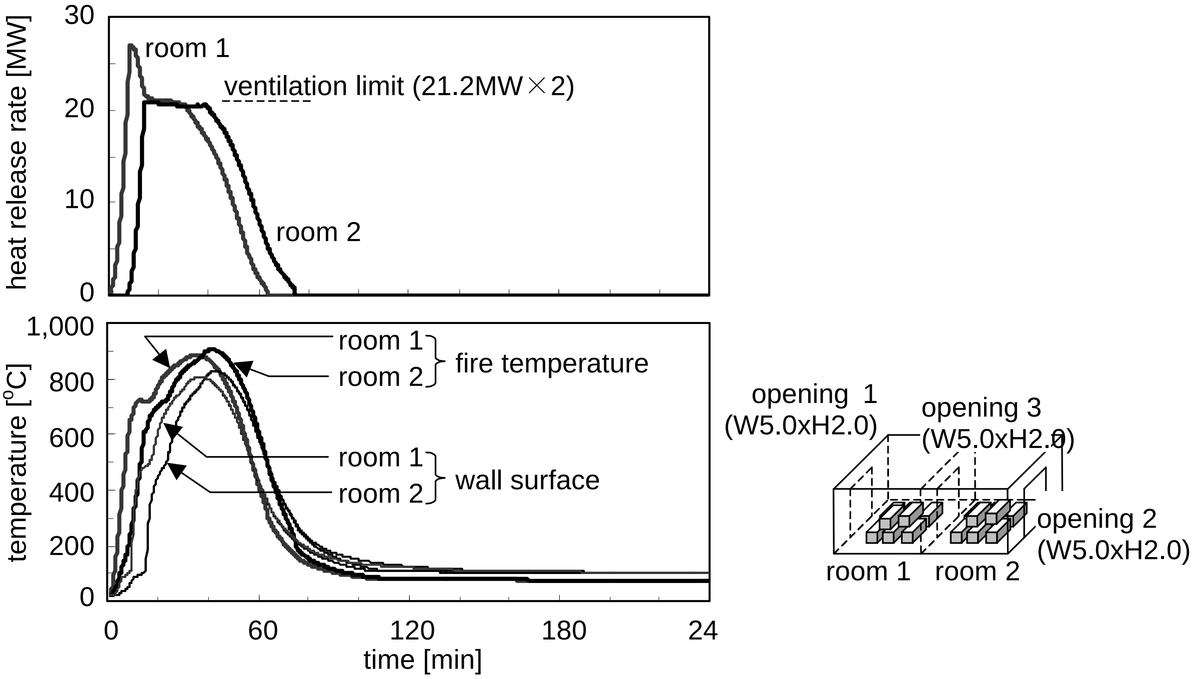

FIGURE 6. Calculation results of two-rooms configuration (opening 1-3: Width 5.0 m × Height 2.0 m)

