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Experimental and theoretical investigation of an adjacent wall on the occurrence of flashover

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Abstract:

In urban or informal settlement fires, the influence of an adjacent inert wall/dwelling on the fire development of the burning dwelling is still unknown. Therefore, 41 compartment fire experiments were conducted with a ¼ scale ISO 9705 room, with a calcium silicate board acting as the inert wall, was placed in front of the burning compartment's opening with distances between 50 to 1250 mm. Parameters such as the mass loss rate of fuel, temperatures of gas and walls, heat flux imposed on the floor, and time to flashover were analyzed. From the experiments, it was found that the flashover occurrence times differed significantly with or without the adjacent dwelling, and the time to flashover increased gradually with increasing distance from 50 to 300 mm between the burning compartment and adjacent wall, but decreased with distance from 300 to 600 mm. The heat flux to the floor was calculated and correlated well with measured values, confirming that the observed experimental phenomenon was primarily caused by the interaction between the combustion efficiency of fuel and the different heat losses from hot gas flowing out from the opening depending on the adjacent wall location. Moreover, a modified MQH method and a theoretical model were proposed to predict the gas temperature and time to flashover, respectively.

Keywords: distance between dwellings; flashover occurrence; compartment fire

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Nomenclature

A Area [m^2]

A_T Area of compartment surface without floor [m^2]

A_v Area of fuel [m^2]

c Specific heat capacity at constant pressure of ceiling/wall material [kJ/(kg·K)]

c_p Specific heat capacity at a constant pressure of air [kJ/(kg·K)]

c_{pg} Fuel specific heat [kJ/(kg·K)]

D Distance of dwellings [m]

$f(D)$ Correction function indicating the degree of ventilation limiting

F_c Geometric configuration factor between the calcium silicate board and the floor

F_u Geometric configuration factor between the thermal discontinuity plane and the floor

g Gravitational constant 9.8 [m/s^2]

H Height of the compartment [m]

H_d Height of thermal discontinuity [m]

h_k Effective heat transfer coefficient [W/(m^2·K)]

h_{fg} Enthalpy of vaporization [kJ/kg]

Δh_c Heat combustion per unit mass of fuel [kJ/kg]

k Thermal conductivity of ceiling/wall material [kW/(m·K)]

k_c Rate coefficient in Arrhenius form

K_g Upper layer absorption coefficient due to H_2O and CO_2

K_{soot} Upper layer absorption coefficient due to soot, 1.9 m^{-1}

L Length of the pool [m]

$\dot{m}_a$ Air flow rate [kg/s]

$\dot{m}_b$ Burning rate [kg/s]

$\dot{m}_g$ Hot gas flow rate without the calcium silicate board in front of the opening [kg/s]

$\dot{m}_{g'}$ Hot gas flow rate with the calcium silicate board in front of the opening [kg/s]

$\dot{m}_v$ Vaporization rate [kg/s]

n Combustion efficiency

$\dot{q}_F''$ Heat flux to the floor [kW/m^2]

$\dot{Q}$ Heat release rate [kW]

r Mass air to fuel ratio

t_p Thermal penetration time

T Temperature

T_∞ Environment temperature [K]

t_{FO} Time to flashover [s]

v Stoichiometric mass ratio

W_0 Width of the opening [m]

$Y_{O_{2,s}}$ Oxygen mass fraction at the fuel surface

α Fire development coefficient [kW/s^2]

ρ Density of compartment wall/ceilings [kg/m^3]

σ Stefan-Boltzmann constant 5.67×10^{-8} [W/(m^2·K^4)]

δ Thickness of ceiling/wall [m]

ϵ Emissivity

Subscripts

a air

c calcium silicate board

f flame

F floor

g gas

o opening

s fuel surface

w wall/ceilings

1. Introduction

Flashover refers to the transition of a compartment fire from the fire growth period to the fully developed stage[1], and plays a key role for compartment fire development or fire spread between dwellings. Thus, the study of the time to flashover of the fire, which is directly relevant to life safety within the building, is significant. Over the past 40 years, experimental studies provided empirical correlations for various aspects, including burning characteristics for different combustibles, the effect of fire locations within a compartment, ventilation, ceiling height, and compartment surface materials, to flashover occurrence[2-6]. Moreover, to reduce experimental costs, artificial intelligence (AI) has recently been applied to predict flashover time with consideration of the internal structural layout and size of the compartment, the type and location of the fuel, and the position and size of the ventilation opening[7-9].

The prior research primarily focused on the factors within the burning compartment that influenced flashover occurrence, however, it is anticipated that flashover will occur differently if there are existing adjacent dwellings close enough to the burning compartment, conditions that can be found in dense urban and informal settlements. Thus, if one was to assume that the time to flashover is not affected by surrounding dwellings/walls, any building-to-building fire spread model may be inaccurate.

Some prior work has investigated the influence of an adjacent wall on the ejected flames. For example, Cheng et al.[10] conducted full-scale experiments to investigate the impact of different window sizes, separation distances between fire compartment and a target wall, with different fuels measuring the radiative heat fluxes on the target wall. Numerical simulations were performed to investigate the vertical temperature profile of the thermal ejected plume affected an adjacent side wall[11]. Wang et al.[12] proposed modified non-dimensional performance models to predict the effects of adjacent space on spilling fire characteristic through numerical investigation and theoretical analysis. However, little is known about what, if any, impact of an external wall/dwelling opposite the opening will have on the flashover occurrence in the burning compartment. This is normally ignored in urban fire spread models, however it is a key trigger of urban/informal settlement fire spread[13,14].

According to full-scale experiments of single and double informal dwellings conducted in Underwriters Laboratories (UL) by the authors[15,16], the time of flashover occurrence of the first-ignited dwelling in double dwelling experiment was considerably longer than that in the single dwelling experiment, namely adding an adjacent dwelling delayed the flashover, which was unexpected. However, the mechanism of the effect of distance between dwellings on compartment fire flashover has not been well revealed to date[16]. This work aims to deepen the understanding of the influence of the distance between dwellings on the time to flashover and attempts to perform quantitative analysis to reveal its mechanism.

In this work, experiments were conducted using a ¼ ISO 9705 compartment made from vermiculite board, and used an n-heptane pool fire as the fire source. Calcium silicate board acted as an adjacent dwelling wall (without windows) placed in front of the compartment opening. Important parameters were measured, including gas layer and wall surface temperature, heat release rates (HRRs), and radiation heat flux to the floor. Based on the conservation of energy and mass theory, the internal energy of the compartment was analyzed, and a theoretical prediction method for the time to flashover was further developed. This study aims to understand flashover mechanisms in a burning compartment with an adjacent dwelling/wall and provide a basis and reference for fire spread model development in urban and informal settlement fires.

2. Experimental configuration

2.1 Experimental setup

A compartment (burning dwelling) with an opening of 500 mm (height) × 200 mm (width) and a calcium silicate board (the adjacent dwelling wall) with the thickness of 12 mm placed in front of the opening were employed to investigate the influence of the distance between dwellings on flashover. The internal dimension of the compartment was identical to the quarter size of the ISO 9705 room, namely, 900 mm (length) × 600 mm (width) × 600 mm (height). This provided a ventilation factor of 0.07 $m^{5/2}$ for the experiments. The material used for the compartment ceiling and walls was 25 mm thick vermiculite board (composed of SiO_2, Al_2O_3, K_2O, TiO_2, Na_2O, MgO, Fe_2O_3 and H_2O) with a density of 807 kg/m^3, specific heat capacity of 0.94 kJ/kg·K, and thermal conductivity of 0.147 W/m·K; the floor was made of a 10 mm thick steel plate. To ensure airtightness, the connection areas between the ceiling/walls were sealed with high-temperature cement and aluminum foil tape. N-Heptane (density 686 kg/m^3, purity 99.5%) was set as the fuel in the square fuel pan (side length of 150 mm and height of 30 mm) with an initial fuel height of 30 mm at the center of the compartment floor.

