



Influence of the temperature of inflow air on the vertical temperature distribution of window spill fire plume

Biao Zhou^{a,c,*}, Hideki Yoshioka^b, Takafumi Noguchi^c, Xukun Sun^{a,c}, Kai Wang^a

^a School of Emergency Management and Safety Engineering, China University of Mining & Technology (Beijing), Beijing, 100083, China

^b Department of Fire Engineering, Building Research Institute, Tsukuba, Ibaraki, 305-0802, Japan

^c Department of Architecture, Faculty of Engineering, University of Tokyo, Tokyo, 113-8654, Japan

ARTICLE INFO

Keywords:

Window temperature distribution
Inflow air
Window spilled flame
Vertical temperature calculation
Large-scale scene

ABSTRACT

The temperature of inflow air through a window is important for the vertical temperature calculation of window spilled flame, which is believed to be the usual fire cause of façade fire. However, the temperature of inflow air differs from a large window height. With an aim to clarify the effects of the inflow air on the vertical temperature of window spilled fire plume, a series of fire plume tests performed a 1.35 m × 1.35 m × 1.35 m fire compartment. The window opening size varied from 0.91 m (Height) × 0.41 m (Width) to 0.91 m (Height) × 0.91 m (Width). The heat release rate (HRR) changed from 300 kW to 900 kW. The temperature distribution of window opening is recorded by a thermocouple tree with a distance of 5 cm and window spill flame is got via 196 thermocouples with a distance of 10 cm. It is found the big disagreement between experimental tests and calculated values using the ambient temperature as the temperature of inflow air. To improve the results, the ambient temperature is replaced by the average temperature in the calculation, interestingly, the agreement of above results are increased by 21.0%, 29.0%, 21.0%, 29.2% and 23.0%, respectively. The temperature of inlet air through window opening should be carefully considered when the Yokoi correlation is used in the large-scale scene. It provides an insight for the understanding of discontinuity resulting from the scale effects.

1. Introduction

A flame ejected from a window of the room could result in a large-scale building façade fire [1]. The investigation into the behaviors of window fire plumes is a popular topic for many fire researchers. Fire performances of fire plumes ejected out of a window over the building have received attention in the last decades. The correlation between dimensionless temperature Θ and vertical position z/r_0 was proposed by Yokoi and used widely [2]. The discontinuity of the Yokoi plot is enlarged as the window spill fire plume increasing from small-scale to real-scale. To improve the continuity, several suggested solutions have been reported in our previous work [3]. In the Yokoi correlation, the ambient temperature is used as the temperature of inflow air. It could result in a deviation when the temperature of the window is high. Therefore, the effects of the temperature of inflow air on the calculation of vertical temperature need to be clarified.

With respect to buoyant window spill plumes, the main emphasis of currently available researches focuses on vertical buoyant spill-plume temperature along building facade [4], the temperature decay beneath a horizontal projection [5], behaviors beneath a

* Corresponding author. School of Emergency Management and Safety Engineering, China University of Mining & Technology (Beijing), Beijing, 100083, China. E-mail address: zhoubiao1088@bme.arch.t.u-tokyo.ac.jp (B. Zhou).

Nomenclature

\dot{m}_a	The inlet mass flow rate
\dot{m}_b	The mass-loss rate or burning rate
\dot{m}_g	The air entering the enclosure
v_a	The inlet velocity
W	The width of window opening
r_0	Yokoi's length scale
\dot{Q}	The convection heat flow rate at the window
T_a	The ambient temperature
T_g	The temperature of window spill gas
z	The vertical distance from half the height of window
c_p	Specific heat at constant pressure
g	The acceleration due to gravity
ρ_g	Density of gas inside the enclosure
ρ_a	The density of ambient temperature
C_d	The flow coefficient at the opening $C_d = 0.7$
ΔT_z	The maximum temperature rise at location z
ΔT_g	The gas temperature difference between hot layer inside the enclosure and ambient
z_h	The distance from neutral plane to the top of window opening
z_0	The distance from the bottom of window opening to the neutral plane
A	The area of window opening
$Q_{v,crit}$	The critical HRR for the generation of window spill plume
A_T	The interior surface
Q_{ef}	The effective HRR of window spill plume
Q	The total HRR
Θ	Dimensionless temperature
z'	The height of the central line in the window spill plume
Δz	The correction distance
Q_{ef}^*	The dimensionless effective HRR of window spill plume
T_{in}	The temperature of inlet air
n	The opening aspect
R_{NL}	The goodness of fit
q	The residual sum of squares
\hat{y}_i	The calculated data

horizontal projection [6], lateral temperature profile of fire plume with the ambient wind [7], façade flame of compartment fires with circular opening [8], numerical and theoretical evaluations of an externally venting flame [9] and so on. However, several researchers focus on the discussion of the Yokoi model in the calculation of vertical temperature. Thomas introduced the opening aspect to the Yokoi model with the variation of fuel consumption rate [10]. Then Ohmiya proposed the virtual heat source Δz to improve the accuracy of the Yokoi model [11]. Yamaguchi rearranged the Yokoi model and introduced a new variable that considers the relationship between opening height and neutral plane [12]. Recently, a new length scale l_1 and l_2 based on the dimensionless scale r_0 in Yokoi's theory was developed by Lee and Delichatsios [13,14]. Although much research on the basis of Yokoi theory helps to have a deep understanding of window spill flame performance and provides a theoretical basis for the fire safety of facade, the little report about the effects of temperature of inlet air on the calculation results is available.

In this contribution, a detailed understanding of temperatures of air inflow influence on calculation was newly discussed by conducting a series of intermediate-scale tests with a 1.35 m (L) \times 1.35 m (H) \times 1.35 m (W) fire compartment under a well-ventilated condition. Authors detail works involving the temperature distribution of window opening varying opening aspect and heating intensity, explore the temperature increase of façade wall differing each test condition, discuss the vertical temperature of window spilled flame by using the average temperature of inflow air.