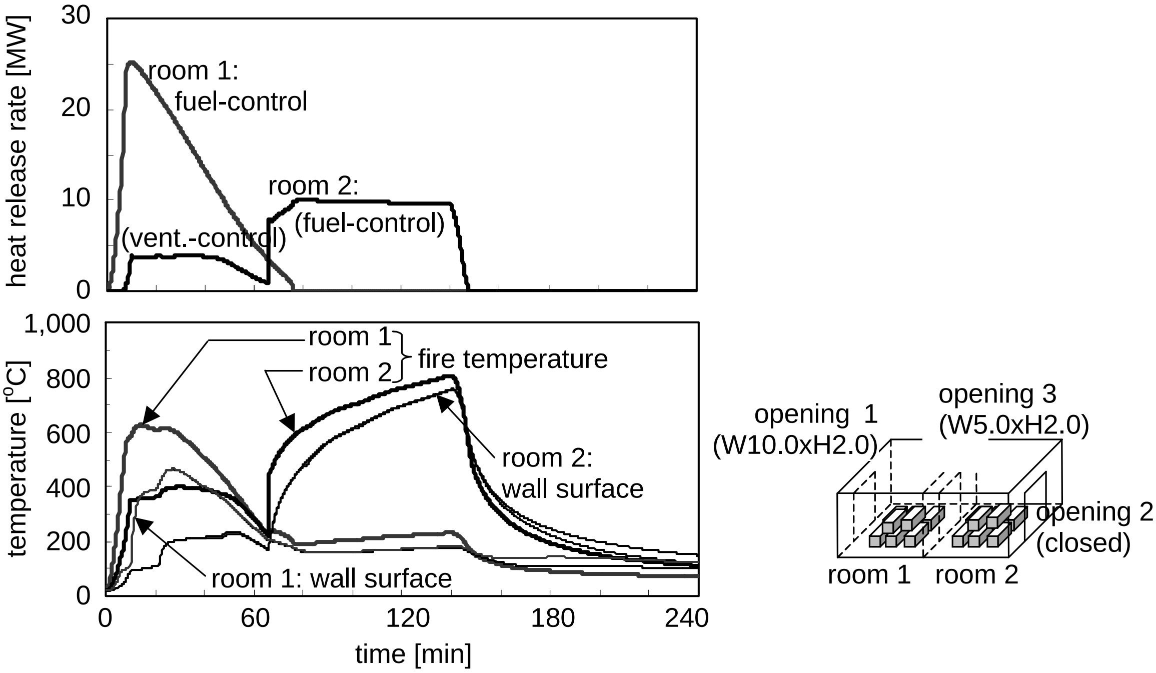

FIGURE 7. Calculation results of two-rooms configuration (opening 1,3: Width 10.0 m × Height 2.0 m, opening 2: closed)

Calculation Examples for Realistic Geometry Building

1) Building Specifications

To simulate the fire severity in realistic building, calculation was carried out for the building shown in Fig. 8. Configuration of rooms is shown in Table 2. Fire load density is 560 MJ/m^2 for offices, 160 MJ/m^2 for meeting rooms, and 80 MJ/m^2 for corridor. Interior linings are semi-noncombustible grade

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materials. Geometry of openings is shown in Table 3. It is assumed that all the doors except for staircases and elevators were opened. All the partition walls keep their initial shape throughout fire.

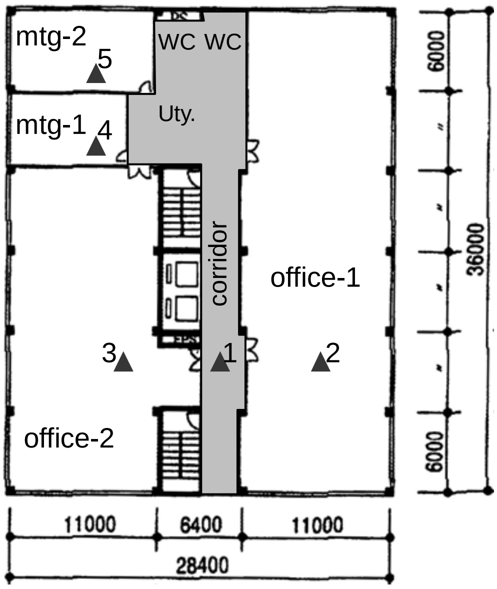

FIGURE 8. Plan of building

TABLE 2. Room configuration

room name	floor area [m^2]	area of opening to outdoor air [m^2]	Fire load [MJ]
Corridor	163	0.8	10,440
office-1	396	13.5	19,744
office-2	282	8	14,106
meeting room -1	54	1.4	4,026
meeting room -2	66	4	4,901

TABLE 3. Geometry of inter-room opening

Position	opening area [m^2]
(office-1) – (corridor)	6.4
(office-2) – (corridor)	6.4
(meeting room -1) – (corridor)	1.6
(meeting room -2) – (corridor)	1.6

2) Fire spread scenario

In realistic buildings, there are many different fire scenarios. However, in this paper, five fires starting at one of the rooms are considered. Triangle symbols in Fig. 8 denote the position of fire initiation for fires 1 to 5. Similar to previous calculations, all the fires spread to adjacent rooms, if the temperature in adjacent rooms is increased by 140^{o}C above initial temperature. For comparison, fires terminated in each room of origin are also calculated.

3) Calculation results

Calculated temperature histories for all the fires are shown in Fig. 9. In case of fire starting at corridor, burning in corridor is finished at 30 minutes. However, at this stage, fire has already spread to office-1 and office 2. These two rooms are in the stage of fully developed fire. Thus the corridor temperature is kept at about 400^{o}C. At 120 minutes, burning in offices is almost finished. Then the

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corridor temperature decays along with office temperature. Similar tendencies are shown for fires starting in another room. Corridor temperatures are kept high until the burning in offices is finished. (post-heating effect) As is exemplified, fire severity of a room is affected by the burning of adjacent rooms. When the single compartment fire models for fire resistance design are applied, burning of adjacent rooms shall have to be considered properly.