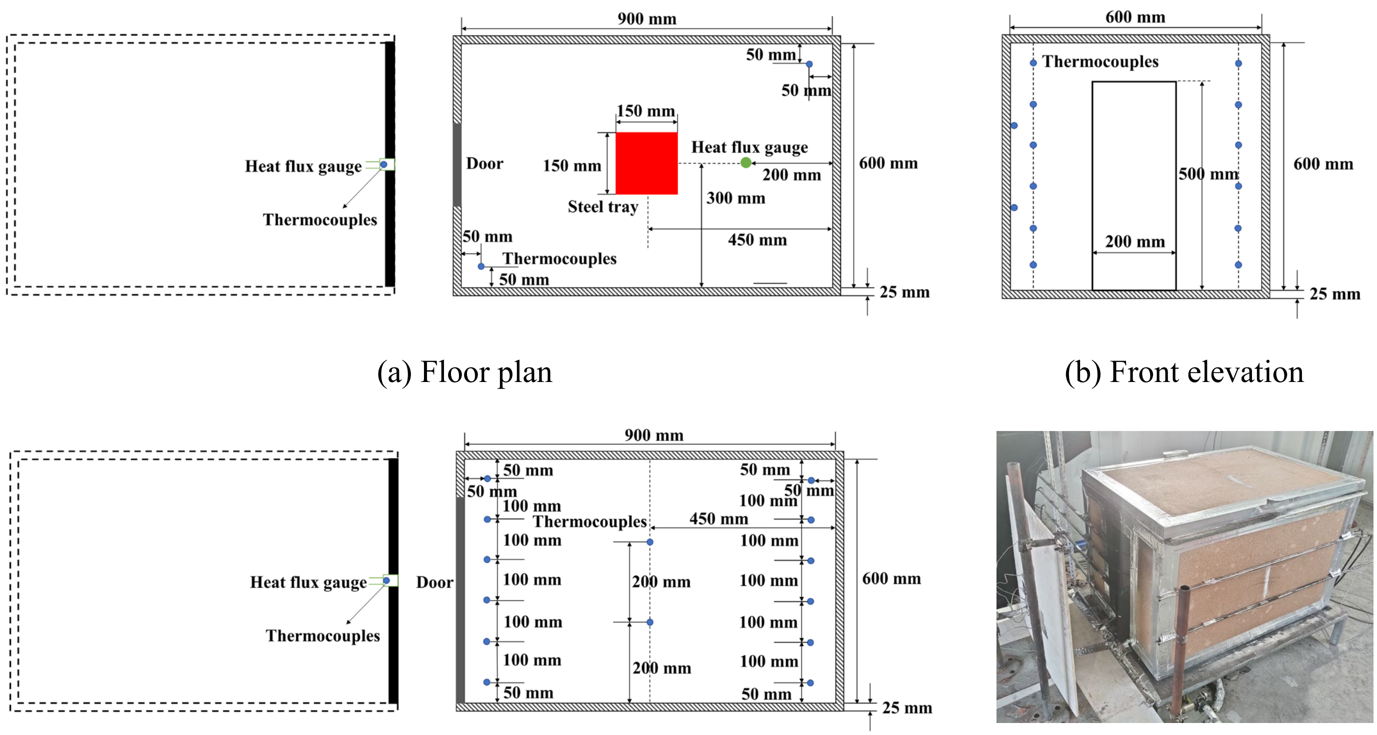
A calcium silicate board with a 600 mm × 600 mm dimension acted as the inert wall (without window) of the adjacent dwelling, parallel to the compartment wall with an opening. Based on the scale modelling, the selected distances are one-quarter of the distances between dwellings specified in the building codes. Moreover, it was found that the experimental phenomenon was similar when the distance exceeded 1250 mm from the preliminary experiments conducted by the authors before the formal experiments. According to the regulations on the dwelling distance of temporary settlements for disaster, workshops and warehouses[17,18], 250 mm (in the disaster area, the distance between the temporary building and its adjacent wall without door is required to be not less than 1 m), 500 mm (in the disaster areas, the distance between the temporary building and its adjacent wall with a door is required to be not less than 2 m), 700 mm, 800 mm (in the disaster areas, the distance between temporary buildings (no cooking inside) is required to be not less than 3 m), 900 mm (the minimum fire separation between civil buildings with lower floors with fire rating of Class II is 3.5 m), 1000 mm (the minimum fire separation between factory buildings is 4 m) and 1250 mm (the minimum distance between the factory enclosing wall and the factory buildings is 5 m) were selected as the different distances between the burning compartment and calcium silicate board, and to further explore the experimental phenomenon through experiments, distances of 50 mm, 100 mm, 150 mm, 200 mm, 300 mm, 400 mm, 600 mm were also selected. In addition, the experiment of the compartment with no board in front of the opening was performed as a benchmark for comparison with other experimental conditions. Under every condition, tests were repeated three times except that the distance was more than 900 mm (because of the high repeatability of the experimental results), thus, a total of 41 experiments were conducted as shown in Table 1 for details.

Table 1. Experimental cases.

Distance (mm)	50	100	150	200	250	300	400	500
Experimental repetition times	3	3	3	3	3	3	3	3
Distance (mm)	600	700	800	900	1000	1250	None	Total number of experiments
Experimental repetition times	3	3	3	2	2	2	2	41

2.2 Measurements

As illustrated in Fig. 1, HRR, gas-phase temperatures, wall surface temperatures, and radiation heat flux to the floor were measured. A mass loss scale with 0.1 g precision was placed under the fuel pan made of 304 stainless steels (thickness of 2.5 mm) with an inner side length of 150 mm and a depth of 30 mm, placed in the middle of the compartment to measure the mass of the fuel and estimate the HRR. Two thermocouple trees were placed in the front and rear corners of the compartment to measure the gas-phase temperature, which were next to the side walls at a distance of 50 mm; each thermocouple included 6 Type-K sheathed thermocouples with a tip diameter of 1.0 mm at heights of 50 mm, 150 mm, 250 mm, 350 mm, 450 mm, and 550 mm from the bottom of the compartment. The internal surface temperatures of the wall were measured by two sheathed Type-K thermocouples with a thin nickel-plated copper sheet on the probe attached at the centerline of the sidewall with high-temperature cement and aluminium foil tape at heights of 200 mm and 400 mm from the floor. To measure the radiation heat flux imposed on the floor, heat flux gauges (Schmidt-Boelter type) with a maximum range of 50 kW/m^2 were placed at a distance of 200 mm to the back wall. Outside the compartment, two cameras (the logging rate of the data was 25 frames per second) were placed directly in front and on the side of the opening at distances of 1800 mm and 2500 mm, respectively, from the center of the opening to record the spilling fire.



(a) Floor plan (b) Front elevation

(c) Cross section (d) Experimental compartment

Fig. 1. Experimental configuration.