2. Geometry description

The geometry consists of fire compartment, non-combustible façade, gas burner, window opening, and thermocouple mesh and so on. It is shown in Fig. 1. The propane gas combustion chamber is sized in an L (length) \times W (width) \times H (height) = 1350 mm \times 1350 mm \times 1350 mm and the fire spreading opening is sized in an L \times W = 910 mm \times 910 mm. The dimension of the gas burner is L \times W = 600 mm \times 600 mm. In the tests, the opening size and opening aspect $n = 2$ W/H changed W \times H = 510 mm \times 910 mm ($n = 1.12$), W \times H = 710 mm \times 910 mm ($n = 1.56$), W \times H = 910 mm \times 910 mm ($n = 2$), W \times H = 910 mm \times 610 mm ($n = 2.98$) and W \times H = 910 mm

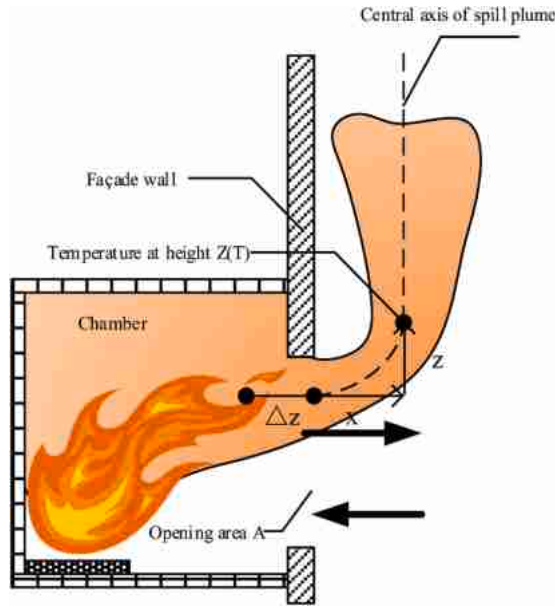


Fig. 1. The description of window spill flame.

× 410 mm (n = 4.44), respectively.

3. Mathematical model

3.1. The calculation introduction of inlet mass flow rate

To improve the accuracy of the model, the mass-produced inside compartment should be taken into account since the burning object will release some small amount of mass, equal to the mass-loss rate or burning rate \dot{m}_b [15]. Fig. 2 features the description of the window spill plume. The conservation of mass indicates that the gases exiting the enclosure must agree with the air entering the enclosure plus the mass-produced in the enclosure [16]:

$$\dot{m}_g = \dot{m}_b + \dot{m}_a \tag{1}$$

The inlet mass flow rate \dot{m}_a varies with height in the z-direction, which can be considered as constant in the direction parallel to the opening. Therefore, the mass flow rate of air inflow the vent could be integrated into the following according to the inlet velocity $v_a = \sqrt{\frac{2g z(\rho_a - \rho_g)}{\rho_a}}$ [17]:

$$\dot{m}_a = \frac{2}{3} C_d W \rho_g \sqrt{\frac{2(\rho_a - \rho_g)g}{\rho_g}} z_0^{3/2} \tag{2}$$

Similarly, the mass flow rate out of the vent can be expressed as the followings based on the outlet velocity $v_g = \sqrt{\frac{2g z(\rho_a - \rho_g)}{\rho_g}}$.

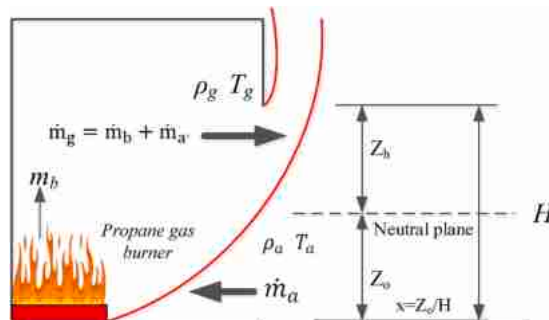


Fig. 2. The sketch of window fire outflow [3].

$$\dot{m}_g = \frac{2}{3} C_d W \rho_g \sqrt{\frac{2(\rho_a - \rho_g)g}{\rho_g}} z_h^{3/2} \tag{3}$$

By combining the conservation between \dot{m}_a and \dot{m}_g in **Equation (1)**, the following equation can be obtained by dividing **Equation (3)** by **Equation (2)**:

$$\frac{\dot{m}_a + \dot{m}_b}{\dot{m}_a} = \left(\frac{z_0}{z_h}\right)^{3/2} \left(\frac{\rho_g}{\rho_a}\right)^{1/2} \tag{4}$$

Considering the definition for the relationship of the neutral plane $z_h + z_0 = H$ and **Equation (4)**, then the height of the lower neutral plain can be rearranged, we find:

$$\frac{H}{z_0} = \left(\frac{1 + \frac{\dot{m}_b}{\dot{m}_a}}{\sqrt{\rho_g/\rho_a}}\right)^{2/3} + 1 \tag{5}$$

With an aim to clarify the impact of burning rate \dot{m}_b and to combine the influence of inlet air temperature, the improved \dot{m}_a is derived by substituting **Equation (5)** into **Equation (2)**, then [18]:

$$\dot{m}_a = \frac{\frac{2}{3} C_d W \rho_g \sqrt{\frac{2(\rho_a - \rho_g)g}{\rho_g}} H^{3/2}}{\left[\left(\frac{1 + \frac{\dot{m}_b}{\dot{m}_a}}{\sqrt{\rho_g/\rho_a}}\right)^{2/3} + 1\right]^{3/2}} \tag{6}$$

The flow coefficient at the opening C_d is 0.7. The W and H are the width and height of the opening, respectively. The g is the acceleration of gravity. For **Equation (6)**, it introduces the variable of fuel mass loss which conforms to the conservation of gas flow.

3.2. The calculation of the vertical temperature of window spill plume

3.2.1. The calculation of varied neutral plane position

It is known to all that when hot and cold gases are at either side of an opening, the hot gases would flow out via the upper part of the opening and the cold gases will flow in through its lower part. When the pressure difference of two parts is zero, it is called the height of the neutral plane [15]. Here, the neutral plane (N.P.) is at the xH ($0 < x < 1$) of the window height, then convective flow at the window is expressed by using Yokoi's equation as [3]:

$$x = \frac{z_0}{H} = \frac{1}{1 + \left(\frac{\rho_a}{\rho_g}\right)^{1/3} \left(1 + \frac{\dot{m}_T}{\dot{m}_a}\right)^{2/3}} \tag{7}$$

When $\rho_a = \frac{353}{T_a}$ and $\rho_g = \frac{353}{T_g}$, **Equation (7)** could be rearranged into the following equation:

$$x = \frac{z_0}{H} = \frac{1}{1 + \left(\frac{T_g}{T_a}\right)^{1/3} \left(1 + \frac{\dot{m}_T}{\dot{m}_a}\right)^{2/3}} \tag{8}$$

Equation (8) indicates that the neutral plane primarily depends on T_g , \dot{m}_T and \dot{m}_a .

