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Experimental Investigation on Lateral Temperature Profile of Window-Ejected Facade Fire Plume with Ambient Wind

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Abstract. The present study investigated experimentally the lateral temperature profiles of window-ejected facade fire plume from compartment with external ambient wind normal to the facade. The previous reports only focused on no wind conditions that the entrainment and diffusion of ambient air with the fire plume, which determines this lateral temperature profiles, is controlled solely by the buoyancy of the plume itself. This could be essentially affected by the external ambient wind, however, has not been revealed or quantified in the past. Hence, in this work, reduced-scale experiments were carried out employing a cubic compartment with an opening (window) and a facade wall, subjected to ambient wind provide by a wind tunnel. The lateral temperature profiles of the fire plume issued through the compartment opening was measured by thermocouples arrays installed along the facade, for various opening dimensions and ambient wind speeds. Results showed that with increasing of wind speed, the temperature at a fixed position decreased gradually, especially at those positions near the facade; while the lateral decay of temperature at a given height was faster as the wind speed was higher. This was interpreted by the physics that the ambient wind normal to the facade enhanced the entrainment and diffusion of ambient fresh air into the plume. Then, a formula (based upon classic Gaussian function) was put forward to characterize the lateral temperature profiles of the facade fire plume, by using the modified effective characteristic plume thickness (a horizontal diffusion length scale) to include wind effect. The obtained data and proposed formula in the present study provide a basic understanding for the window-ejected facade fire plume characteristics with ambient wind.

Keywords: Window-ejected facade fire plume, Lateral temperature profile, Gaussian profile, Urban fire, Ambient wind

List of Symbols

A	Opening area (m^2)
$A\sqrt{H}$	Ventilation factor of compartment opening ($m^{2.5}$)
g	Gravitational acceleration (m/s^2)
H	Opening height (m)
K	The ratio of the characteristic size of the facade fire plume in the direction normal to the facade to that parallel to the facade (dimensionless)
K_w	The ratio of the characteristic size of the facade fire plume in the direction normal to the facade to that parallel to the facade with wind (dimensionless)

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ℓ_1	Characteristic length scale of assumed rectangular fire source (m)
ℓ_2	Characteristic length scale of assumed rectangular fire source (m)
ℓ_x	Characteristic size of facade fire plume in the direction normal to facade (m)
ℓ_y	Characteristic size of facade fire plume in the direction parallel to facade (m)
L	Effective characteristic thickness of the facade fire plume (m)
L_w	Effective characteristic thickness of the facade fire plume with wind (m)
$\dot{Q}^*_{ex}$	Non-dimensional excess heat release rate (dimensionless)
U_w	Ambient wind speed (m/s)
W	Opening width (m)
x	Lateral distance away from the facade wall (m)
x_m	Lateral horizontal coordinate of the maximum temperature (m)
z	Vertical height (m)
z_n	Neutral plane height of the window (m)
z_0	Virtual origin height (m)

Greek Symbols

α	Entrainment coefficient (dimensionless)
β	Gaussian profile constant (dimensionless)
ΔT_x	Temperature rise above the ambient (°C)
ΔT_{max}	Maximum temperature rises above the ambient for a given height (°C)
λ	A coefficient to describe wind effect on air entrainment (dimensionless)

1. Introduction

The characteristics of window-ejected facade fire plumes from a room fire are important for building/urban safety. Study on its characteristics is an essential topic for building fire dynamics as well as the assessment of its impact on facade thermal insulation system and urban environment [1–6]. There has been extensive works reported in the literatures, addressing the flame height [4–9], vertical temperature profile [10, 11] and heat flux profile [12, 13] for window-ejected facade fire plumes. However, the reports on its lateral temperature profile are still relatively limited [14–16], while it is a basic quantity of a buoyant fire plume for essentially characterizing its environmental impact to urban.

For the available knowledge about the lateral temperature profiles of window-ejected facade fire plumes, Himoto et al. [14] obtained two-dimensional temperature profile (contour) outside the opening by conducting a series of reduced scale experiments. An equation was provided for predicting temperature rise along trajectory with the dimensionless heat release rate derived from the governing equations. Yamaguchi and Tanaka [15] also studied the two-dimensional temperature profile (contour) outside the compartment with eave for preventing fire spread. More recently, based upon the Gaussian profile approximation which has been widely used in free fire plume theories [17–19], Hu et al. [16] proposed a mathematical model to characterize the lateral temperature profile by re-considering the evolution of effective characteristic thickness (L) with height and the constant (β) in Eq. (1) (Gaussian function) of such window-ejected facade fire plumes,