3. Experimental results and analysis

Flashover is a phenomenon whereby a room fire undergoes a rapid increase in size and intensity[19], which can result from a thermal instability caused by the energy generation rate increasing faster with temperature than the rate of aggregated energy losses[20,21]. According to the study on the nature of flashover from Babrauskas et al., at least two types of fundamental definitions for flashover are possible: the occurrence of criticality in a thermal balance sense (the heat generation rate, at a certain point, exceeds the ability of the system to lose heat at the boundaries), or a fluid-mechanical filling process (the room goes from being mostly filled with cold air, to being mostly filled with hot fire gases)[20]. Moreover, the criteria of flashover are also often given as the temperature criterion, heat flux criterion, ignition of floor targets, or flames out the doorway[22], and although these criteria may be the consequence caused by flashover[20], they are still widely used to judge the onset of flashover in order to facilitate the analysis of experimental data[16,23,24]. In this work, the judgment of flashover was based on the fact that the flame in the compartment was ejected from the opening (and the time interval between ignition and flame out the opening was recorded as the time to flashover), but this basis cannot be quantitatively analyzed in a mathematical form. Therefore, the radiation heat flux to the floor corresponding to the beginning of the flame out the opening was selected to quantitatively analyze the flashover because when the flame was ejected from the opening, the measured radiation heat fluxes to the floor were consistent, approximately 10 kW/m^2 with a standard deviation of 1.09 kW/m^2.

This paper aims to reveal the influence of the distance between dwellings on the time to flashover of compartment fires. Therefore, the experimental phenomenon was first described, and a detailed analysis of the phenomenon based on the theoretical models was then conducted in this section.

3.1 Experimental results

As shown in Fig. 2, when the distance between the calcium silicate board and the compartment opening was 50 to 300 mm, the time to the flashover gradually increased as the distance increased. When the distance between the calcium silicate board and the compartment opening was 300 to 600 mm, the time to flashover gradually decreased with increasing distance. However, when the distance was larger than 600 mm, the time to flashover tended to be stable; that is, the time required was the same as without the calcium silicate board in front of the opening. In addition, compared with the time to flashover without a calcium silicate board, when the distance was 50 to 150 mm, the time to flashover was smaller than that, and when the distance was 200 to 600 mm, the time to flashover was greater.

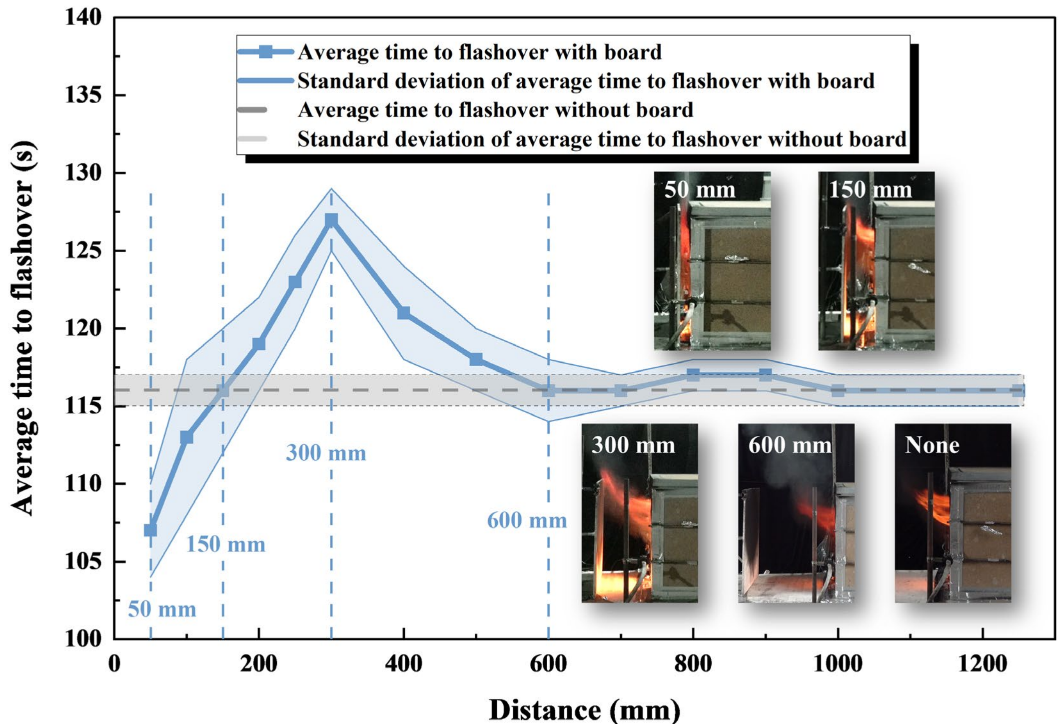


Fig. 2. Time to flashover with different experimental conditions (photographs show the onset of continuous spilling fire at different distances).

3.2 Theoretical models

Three theoretical models have been developed in the paper based on a two-zone model (an upper volume with uniformly distributed hot gas and a lower volume of ambient temperature)[25] and the conservation of energy and mass principles. These three models include radiation model, temperature model, and time to flashover prediction model: the first theoretical model was to calculate the variation of radiation heat flux on the floor level based on experimental temperature data; the second theoretical model was a modified MQH model developed to replace the measured temperature in the first model; and the third theoretical model was developed based on the first and second models to predict the time to flashover. In the paper, because the basis of the theoretical model has been derived previously[1,26-28], detailed derivation will not be provided; however, a description of these equations and their significance will be listed. Fundamentally, these equations can be derived by applying the conservation laws to different spatial regions (or control volumes) with approximately uniform characteristics.

3.2.1 Radiation theoretical model

In the compartment fire experiments shown in Fig. 3, according to the energy conservation law, the energy released by the fuel is primarily used to heat the gas inside the compartment, the compartment surface, and the air entering the compartment from the opening and lost from the opening[1]. Likewise, the energy stored in the hot gas layer, compartment walls and ceiling, fire plume, and calcium silicate board will all accelerate the development of the fire through heat feedback[29]. Thus, based on the two-zone model and energy balance, the radiation to the floor of the compartment developed according to the experimental conditions of the experiments, $\dot{q}_F''$, can be expressed by

$$\dot{q}_F'' = \underbrace{\sigma F_u\left[\epsilon_g T_g^4 + (1-\epsilon_g)T_w^4 - T_a^4\right]}_{\boxed{\text{1st}}} + \underbrace{\epsilon_f \sigma T_f^4 \frac{2H_f\sqrt{\pi A_v}}{A_F}}_{\boxed{\text{2nd}}} + \underbrace{\sigma F_c \epsilon_w T_c^4}_{\boxed{\text{3rd}}} \tag{1}$$

where the first term represents the radiation heat flux from the upper hot layer and wall/ceilings, the second term represents the radiation heat flux from the flame plume, and the third term represents the radiation heat flux from the calcium silicate board. The emissivity of the hot upper layer, ϵ_g, is represented as a function of the soot concentration and the H_2O and CO_2 composition of the layer, which can be calculated by[29]

$$\epsilon_g = 1 - \exp\left[-(K_g + K_{soot})(H - H_d)\right] \tag{2}$$

K_g and K_{soot} are the upper layer absorption coefficients due to combustion products (H_2O and CO_2) and soot; $K_{soot} = 1.9\ m^{-1}$[29] and considering incomplete combustion, $\dot{m}_b$ was replaced with $\dot{m}_v$ in the calculation of the absorption coefficient of the hot gas in the upper layer suggested by Quintiere et al.[29], thus, K_g can be given by

$$K_g = 0.3 + \frac{4.64\dot{m}_v}{\dot{m}_a + 0.6\dot{m}_v} \tag{3}$$

H and H_d are the height of the compartment and thermal discontinuity, $H = 0.6\ m$; according to the Bernoulli equation, the height of the thermal discontinuity through the derivation of the authors, H_d, can be expressed as

$$H_d = \frac{H_0}{1+\left(\frac{1+\dot{m}_v/\dot{m}_a}{\sqrt{\rho_g/\rho_a}}\right)^{2/3}} = \frac{H_0}{1+\left(\frac{1+\dot{m}_v/\dot{m}_a}{\sqrt{T_a/T_g}}\right)^{2/3}} \tag{4}$$

where H_0 is the height of the opening, ρ_a and ρ_g are the densities of air and hot gas, respectively, and T_a and T_g are the temperatures of air and hot gas, respectively. In addition, due to the existence of calcium silicate board (as a wall limiting the free air flow), there is insufficient air for complete combustion of the fuel. The combustion efficiency of fuel, n, may differ when the distance between the calcium silicate board and the compartment opening changes: n increased from 0.35 to 0.75 with distance because space for air flow increases with distance. Therefore, based on the above analysis and the introduction of the stoichiometric air-fuel ratio[27], r, a relationship can be obtained as follows:

$$n\dot{m}_v = \dot{m}_b = \dot{m}_a/r \tag{5}$$

$\dot{m}_a$, $\dot{m}_b$ and $\dot{m}_v$ are the air flow rate, burning rate and vaporization rate of the fuel, respectively. r is the mass air to fuel ratio of n-heptane.