3.2.2. The vertical temperature of window spill plume

The critical HRR for the generation of window spill plume could be got by the following [19]:

$$Q_{v,crit} = 150 \left(\frac{A_T}{A\sqrt{H}}\right)^{2/5} A\sqrt{H} \tag{9}$$

Considering the definition of the total HRR $Q = c_p \dot{m}_g (T_g - T_a) + Q_{source}$, the effective HRR of window spill plume can be expressed as $Q_{ef} = Q - Q_{v,crit}$. Then the temperature of the central line of the window spill plume could be got:

$$T = \Theta \frac{\left(\frac{T_\infty Q_{ef}^2}{c_p^2 \rho^2 g}\right)^{1/3}}{T_0^{5/3}} + T_a \tag{10}$$

For the outlet gas $\rho = \frac{353}{T}$, **Equation (10)** can be rearranged as:

$$\frac{T - T_a}{(T_a T^2)^{1/3}} = \left(\frac{Q_{ef}^2}{353^2 c_p^2 g r_0^5} \right)^{1/3} \Theta \tag{11}$$

For Equation (11), the outlet gas temperature T is difficult to be calculated directly. The utilization of the iterative method could be used to solve it. It is known that the left side of Equation (11) can be treated by using logarithmic approximation when the range of T is lower than 1500 K, then the new correlation Equation (12) is derived as the following:

$$\frac{T - T_\infty}{(T_a T^2)^{1/3}} = \frac{1}{1.16} \ln \left(\frac{T}{T_a} \right) \tag{12}$$

According to Equation (11) and (12), the temperature of the window spill plume could be rearranged as the following:

$$T = T_a \exp \left[1.16 \left(\frac{Q_{ef}^2}{353^2 c_p^2 g r_0^5} \right)^{1/3} \Theta \right] = T_a \exp \left[0.0109 \left(\frac{Q_{ef}^2}{r_0^5} \right)^{1/3} \Theta \right] \tag{13}$$

According to the Yokoi correlation between dimensionless temperature Θ and vertical position z/r_0 , the T of the window spill plume could be got. The detailed calculation method of the dimensionless temperature Θ can be expressed as follow [20]:

$$\Theta = \frac{1}{2} \exp \left[-\frac{1}{4} \left(\frac{z' + \Delta z}{r_0} \right)^{4/5} \right] \tag{14}$$

To simplify the calculation, the height of the center-line of the spill plume z' will be approximated as the vertical height z in the solution process. Using the definition for the dimensionless effective HRR of window spill plume $Q_{ef}^* = \frac{Q_{ef}}{c_p T_a \rho_a \sqrt{g r_0^{3/2}}}$, the correction distance Δz can be defined in detail as follows [11]:

$$\Delta z = 0.04 Q_{ef}^{*2} r_0 \tag{15}$$

Based on the above discussion, the temperature of outlet gas T is mainly effected by the mass flow rate of opening, enclosure size, and burner HRR. Because the enclosure size and burner HRR can be directly measured by experimental method, the deviation of the Yokoi model is considered to be caused mainly by the approximate simplification of the mass flow rate with respect to the inlet and outlet gases.

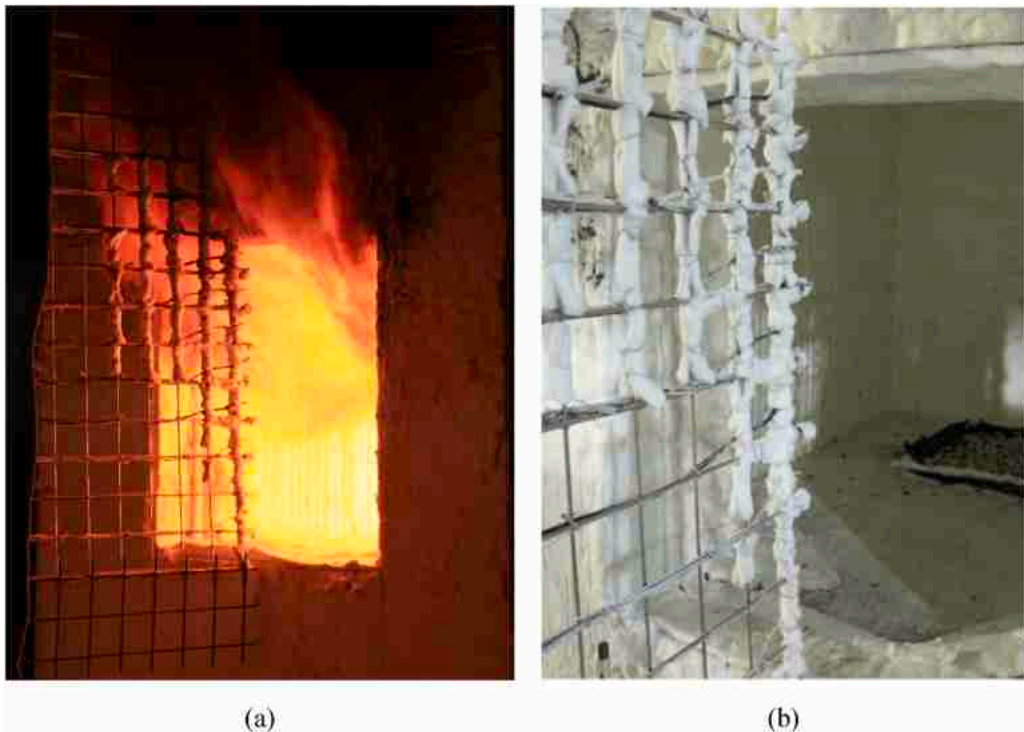


Fig. 3. The description of experimental layout (a) The experimental scene during the test (b) the thermocouple tree in front of the opening.

4. Experimental design and method

The experiment method is set up according to the JIS A 1310 façade fire test of Japan [21], just as shown in Fig. 3. A simple model of the experiment is described in Fig. 3 (a). The HRR of the window spill flame increased from 300 kW to 900 kW. Because of the high combustion heat and ease of handling, propane gas is used as a combustion fuel. The specimen substrate, specimen support frame, and a k-type thermocouples mesh are the same as the one used in previous tests [3]. The thermocouple mesh used to measure the temperature of the opening is shown in Fig. 3 (b).