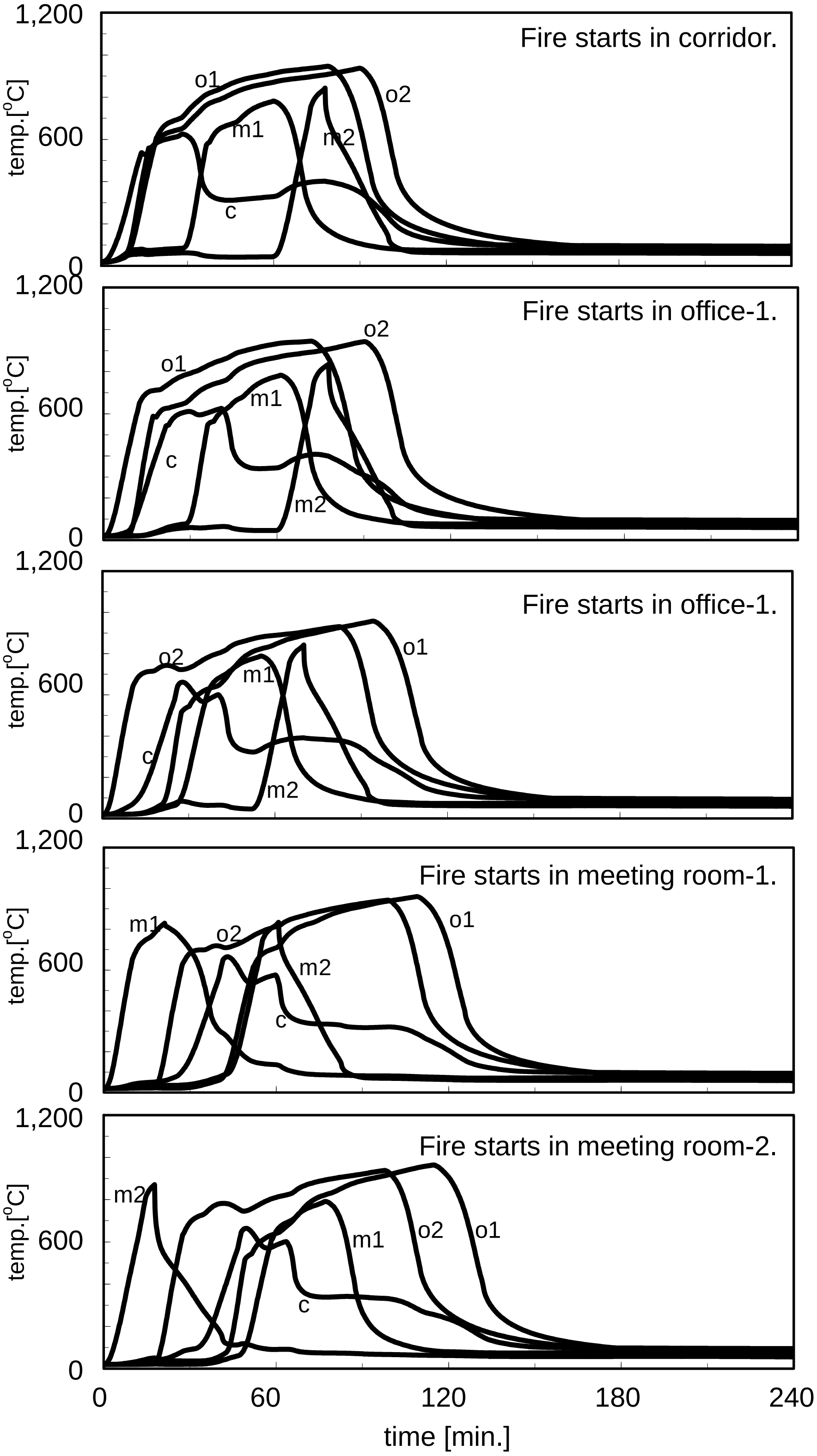

FIGURE 9. Calculation results of spreading fires in realistic building (c = corridor, o1 = office-1, o2 = office-2, m1 = meeting room-1, m2 = meeting room-2)

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In summary of calculation results, maximum temperature and equivalent fire duration were extracted and summarized in Fig. 10. The effect of initial fire room is not so significant in this series of calculation. The difference is less than 10% both in maximum temperatures and equivalent fire duration.

In the same graph, calculated results of fires terminated only in the room of origin are shown by black bars. In the maximum temperatures, the error is not so significant. On the other hand, considerable differences are found in equivalent fire duration. Especially in case of corridor, equivalent fire duration is underestimated to half of spreading fires. This is because of the effect of burning in adjacent rooms as was already pointed out.