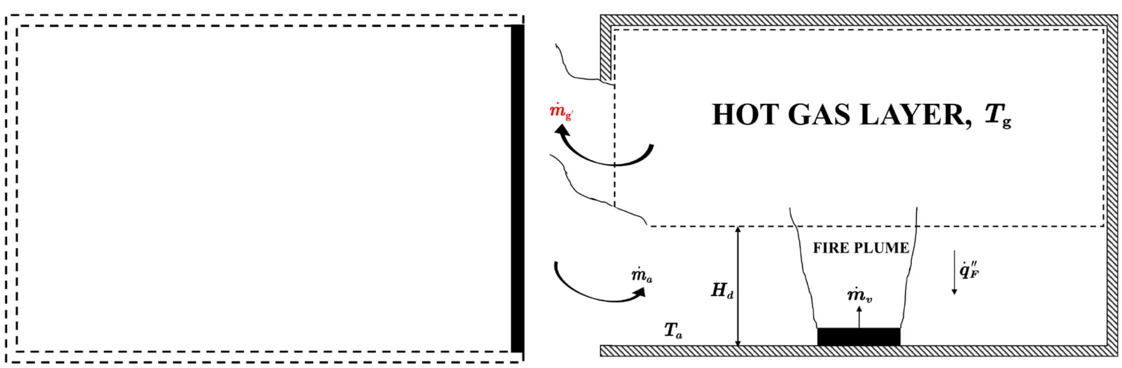
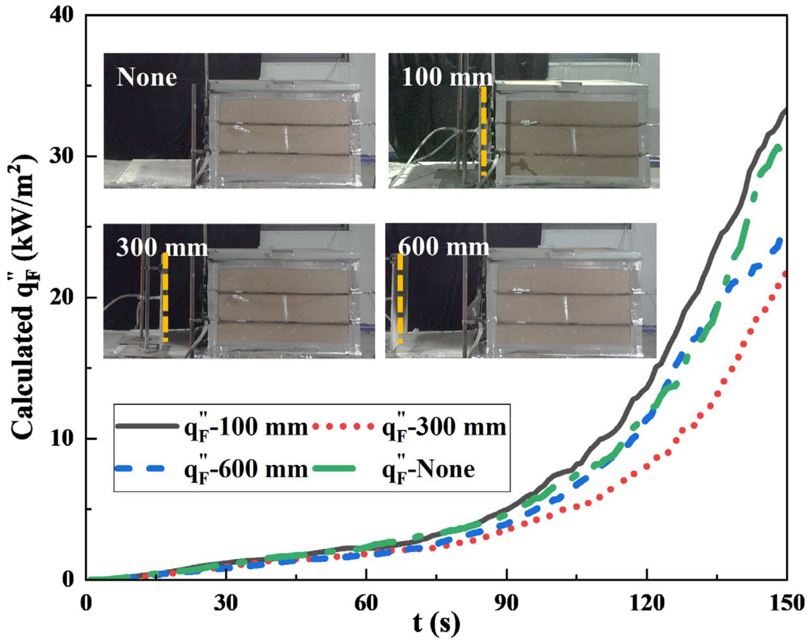
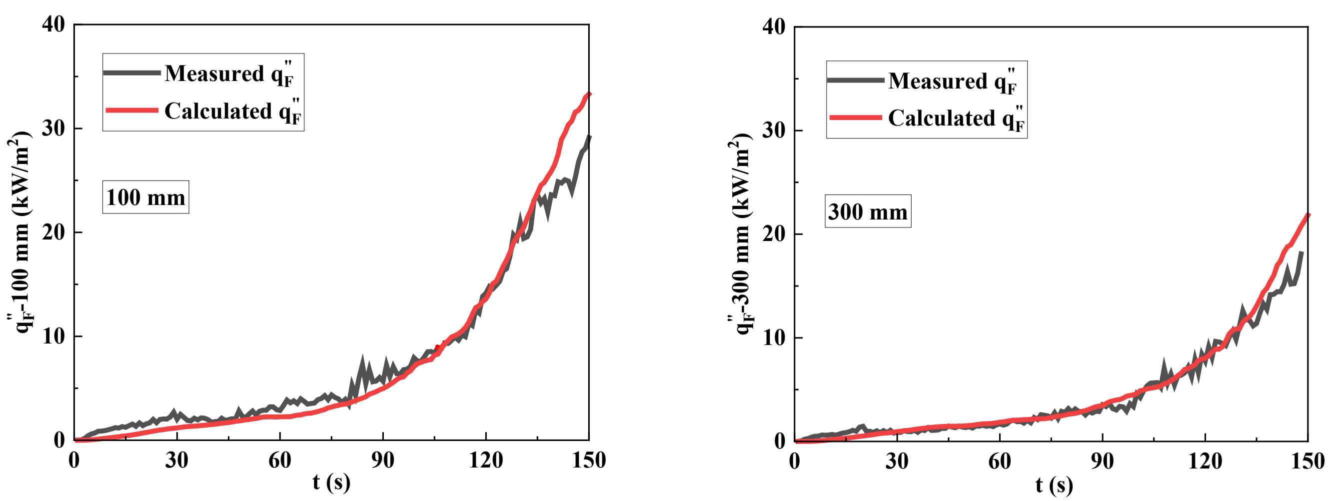


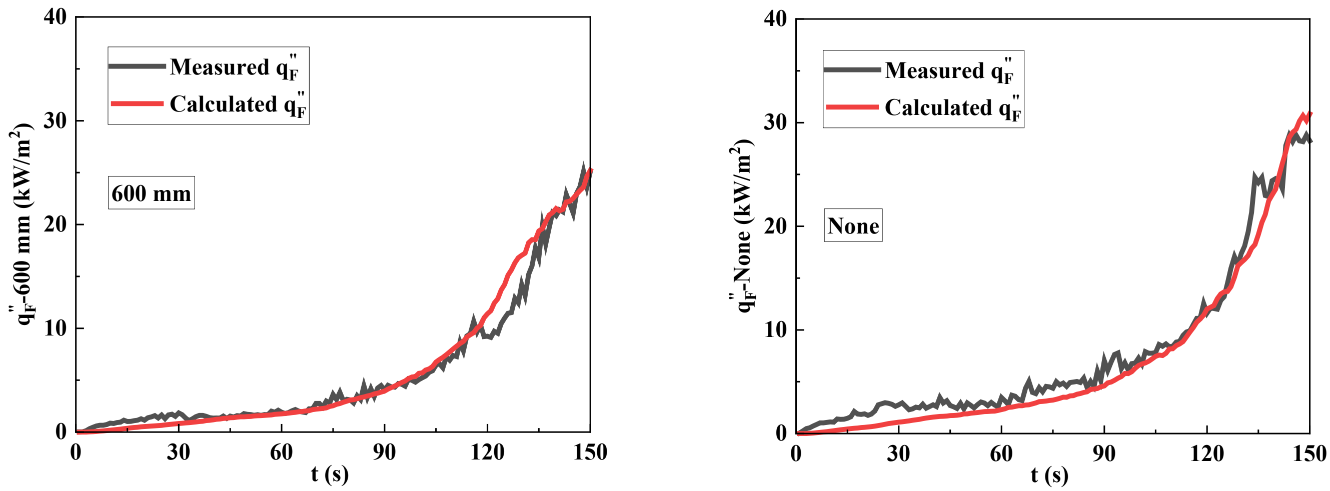
Fig. 3. Control volumes used in the mathematical model.