Heat release rate (HRR) and total heat release rate (THR) were calculated by the common methodology Oxygen Consumption Calorimetry (OC). During OC measurement, the gas-analysis equipment was used to record oxygen concentration ranging from 0.009% to 20.9% every 2 s. Detailed experimental conditions are shown in Table 1. The side view of fire plume behavior was measured by employing a thermal camera named FLIR SC620 with a temperature measurement range from 150 to 2200 °C, which was bought from FLIR Systems, Inc. K-type thermocouple has an accuracy of ± 2.2 °C. The gas analysis has an accuracy of $\pm 0.02\%$ O₂, $\pm 0.02\%$ CO and $\pm 0.02\%$ CO₂. All the experiments were finished in the Building Research of the Institute of Japan located in Tsukuba.

5. Results and discussion

5.1. The central-line distribution of window spill plume varying opening aspect and HRR

The behaviors of window spill flame differed from n and HRR are recorded and as shown in Fig. 4. It is observed that when the HRR of window flame increases from 300 kW to 900 kW, the fire plume changes from weak to luminous. Compared with the same HRR (test No.1, No.3, No.5, No.8, and No.10.), the intensity of the external flame is influenced by the opening aspect n. It has a significant flame shape when $n = 4.44$ and a relatively weak spilled fire when $n = 2.00$, which is due to the existing of critical HRR $Q_{v,crit}$. The critical HRR is also an experiential parameter related to the opening size, the lower critical value means a higher intensity of the external fire in the same HRR which can effectively illustrate the variation of façade flame. Except for test No.11, all the tests are conducted in the over-ventilated condition. Compared with the under-ventilated condition, the over-ventilated condition presents a spill plume with a low intensity. In addition, re-attaching to the façade wall is also found with respect to a window spill with the small HRR (for example, test No.1, No.3 and No.5.). As the opening aspect n and HRR increase, the fire plume seems easier get close to the wall. Once the combustible façade walls are exposed to a reattaching-to-wall fire plume, it could result in a whole façade fire. In the engineering design of the building, such kind of fire plume should be avoided by the utilization of optimal opening aspects and non-combustible interior materials.

To capture the central line of the window spill plume, both IR camera and thermocouple mesh are used. The results are shown in Fig. 5. According to the results of the thermocouple mesh, the trajectory of the window spill plume is clearly obtained and mathematically illustrated. For the illustrated temperature distribution, it is also found that the low HRR spill plume presents an obvious reattachment on the façade. Regarding the window spill plume with a high HRR, the elevated temperature area mainly exists in the upper of opening. Therefore, a good opening treatment method could effectively prevent a flame propagation. By comparing the result of the IR camera and thermocouple mesh, the vertical temperature of the window spill plume could be obtained via this model accurately. In addition, the vertical temperature distribution of window opening is found to be varied with vertical distance.

5.2. The calculation of m_{in} using T_{in} and T_a

As detailed in Equation (6), the ambient temperature (T_a) is traditionally used in the calculation model to obtain the inlet mass flow rate of air. It is a fact that the temperature of inlet air could be approximated as the ambient temperature since the HRR of the window fire plume is small. However, it perhaps leads to an error when the HRR of the window spill plume is large. In the real situation, the temperature of inflow air could be raised dramatically during it approaching the opening, which has an increased temperature ranging from 500 K to 900 K. In the current work, the 300 kW, 600 kW, 900 kW of window spill plume are produced by the combustion of propane gas with a mass flow of 153.5 L/min, 393.5 L/min, and 633.5 L/min, respectively. The temperature of inlet air (T_{in}) is got by a thermocouple mesh, which can calculate the average value of the thermocouple below the neutral plane. The parameters obtained by using both T_{in} and T_a are summarized in Table 2. Then the comparison of experimental and calculated temperature increase is reported in Fig. 6. In general, the goodness of fit is highly improved after calculating the Yokoi plot using T_{in} . The

Table 1
The description of test conditions.

Test No.	HRR (kW)	Width (mm)	Height (mm)	Opening aspect n
1	300	510	910	1.12
2	600	510	910	1.12
3	300	710	910	1.56
4	600	710	910	1.56
5	300	910	910	2.00
6	600	910	910	2.00
7	900	910	910	2.00
8	300	910	610	2.98
9	600	910	610	2.98
10	300	910	410	4.44
11	600	910	410	4.44