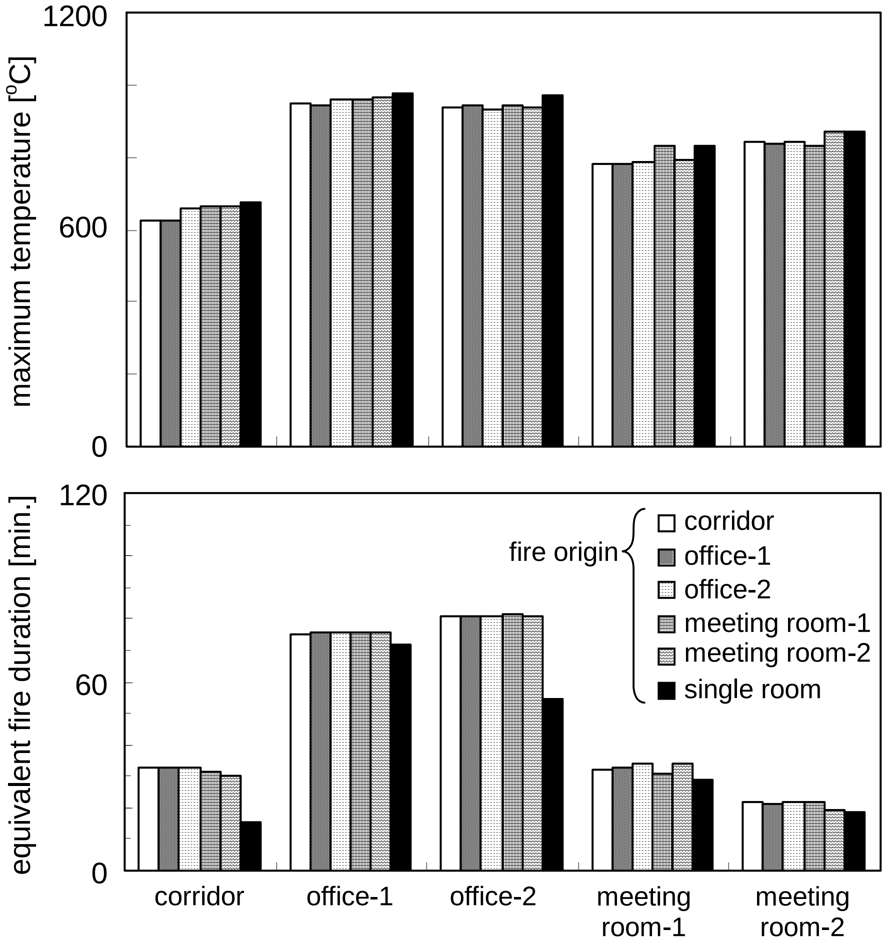

FIGURE 10. Variation of maximum temperature and equivalent fire duration depending on the room of fire origin

CONCLUSIONS AND FUTURE DEVELOPMENT

In this paper, a model was proposed to calculate the severity of fully developed fires in multi room spreading scenario. The model consists of heat balance of rooms, network ventilation for mass flow rates through openings and heat conduction in enclosure walls. The model was compared with a full scale experiment carried out so far. Even though the verification is not perfect, the model could calculate the corridor temperature properly.

By using the model, multiple fire-spreading scenarios were analyzed. By the calculation of simple two-room building it was found that,

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1) If the openings to outside are evenly distributed, the fire behavior is not affected by the burning of adjacent rooms.
2) On the contrary, if the opening is unevenly distributed, fire severity of a room is affected by the burning in adjacent rooms.

Fire severity was calculated for multiple fire scenarios. As a result, the following feature was analyzed;

3) The effect of selection of fire origin is relatively small.
4) The effects of burning in adjacent rooms are not negligible.

As a future development the author would like to mention that;

5) For the use in practical fire resistance design, use of single compartment fire model is not adequate.
6) A simple and rational method to account for the effect of burning in adjacent rooms is desired.

REFERENCES

1. Ministry of Land, Infrastructure and Transportation, Notification 1433, 2000.
2. Sekine, T. and Kawagoe, K., “Estimation of Fire Temperature Rise Curves in Concrete Buildings”, Transaction of Architectural Institute of Japan, No. 85, pp. 38-43, 1963, No. 86, pp. 40-45,1963, No. 140, pp. 63-70, 1977.
3. McCaffrey, B.J., Quintiere, J.G. and Harkleroad, M.F., “Estimating Room Temperatures and the Likelihood of Flashover Using Fire Test Data Correlations”, Fire Technology, 17:2, 98-119, 1981.
4. Matsuyama, K., Fujita, T., Kaneko, H., Ohmiya, Y., Tanaka, T. and Wakamatsu, T., “A Simple Predictive Method for Room Fire Behavior”, Journal of Structural and Construction Engineering, 469, 159-164, Architectural Institute of Japan, 1995.
5. Ohmiya, Y., Sato, M. Tanaka, T. and Wakamatsu, T., “Incident Heat Flux to Fuel and Burning Rate in Ventilation Controlled Fires”, Journal of Structural and Construction Engineering, 472, 169-176, Architectural Institute of Japan, 1995.
6. Matsushita T., SMKFLW-Single Layer Smoke Transport Model, Building Center of Japan, 1990.
7. Tokyo Fire Department, Tokyo Kaijo Building Fire Experiment Report, 1967.