To verify the applicability of Equation 1, the measured upper gas temperature, compartment wall surface temperature, and the calcium silicate board surface temperature were substituted into Equation 1 to obtain the radiation to the floor of the compartment as shown in Fig. 4(a), and the calculated heat flux to the floor was compared to the experimentally measured radiation to the floor in Fig. 4(b), which shows good agreement due to the detailed consideration of radiation from the surrounding to the floor. In addition, in the actual calculation process, it was found that the radiation from the flame plume to the floor and the radiation from the calcium silicate board to the floor are minimal, accounting for less than 8% of the total heat radiation to the floor. Therefore, the following sections primarily consider the radiation from the hot gas layer and the radiation from the upper walls and ceiling surfaces.



(a) Calculated heat flux to the floor (based on experimental temperatures)





(b) Comparison of calculated heat flux to the floor and measured results

Fig. 4. Calculated heat flux to the floor (based on experimental temperatures) and its comparison with the measured results.

3.2.2 Temperature theoretical model

The MQH method is often used to predict the hot gas layer temperature in compartment fires[4,30]. The method is based on a two-zone, energy balance and gas flow model, derived from a large amount of experimental data in conventional-sized rooms[4] with no obstacles in front of the openings. However, as our compartment was not conventionally sized and had a degree of restricted ventilation out of the opening, it was found that the results of the MQH method have large errors when compared with the experimental data. The average error for the distances between the calcium silicate board and the opening from 50 mm to 600 mm in the range of 500 °C to 600 °C was 29%, and the average error within the temperature range of 500 °C to 600 °C reached a maximum value of 46% when the distance between the calcium silicate board and the opening was 50 mm due to the highest degree of ventilation limitation. Thus, the MQH method will be amended to incorporate the experimental conditions by estimating the degree of ventilation limitation in the experiments caused by the inert wall in front of the opening.

The MQH method is first based on a simple energy balance relationship; that is, the rate of energy released in the compartment is equal to the rate of energy lost due to fluid flow out through the opening plus the rate of heat loss by the hot gases to compartment boundaries, which can be expressed as[1]:

$$\dot{Q} = \dot{m}_g c_p (T_g - T_a) + h_k A_T (T_g - T_a) \tag{6}$$

However, due to the limitation of ventilation (although the energy balance relationship is still applicable), the equation needs to be modified on the basis of the original correlation (the gas flow model without ventilation limitation) and can be expressed as follows:

$$\Delta T = \frac{\dot{Q}}{\dot{m}_{g'} c_p + h_k A_T} \tag{7}$$

$$\dot{m}_{g'} = f(D) \dot{m}_g \tag{8}$$

where $\dot{m}_g$ and $\dot{m}_{g'}$ are the fluid flow rates out through the opening without the calcium silicate board and with the calcium silicate board in front of the opening, respectively, and $f(D)$ is a correction function indicating the degree of ventilation limitation caused by the calcium silicate board, which is a function of distance and would increase within a certain range if increasing distance between the calcium silicate board and the opening; when both sides of Equation 8 are multiplied by c_p and ΔT, $f(D)$ can also be considered a function of the degree of energy loss. Based on the above analysis, the MQH equation was re-derived and finally expressed as follows:

$$\frac{\Delta T}{T_a} = 1.63 \left(\frac{\dot{Q}}{f(D) \sqrt{g} \rho_a c_p T_a A_0 \sqrt{H_0}} \right)^{2/3} \cdot \left(\frac{h_k A_T}{f(D) \sqrt{g} \rho_a c_p A_0 \sqrt{H_0}} \right)^{-1/3} \tag{9}$$

where A_0 and A_T are the areas of opening and compartment surface with opening, respectively, and the term h_k is an effective heat conduction term for the solid boundaries and is defined in the following manner[1]:

$$t < t_p,\ h_k = \sqrt{\frac{k \rho c}{t}};\ t \geqslant t_p,\ h_k = \frac{k}{\delta} \tag{10}$$

k, ρ, c and $\delta$are the thermal conductivity, density, specific capacity and thickness of the wall/ceiling material, respectively, and for the vermiculite board in this experiment, $k = 0.147\ W/m \cdot k$, $\rho = 807\ kg/m^3$, $c = 0.94\ kJ/kg \cdot K$, $\delta = 0.025\ m$. In addition, t_p is termed the thermal penetration time at which the conduction can be considered to be approaching stationary heat conduction. This time can be given as[1]

$$t_p = \frac{\delta^2 \rho c}{4k} \tag{11}$$

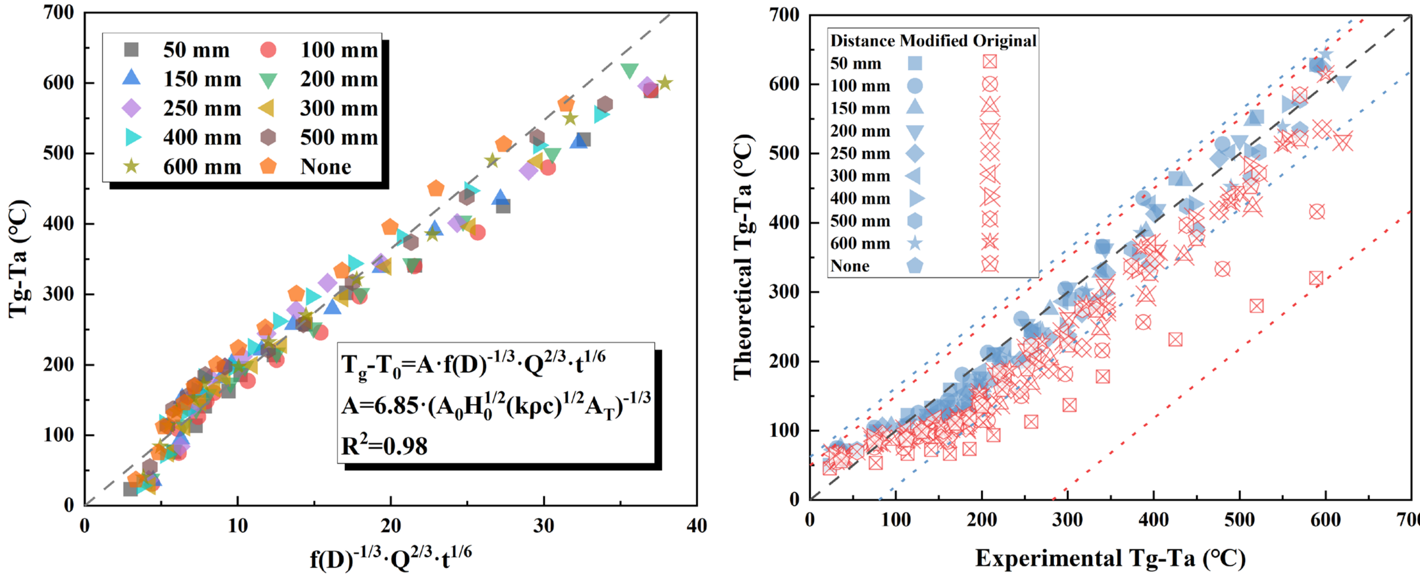
First, the thermal penetration time of the calcium silicate board is calculated from Eq. (11), which is over 13 minutes longer than the experimental time, so the conduction will be transient during the experiments. Therefore, in all calculations involving h_k in this paper, h_k is taken as $\sqrt{k\rho c/t}$. The experimental data, T_g and HRR, during the pre-flashover stage in all conditions, were used in Eq. (9), and $f(D)$ is obtained by fitting with experimental values as follows:

$$f(D) = \frac{[\ln(10D)]^4}{11.6 \cdot (10D)^{0.8}} \tag{12}$$

Thus, by substituting Equation 12 into Equation 9, the theoretical gas temperature is obtained as follows:

$$T_g = 18.25 f(D)^{-1/3} \cdot Q^{\frac{2}{3}} \cdot t^{1/6} + T_a \tag{13}$$

To verify the fitting effect of Equation 13, the experimental results of ΔT are compared with the fitting results, and Equation 13 is shown as a dashed line in Fig. 5(a). The results show that the experimental gas temperature rise ($T_g - T_a$) and fitting data are close to the dashed line, demonstrating a good agreement ($R^2 = 0.98$). In addition, to illustrate the necessity of the correction of MQH method, a comparison of the theoretical results of the original and modified MQH methods as well as their comparison with experimental results is shown in Fig. 5(b). The results calculated by the modified MQH method showed a significant improvement compared to the original MQH method. The average error for the distances between the calcium silicate board and the opening from 50 mm to 600 mm in the range of 500 °C to 600 °C decreased from 29% to 4%, and for the distance of 50 mm, the average error within the temperature range of 500 °C to 600 °C decreased from 46% to 7%.



(a) The upper gas temperature rise correlated with $f(D)$, $\dot{Q}$, and t, showing the least squares fit of the data

(b) Comparison of the original and modified MQH methods, as well as their comparison with experimental value

Fig. 5 Theoretical model of upper gas temperature.

3.2.3 Theoretical model of time to flashover

In this section, the time to flashover will be derived primarily based on a theoretical radiation model. Since it was found in the previous calculations that the thermal radiation to the floor primarily comes from the hot gas layer and the upper wall and ceiling surfaces, the thermal radiation calculation equation used to derive the time to flashover will be simplified as

$$\dot{q}''_F = \sigma F_u \left[\epsilon_g T_g^4 + (1-\epsilon_g) T_w^4 - T_a^4\right] \tag{14}$$

In addition, the calculation equation of the temperature of the hot gas layer will be obtained based on Equation 9 as follows:

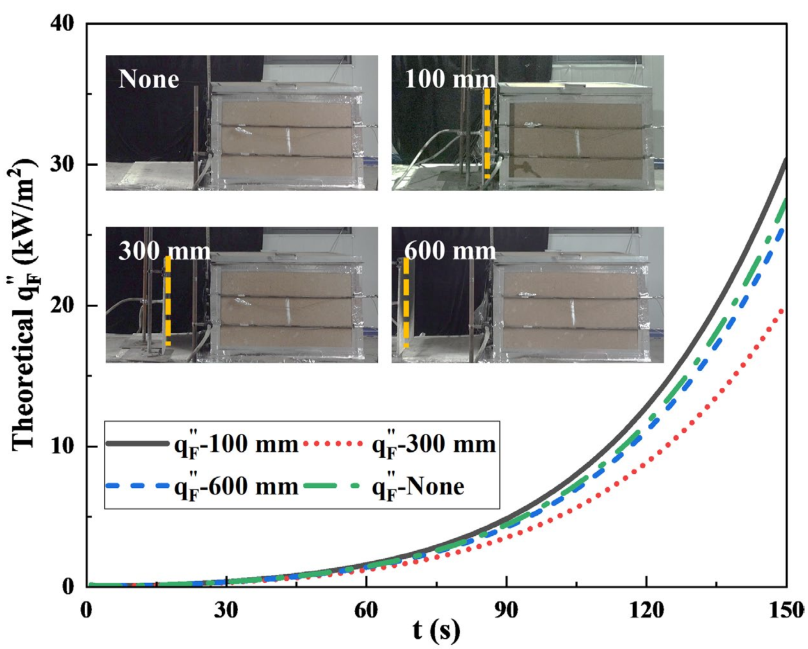
$$T_g = 6.85\left(\frac{\dot{Q}^2}{f(D) A_0 \sqrt{H_0}\, h_k A_T}\right)^{1/3} + T_a \tag{15}$$

$$T_w = \frac{h_k}{k}\delta T_g + T_a \tag{16}$$

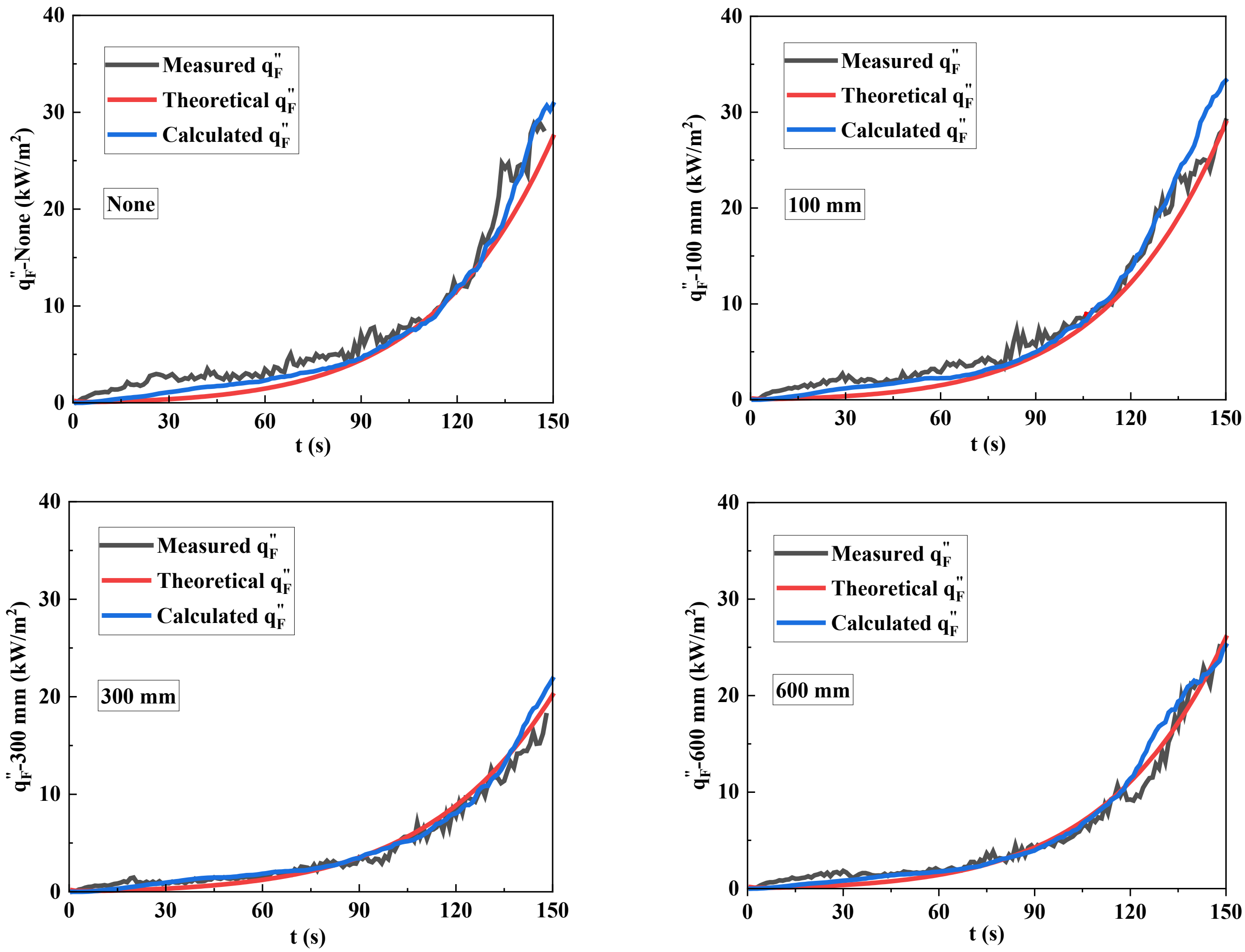
For the heat release rate, $\dot{Q}$, its growth rate during pre-flashover stage meets the t-squared law, so the t-squared law was used to replace the HRR measured in the experiment to calculate T_g. However, because ventilation is limited by the calcium silicate board, the theoretical t-squared law of HRR needs to be modified based on combustion efficiency, expressed as:

$$\dot{Q} = n \cdot \alpha \cdot t^2 \quad (17)$$

Equations 15-17 and the coefficients σ, F_u (the calculation method can be found in Chapter II of Ref. [22]), and ϵ_g are substituted into Equation 14 to calculate the theoretical value of the radiation heat flux of the floor as shown in Fig. 6(a). To verify the accuracy of the calculation results, the results are compared with the experimentally measured radiation heat flux of the floor and the calculated value in Fig. 4, which is in good agreement, as shown in Fig. 6(b). It should be noted that the theoretical result in Fig. 6(a) was obtained without substituting experimental values, which is different from the value based on experimental temperatures in Fig. 4(a). Moreover, in the theoretical calculation process, the most dominant processes (the radiation heat flux from the upper hot layer and wall/ceilings) are considered, and less influence terms are ignored, so the theoretical values in most cases are slightly smaller than the calculated values based on experimental temperatures.



(a) Theoretical heat flux to the floor (without experimental temperatures)



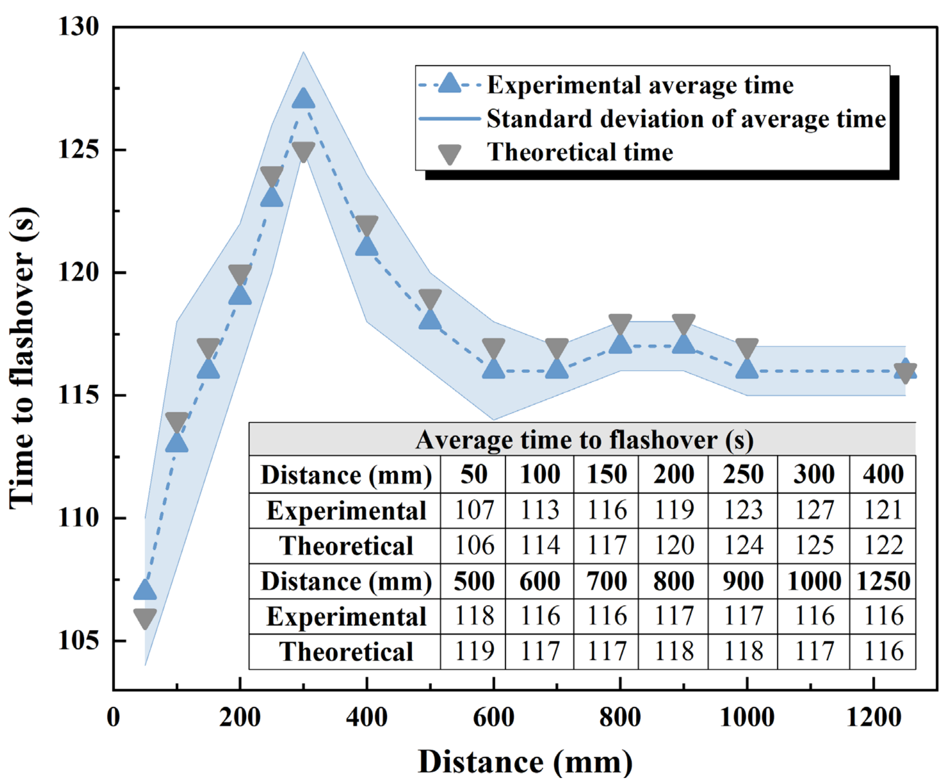
(b) Comparison of theoretical heat flux to the floor, measured results and calculated results

Fig. 6. Theoretical heat flux to the floor (without experimental temperatures) and its comparison with measured results and calculated results.

To predict the time to flashover in the experiments, Equations 14-17 are used to obtain the equation for time t. The result shows that the equation is a function related to the distance between the calcium silicate board and opening, D, and combustion efficiency, n, and the simplified functional form can be expressed as

$$f\left(n,\ D,\ t,\ \dot{q}_F''\right) = C \tag{18}$$

In this equation, there is still the radiation heat flux to the floor, $\dot{q}_F''$, but here, $\dot{q}_F''$ is not a value that changes with time or external conditions. It is actually the radiation heat flux to the floor as the compartment fire just reaches the flashover stage. What is more, the measured value in these reduced-scale experiments was approximately 10 kW/m^2 when flashover occurred (flame ejection). Therefore, $\dot{q}_F^{"}$ is taken as 10 kW/m^2. Taking the corresponding combustion efficiency, n, and distance value, D, into Equation 18, calculate the corresponding time to flashover, t_{FO}, through iteration, and compare the calculated value with the actual experimental value, as shown in Figure 7. It can be seen that the theoretically calculated time to flashover in Equation 18 is in very good agreement with the experimental results, thus, this method may be considered suitable for flashover occurrence prediction. It can be found that the theoretically calculated trend of the time to flashover with distance is consistent with the experimental values, which is not a monotonic trend, but a trend that first increases, then decreases, and finally remains unchanged with distance. This is because as the distance between burning compartment and adjacent wall changes, the varied ventilation conditions lead to changes in energy loss rate and combustion efficiency. In addition, these two factors have opposite effects on the occurrence of flashover (as the distance increases, both energy loss rate and combustion efficiency increase, but higher energy loss rate leads to an increase in time to flashover, while higher combustion efficiency leads to a decrease in time to flashover), and their competing mechanism causes a non-monotonic trend in the time to flashover. More detailed analysis has been developed in section 3.3.



Average time to flashover (s)							
Distance (mm)	**50**	**100**	**150**	**200**	**250**	**300**	**400**
Experimental	107	113	116	119	123	127	121
Theoretical	106	114	117	120	124	125	122
Distance (mm)	**500**	**600**	**700**	**800**	**900**	**1000**	**1250**
Experimental	118	116	116	117	117	116	116
Theoretical	119	117	117	118	118	117	116

Fig. 7. Comparison of experimental and theoretical times to flashover.