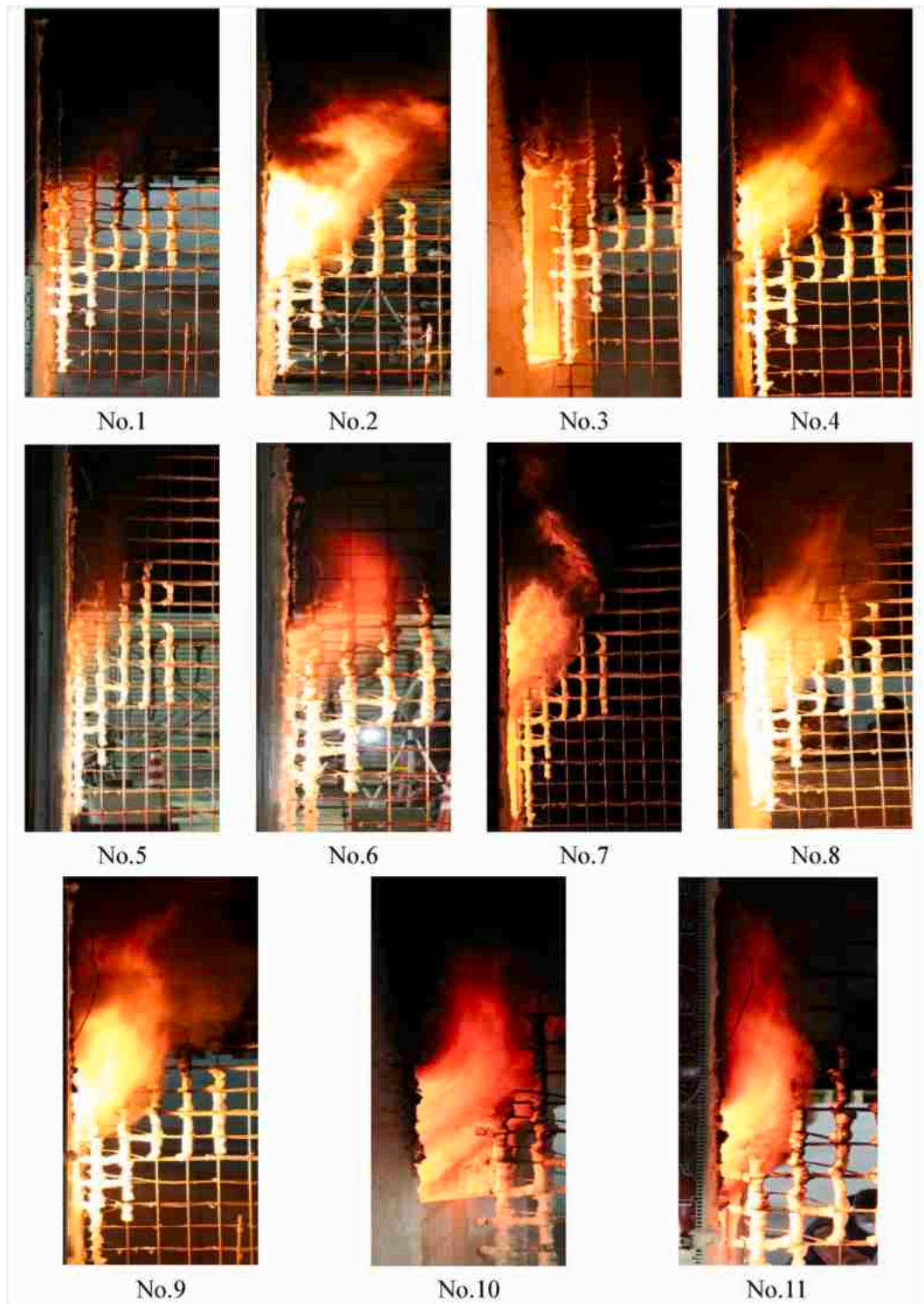


Fig. 4. The side view of fire plume.

disagreement is observed clearly at the location near the upper window opening. When the HRR of the window fire plume is low, the calculation results performed by T_a are found to show a better agreement with experimental values. In comparison, the results of Yokoi calculation using T_{in} are more consistent with experimental data with respect to a window spill plume with a large HRR. This is important for the application of the Yokoi model in the calculation of a window spill plume which has a large HRR, which agrees with

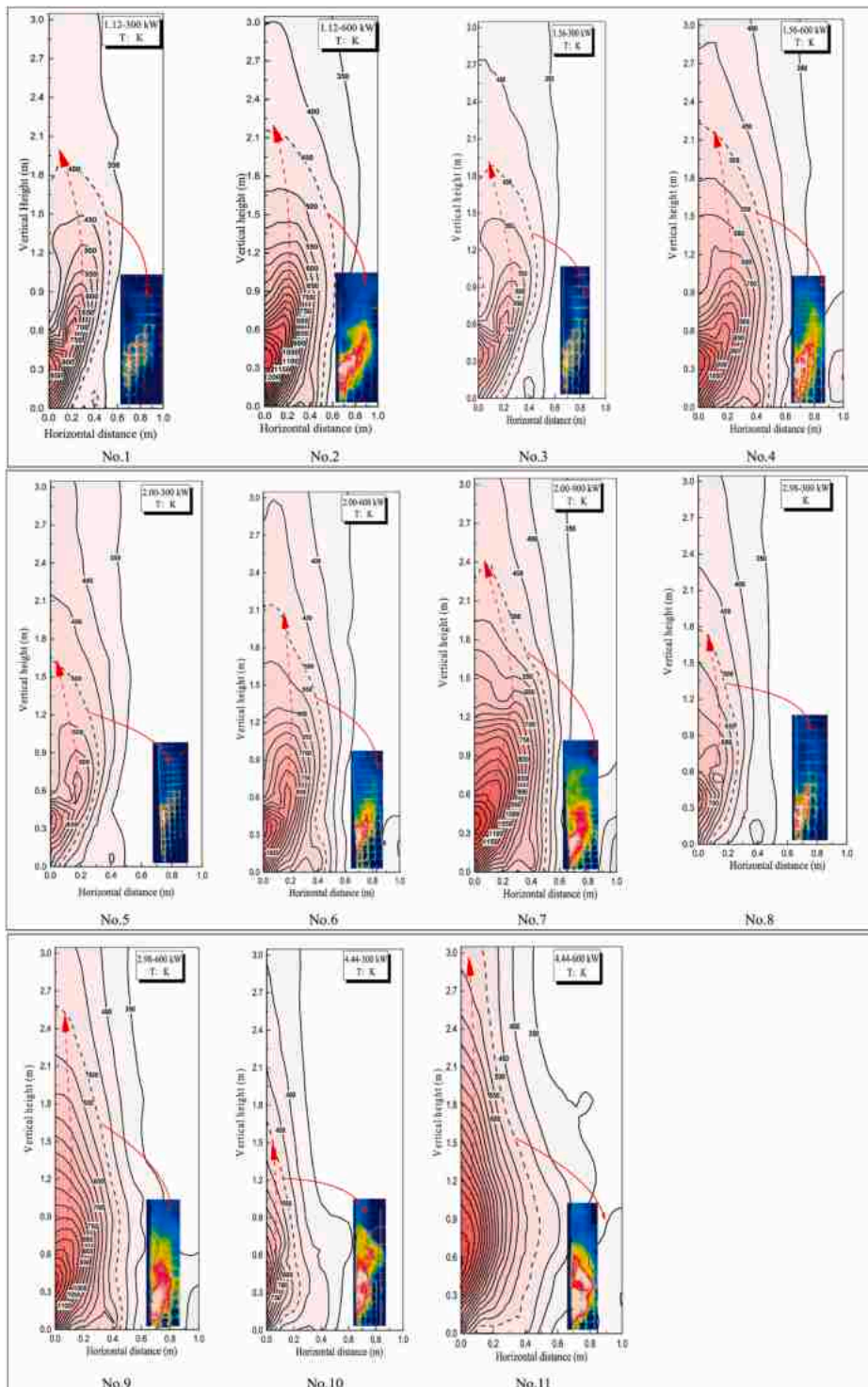


Fig. 5. The central-line distribution of fire plume.

the real-scale of building fire.

It is a fact the agreement of the Yokoi calculation with experimental results using T_{in} is increased. The opening aspect n is found to be a significant factor influencing the goodness of fit. In this work, the opening aspect n is related with the varied ventilation capacity of the enclosure, where 2.00 and 1.56 are strong but 2.98, 1.12, and 4.44 are relatively weak. With respect to the calculated results

Table 2
The parameters of inlet air mass flow rate by using T_{in} and T_a .

No.	HRR (kW)	Outlet T (K)	Inlet T (K)	m_b (g/s)	m_{in} (g/s)	m_a (g/s)	m_g (g/s)
1	300	961	568	4.7	115.3	221.4	119.9
2	600	1312	782	12.0	95.6	221.4	107.6
3	300	836	510	4.7	168.9	308.2	173.5
4	600	1199	796	12.0	103.4	308.2	115.4
5	300	756	471	4.7	234.0	395.0	238.7
6	600	1086	683	12.0	164.9	395.0	176.9
7	900	1218	736	19.3	170.2	395.0	189.5
8	300	816	496	4.7	127.2	216.8	131.8
9	600	1152	707	12.0	92.7	216.8	104.7
10	300	941	804	4.7	34.7	119.5	39.4
11	600	1139	848	12.0	35.5	119.5	47.5

performed by T_{in} , it can be seen from Fig. 6 that when $n = 2.00$ and $n = 1.56$ of 600 kW and 900 kW, a better agreement with the experimental data is illustrated. Based on this characteristic, it provides a method to further improve the accuracy of the Yokoi model depending on the variation of ventilation capacity. For the result of the Yokoi model using T_a , except for test No.3 and No.4, all the profiles have a deviation from the experimental data. It can be found that the goodness of fit in the T_a profile lacks a corresponding relationship with the variation of the opening aspect and HRR. In all, the calculated results of Yokoi model using T_{in} are found to be more agree with the values performed by T_a .

It is also found that when the window spill plume approaches an under-ventilated condition, the disagreement between calculated values (calculation using both T_{in} and T_a) and experimental data is enlarged. It indicates that the Yokoi model seems not well used for the under-ventilated condition, just as described in Fig. 6 (test No.11). Even under this condition, the results of Yokoi performed with T_{in} show a better agreement compared with calculation results using T_a .

5.3. The improvement discussion after new T_{in}

The correlation analysis is a necessary index to quantitatively describe the accuracy of the Yokoi model which is calculated by the utilization of T_{in} and T_a , respectively. The goodness-of-fit is currently calculated by using an equation, $R_{NL} = 1 - \sqrt{\frac{Q}{\sum y_i^2}}$. In it, R_{NL} represents the goodness of fit. Q is the residual sum of squares, which could be got by $Q = \sum (y_i - \hat{y}_i)^2$. \hat{y}_i is the calculated data by the Yokoi model. y_i is the experimental data. The goodness-of-fit of the Yokoi model and experiments is compared in Fig. 6. It is found that after using T_{in} in the Yokoi model, the accuracy of the calculation model is highly improved in general.

The goodness-of-fit for 300 kW and 600 kW are described in Fig.6 (a) and Fig.6 (b), respectively. With respect to a 300 kW of window spill plume, when the opening aspect n changes from 1.12 to 4.44, the goodness-of-fit of calculation performed with T_{in} decreases from 0.45 to 0.43. The goodness-of-fit of calculation performed with T_a changes from 0.38 to 0.35. After using T_{in} in the calculation of Yokoi model, the averaged goodness-of-fit with experimental result is increased by 21.0%. Regarding a 600 kW of window spill plume, the goodness-of-fit of calculation performed with T_{in} decreases from 0.43 to 0.41 as n increases from 1.12 to 4.44. The goodness-of-fit of calculation performed with T_a varies from 0.31 to 0.34. After using T_{in} in the calculation of Yokoi model, the averaged goodness-of-fit with experimental result is increased by 29.0%. Therefore, it is found that the goodness-of-fits of two HRR window spill plumes are highly improved. In general, the averaged goodness-of-fit of experimental data and calculation results by the Yokoi model with T_a are highly improved.

Fig.6 (c) and Fig.6 (d) describe the goodness-of-fit of experimental data and calculation results varying with the critical HRR of chamber. With respect to a 300 kW of window spill plume, when the critical HRR of chamber changes from 358 kW to 1185 kW, the goodness-of-fit of calculation performed with T_{in} decreases from 0.45 to 0.43. The goodness-of-fit of calculation performed with T_a varies from 0.35 to 0.38. After using T_{in} in the calculation of Yokoi model, the averaged goodness-of-fit with experimental result is increased by 21.0%. Regarding a 600 kW of window spill plume, the goodness-of-fit of calculation performed with T_{in} decreases from 0.43 to 0.41 as the critical HRR of chamber changes from 358 kW to 1185 kW,. The goodness-of-fit of calculation performed with T_a varies from 0.31 to 0.34. After using T_{in} in the calculation of Yokoi model, the averaged goodness-of-fit with experimental result is increased by 29.2%. Therefore, it is found that the goodness-of-fits of two HRR window spill plumes are highly improved. To get an improved prediction of vertical temperature of window spill plume, the T_{in} are suggested to be used in the calculation.

Regarding the goodness-of-fit of experimental data and calculation results varying with the HRR of window spill plume, it is given in Fig. 6 (e). Regarding the $n = 2$, when the HRR of window spill plume changes from 300 kW to 900 kW, the goodness-of-fit of calculation performed with T_{in} decreases from 0.44 to 0.42. Comparably, the goodness-of-fit of calculation performed with T_a decreases from 0.38 to 0.32. After using T_{in} in the calculation of Yokoi model, the averaged goodness-of-fit with experimental result is increased by 23.0%.

6. Conclusions

As a result of the study, the following conclusions can be drawn.