The above description is only an introduction to the theoretical models and an analysis of their applicability. It does not explain the problems of experimental study in detail through the physical meaning contained in these calculation models, which will be analyzed in detail below. Due to the fact that the value of n and the equation of $f(D)$ were analyzed based on experimental data, there may be differences in numerical values among different scales of experiments (or using different types of fuels in experiments). However, since the factors related to length were not given a fixed value, these analysis methods in this paper are theoretically applicable to experiments with other dimensions (or other fuels). In addition, the combustion efficiency n is not the actual experimental value of the combustion efficiency through measurement, but the assumed value, which may not be completely equal to the actual value. If the assumed combustion efficiency is too large, that is, the theoretical heat released by the fuel is greater than the actual value, it will lead to a higher theoretical compartment gas and ceiling/wall temperature, resulting in greater theoretical heat radiation to the floor, therefore, the theoretical time to flashover is shorter than the experimental measurement value. On the contrary, if the assumed combustion efficiency is less than the actual value in experiment, it will cause the theoretically calculated time to flashover to be greater than the experimental value.

3.3 Short Discussions

Due to the existence of the calcium silicate board, the ventilation conditions of the compartment directly changed, from free ventilation to limited ventilation, despite being in the pre-flashover fuel control stage. From the perspective of energy balance and mass conservation, the existence of the calcium silicate board reduces the loss of energy primarily from the hot gas layer in the compartment due to the limited ventilation, and the calcium silicate board also has thermal feedback on the interior of the compartment (because its value is minimal, it is not considered in the following analysis). This is also combined with a reduced combustion efficiency of the fuel due to limited ventilation caused by the calcium silicate board.

In Equation 8, $f(D)$ represents the degree of ventilation restriction. However, when both sides of Equation 8 are multiplied by c_p and ΔT, this equation will be transformed into the energy loss rate of the hot gas layer. Therefore, in addition to indicating the degree of ventilation limitation, $f(D)$ can also be considered a function of the effect of the calcium silicate board on energy loss; that is, the larger $f(D)$ is, the more severe the energy loss, which is more unfavorable to flashover. In addition, as combustion efficiency n increases, more energy will be released by the combustion of fuel, resulting in higher gas and ceiling/wall temperatures inside the compartment, and the higher gas and ceiling/wall temperature will cause greater heat radiation feedback inside the compartment, which is more beneficial to flashover. Equation 18 was further simplified, and the relationship between the variable expression equation in this equation and the time to flashover was extracted and can be expressed as follows:

$$t'_{FO} \propto \left(\frac{f(D)}{n^2}\right)^{2/9} \tag{19}$$

Note that, as the constants do not affect the trend of the results of the expression with distance variation, the above expression was developed by omitting the constants contained in Equation 18 for the purpose of analyzing the experimental phenomenon. From this relationship, it can be found that the time to flashover increases with the increase of $f(D)$, that is, when the energy loss increases, the time to flashover will be delayed. In addition, when n increases, the time to flashover will be reduced, that is, the improvement of the combustion efficiency will advance the time to flashover. Therefore, when the distance between the calcium silicate board and the opening gradually increases, $f(D)$ will gradually increase, and n will also gradually increase. However, since the influence of the two factors on flashover is opposite, that is, $f(D)$ delays flashover and n promotes flashover, the interaction of these two factors is complex, as presented in Figure 7, which can lead to the significant difference in the time to flashover with or without the adjacent calcium silicate board.

For instance, considering the distance between the calcium silicate board and the opening increased varying between 50 to 300 mm, at first, the high energy accumulation made the time to flashover earlier; then as the energy loss increased with increasing distance, so the time to flashover gradually increased. When the distance between the calcium silicate board and the opening increased from 300 to 600 mm, the combustion efficiency gradually increased becoming more significant with increasing distance, so the time to flashover gradually decreased with increasing distance. When the distance between the calcium silicate board and the opening was greater than 600 mm, the influence caused by the calcium silicate may be very small, and the combustion efficiency and energy loss tended to a stable equilibrium.

Considering the authors' previous full-scale experimental work[16], it was found that the time to flashover of the burning dwelling was delayed when the distance to an opposite dwellings was 1.0 m (using wood crib as fuel, solid fuel). This potentially corresponds to 250 mm in the ¼ scale reduced-scale experiments (n-heptane as fuel, liquid fuel) in this work, which also showed a delayed flashover time compared to uninhibited openings. However, a significant difference from the experimental results of the reduced-scale experiments, where very similar mass loss rates of the heptane was observed regardless of wall distance, the mass loss rate of the wood cribs in the full-scale experiments differed greatly when there was or was no adjacent dwelling.

Based on the Shvab–Zeldovich energy equation and the Clausius–Clapeyron equation, the mass loss rate of the liquid fuel is proportional to $ln\,\{1 + [\Delta h_c/v + c_{pg}(T_\infty - T_s)]/h_{fg}$[26]. Therefore, the mass loss rate of liquid fuel is primarily determined by temperature under identical conditions, and the enthalpy of vaporization of n-heptane is small, for liquid fuel; when the temperature rises by 100 °C, its mass loss rate only increases by 5% according to calculation by the authors. The temperature inside the compartment only has a small influence on its mass loss rate. Therefore, even if the temperature inside the compartment varies with the separation distance, the mass loss of heptane in the experiments would not be significantly influenced.

However, for solid fuels, combustion is a heterogeneous chemical reaction. If conceptually the wood cribs in the full-scale experiments were simplified to a fully carbonized fuel for analysis, its mass loss rate is proportional to $k_c Y_{O_{2,s}}/T_s$[26]. Solid fuels only have a significant reaction only they reach a high temperature, and their mass loss rate (combustion rate) is significantly affected by both temperature and oxygen concentration. Therefore, there is a significant difference between single- and double-compartment experimental measurements.

4. Conclusions

In this work, to investigate the influence on the time to flashover of different distance conditions between dwellings where one is on fire, 41 experiments using n-heptane as fuel were conducted in a ¼ ISO 9705 compartment. Important parameters, such as HRR, gas and wall/ceilings surface temperature, time to flashover and radiation heat flux to the floor, were measured and analyzed. Moreover, based on energy balance and mass conservation, the theoretical radiation model, the temperature theoretical model and the theoretical model of time to flashover were developed and applied to calculate the corresponding radiation heat flux to the floor, upper gas temperature and time to flashover. In addition, the corresponding calculated values were compared with the experimentally measured values to verify the applicability of the models. To analyze the relationship between the time to flashover and the distance between the calcium silicate board and the compartment opening, the theoretical model of time to flashover was further simplified. The primary conclusions are as follows:

(1) The combustion efficiency and heat accumulation were affected by the distance between burning dwelling and adjacent dwelling, resulting in significant differences in flashover occurrence time with or without the adjacent dwelling; consistent with observations in a previous full-scale experiment.

(2) With the increase in distance between the calcium silicate board and the compartment opening, the time to flashover of the compartment first increased and then decreased and finally remained stable: the time to flashover at 50 mm was lower than when there was uninhibited flow at the opening, time to flashover then gradually increased as the distance increased from 50 to 300 mm; the time to flashover then decreased with increasing distance from 300 to 600 mm; and when the distance was greater than 600 mm, the time to flashover was uniform and stable at the same time as when there was uninhibited flow at the opening.

(3) To calculate the temperature of the hot gas layer in the compartment when the distances were different between the calcium silicate board and the compartment opening at pre-flashover stage, a model was developed to modify the MQH method by implementing the impact of the degree of ventilation restriction on gas flow rate, which correlated well with the experimental results.

(4) To predict the influence of different distances between the calcium silicate board and the compartment opening on time to flashover, a correlation, dependent on the degree of energy loss $f(D)$ (is also degree of ventilation limiting) and combustion efficiency n, was proposed based on the theoretical model of radiation heat flux to the floor, and can reasonably estimate the time to flashover in the compartment as the distances differ.

(5) Due to competing mechanism of $f(D)$ (the higher its value is, the more unfavorable it is to flashover) and n (the higher the value, the more beneficial to flashover), the time to flashover at first increased and then decreased as the distance between the calcium silicate board and the compartment opening increased.

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