According to the literature review results, it was found that the temperature of inflow air plays an important role in the calculation of vertical temperature distribution of window spilled flame, however, studies on the effects of the temperature of inflow air on the

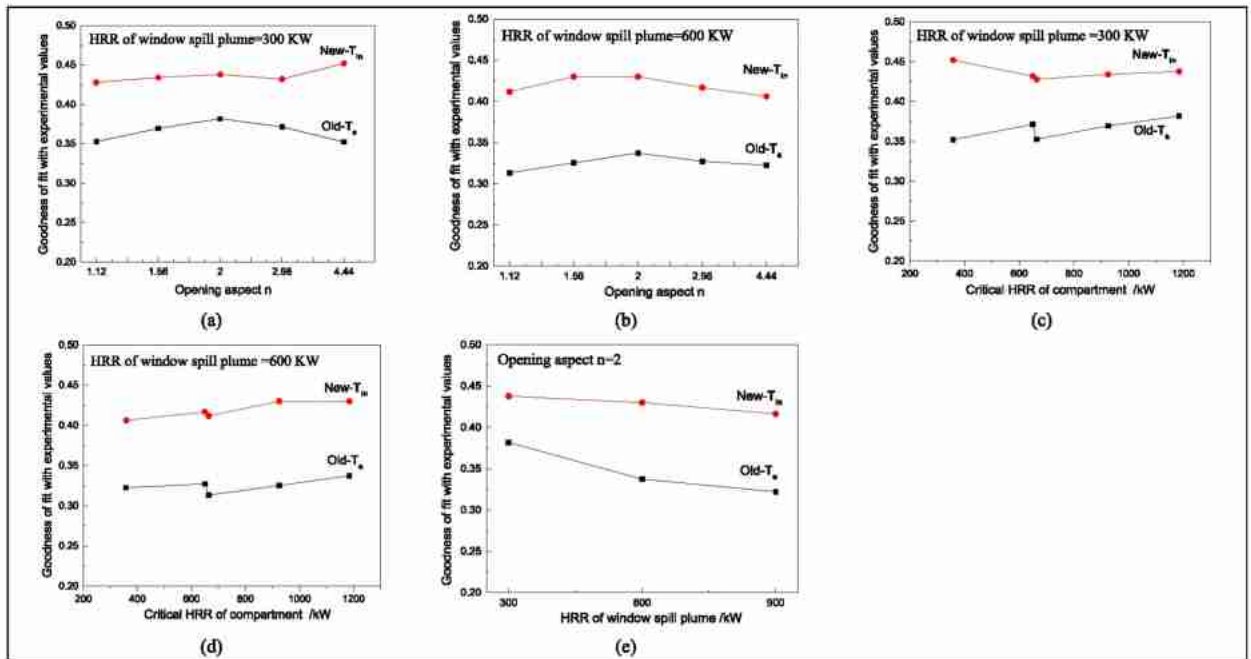


Fig. 6. Comparison of goodness-of-fit results using T_{in} and T_a in the Yokoi model (a) goodness-of-fit vs. n , HRR = 300 kW (b) goodness-of-fit vs. n , HRR = 600 kW (c) goodness-of-fit vs. critical HRR, HRR = 300 kW (d) goodness-of-fit vs. critical HRR, HRR = 600 kW (e) goodness-of-fit vs. HRR.

calculation results have not been carried out so far.

An experimental layout for measuring temperature of window spilled flame was set up, test conditions were determined.

The mathematical calculation model for vertical temperature was described to stress the role of air temperature during calculation regarding a large-scale scene.

The influence of inlet air temperature used in the calculation of vertical temperature of window spill plume is clarified. From the observation of experimental tests, when the HRR of window flame increases from 300 kW to 900 kW, the fire plume was found to be changed from weak to luminous. Re-attaching to the façade wall was also observed regarding a small HRR of window spill plume. The fire plume is found to be easier to get close to the wall when the opening aspect n and HRR increases.

Based on the analysis of comparison with experimental data and calculation results, it is found that after using T_{in} in the model, the accuracy of the calculation model is increased by an averaged 24.6%, which is highly improved in general. This is important for the vertical temperature of a real-scale window spill plume in engineering.

However, neutral plane change caused by the HRR affected also slightly influences the central-line distribution of fire plume, which is needed to be further verified.

CRedit authorship contribution statement

Biao Zhou: Conceptualization, Methodology. **Hideki Yoshioka:** Data treatment, Writing – original draft. **Takafumi Noguchi:** Investigation. **Xukun Sun:** Supervision. **Kai Wang:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors gratefully acknowledge Mr. Masamichi Tamura, Mr. Yutaka Tanaike, Dr. Yuhei Nishio, Miss. Miki Nakamura, Mr. Yuji Kanda for their help in the experimental operation. This work was supported by the Beijing Nova Program (Z211100002121102) and the Fundamental Research Funds for the Central Universities (No.2022JCCXAAQ01).

Appendix

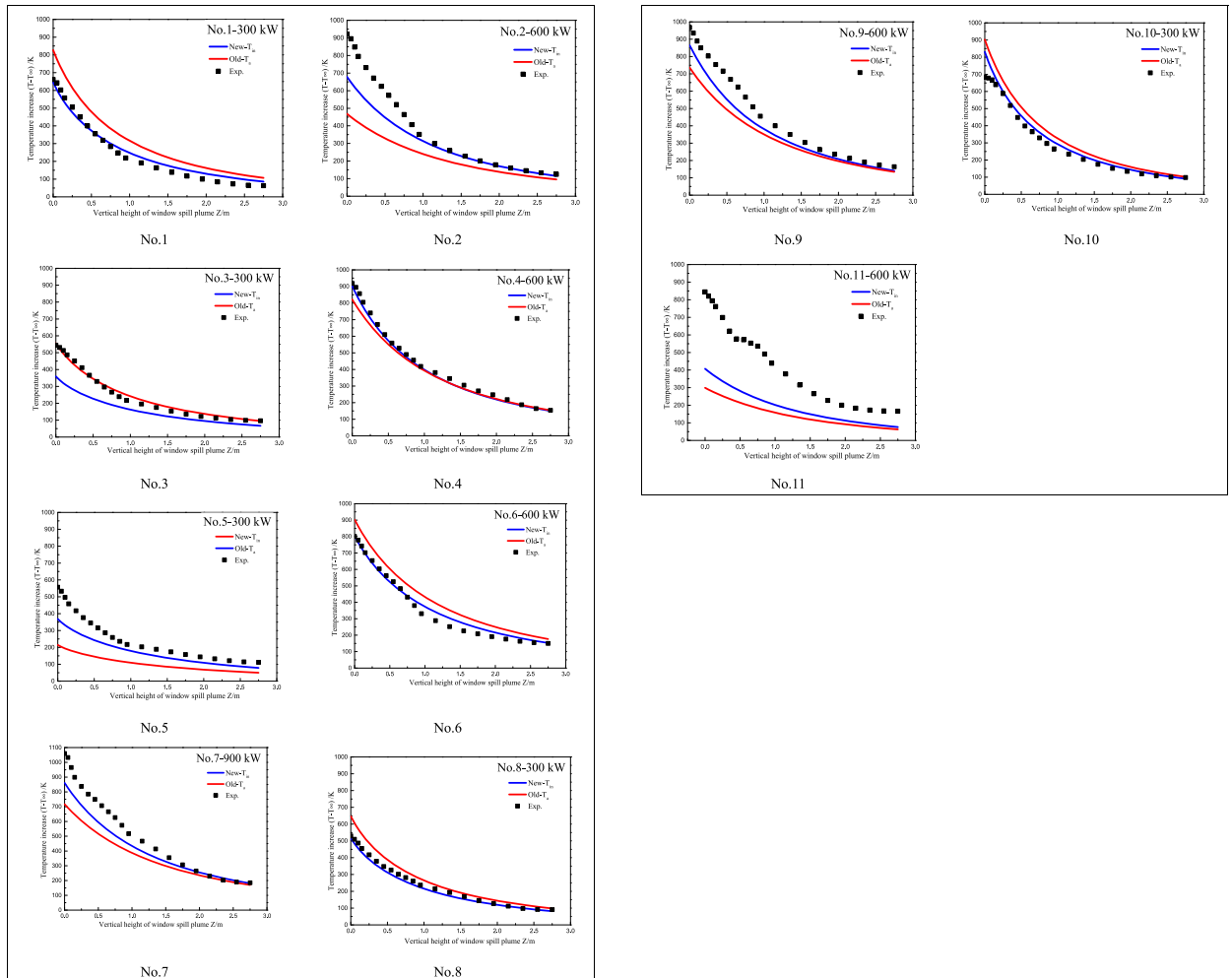


Fig. 6. Comparison between experimental and calculated temperature.

References

- [1] L. Miao, Y.Z. Yang, C.L. Chow, Experimental study on the variation regimes of window ejecting flame height, *Fire Saf. J.* 109 (2019) 102864.
- [2] S. Yokoi, Study on the Prevention of Fire-Spread Caused by Hot Upward Current, report No. 34 Building Research Institute, Japan, 1960.
- [3] B. Zhou, H. Yoshioka, T. Noguchi, T. Ando, Experimental study on vertical temperature profile of buoyant window spill plume from intermediate-scale compartments, *Fire Mater.* 44 (2020) 516–529.
- [4] T. Xu, F. Tang, Predicting the vertical buoyant spill-plume temperature along building facade with an external sloping facing wall, *Int. J. Therm. Sci.* 152 (2020) 106307.
- [5] Y. Tao, K.H. Lu, Z.L. Wang, Y.M. Ding, J. Wang, S.H. Mao, Experimental investigation on the temperature decay beneath a horizontal projection of spilled plumes from a compartment window, *Int. J. Therm. Sci.* 154 (2020) 106409.
- [6] C. Zhao, D. Yang, F. Tang, Y. Jiang, Buoyant opening spill flame behaviors beneath a horizontal projection induced by a compartment fire, *Exp. Heat Tran.* 32 (2019) 284–301.
- [7] F. Ren, L. Hu, X. Sun, Experimental investigation on lateral temperature profile of window-ejected facade fire plume with ambient wind, *Fire Technol.* 55 (2019) 903–913.
- [8] X. Zhang, Z. Zhang, Z. Zhang, W. Xu, Q. Luo, H. Tao, X. Li, Experimental investigation of compartment fires with circular opening: from the aspects of internal temperature and facade flame, *Combust. Flame* 213 (2020) 107–116.
- [9] M. Duny, D. Dhima, J.-P. Garo, H.-Y. Wang, Numerical and theoretical evaluations of a full-scale compartment fire with an externally venting flame, *Fire Technol.* 55 (2019) 2087–2113.
- [10] P.H. Thomas, M. Law, The projection of flames from burning buildings, *Fire Technol.* 5 (1972) 43–51.
- [11] Y. Ohmiya, Y. Hori, K. Sagimori, T. Wakamatsu, Predictive method for properties of flame ejected from an opening incorporating excess fuel [C], in: *Proceedings of 4th Asia-Oceania Symposium on Fire Science and Technology*, 2000, pp. 375–387.
- [12] J.-i. Yamaguchi, T. Tanaka, Temperature profiles of window jet plume, *Fire Sci. Technol.* 24 (2005) 78–85.
- [13] Y.P. Lee, M.A. Delichatsios, Y. Ohmiya, The physics of the outflow from the opening of an enclosure fire and re-examination of Yokoi's correlation, *Fire Saf. J.* 49 (2012) 82–88.

- [14] Y.P. Lee, M.A. Delichatsios, G.W.H. Silcock, Heat fluxes and flame heights in facades from fires in enclosures of varying geometry, *Proc. Combust. Inst.* 31 (2007) 2521–2528.
- [15] B. Karlsson, J. Quintiere, *Enclosure Fire Dynamics*, CRC press, 1999.
- [16] Y.-P. Lee, M. Delichatsios, Y. Ohmiya, The physics of the outflow from the opening of an enclosure fire and re-examination of Yokoi's correlation, *Fire Saf. J.* 49 (2012) 82–88.
- [17] Y.P. Lee, M.A. Delichatsios, Y. Ohmiya, theStudy for the physics of the outflow from the opening of a burning enclosure, in: *Proceedings of the 5th International Seminar on Fire and Explosion Hazards Edinburgh, 2007*, pp. 23–27. UK.
- [18] Quintiere, *Enclosure Fire Dynamics*, CRC press, 2002.
- [19] Architectural Institute of Japan, *Handbook on Design Calculation Methods of Fire Behavior*, 2018.
- [20] Y. Ohmiya, T. Tanaka, T. Wakamatsu, A room fire model for predicting fire spread by external flames, *Fire Sci. Technol.* 18 (1998) 11–21.
- [21] JIS A 1310, *Test Method for Fire Propagation over Building Facades*, Published By: Japanese Standards Association (JSA), Japan, 2015, 2015.