$$\frac{\Delta T_x}{\Delta T_{max}} = \exp\left\{-\beta\left[\frac{x}{L}\right]^2\right\} \tag{1}$$

$$L = \ell_2 + \alpha\left(\frac{2K+1}{2}\right)(z - z_n - z_0) \tag{2}$$

$$K = \frac{\ell_x}{\ell_y} \approx \frac{\ell_2}{\ell_1} = \left(\frac{H}{W}\right)^{3/20} \tag{3}$$

where ΔT_x is the temperature rise above ambient and ΔT_{max} is the maximum value of ΔT_x at a given height, x is the lateral distance away from the facade, α is the entrainment coefficient (usually taken as 0.11) [16], z_0 is the virtual origin [16, 20], ℓ_x and ℓ_y is the plume scale in the direction perpendicular and parallel to the facade, respectively. The "rectangular fire source" theory proposed by Lee and Delichatsios [12, 21] was used to develop the functions mentioned above, where ℓ_1 (parallel to facade) and ℓ_2 (perpendicular to facade) were the two basic characteristic length scales determined by the dimensions of the opening (width; height). Then, the above functions can be derived [16] based on the air entrainment and diffusion into the facade fire plume, which is driven by the buoyancy of the plume.

However, there is still no work yet studying the lateral temperature profiles of a window-ejected facade fire plume subjected to ambient wind, despite that wind commonly exists in urban areas. One can imagine that once the ambient wind is involved, the entrainment and diffusion of air with the buoyant facade fire plume will be considerably changed. Hence, the lateral temperature profile in the plume will change accordingly, while has not been quantified yet. This is an essential knowledge gap to be addressed for this important topic.

So, a series of experiments were conducted in the present work to study the effect of ambient wind (normal to facade) on the lateral temperature profiles of window-ejected facade fire plumes. The lateral temperature profiles were measured for various window (opening) dimensions, heat release rates and ambient wind speeds. A basic formula was proposed based on the Gaussian function with a modified effective characteristic thickness (a horizontal diffusion length scale) to describe the lateral temperature profiles for the facade fire plume including wind effect.

2. Experiment

Figure 1 depicts the experimental equipment. The experimental facility is situated in the exit of a wind tunnel (providing stable wind speed range from 0 m/s to 2 m/s with fluctuation no more than 5%). The increasing interval of wind speed for various test cases in this work is 0.5 m/s. Real-time measurement of wind speed is employed by a four-probe anemometer (sampling interval: 1 s; measure-

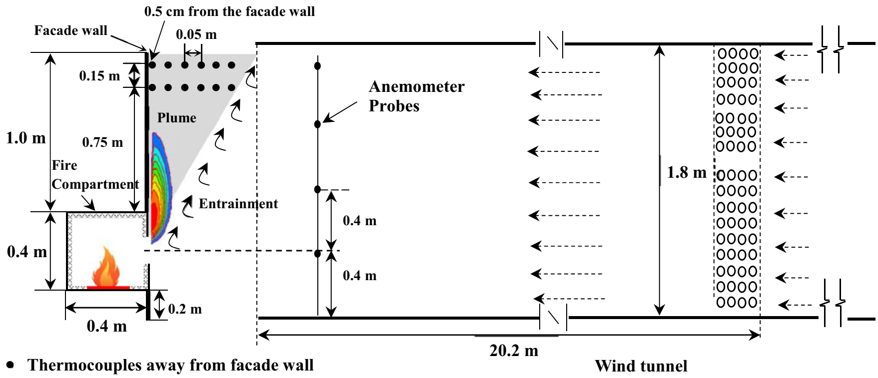


Figure 1. Experimental setup.

ment accuracy: 0.01 m/s). The experimental model consists of a 0.4 m cubic compartment and a facade. It is designed to be around a 1:8 physical scale models [22, 23] based on Froude modeling [24] for a room fire. A facade wall (1.2 m in width and 1.6 m in height) made by a 5 mm thick fire resisting board is placed at the top of the compartment. The ceramic fiber board (3 mm thick) was employed as inner wall for good thermal insulation (density: 285 kg/m^3, thermal conductivity: 0.18 W/(m K), specific heat: 1390 J/(kg K), thermal inertia: 267 J/(m^2 K s$^{0.5}$)). An opening (window) is set at one side wall of the fire compartment (same side with the facade wall). Three opening sizes representing diverse ventilation factors are considered in the experiments ($A\sqrt{H}$; A is the opening area and H is the opening height), as summarized in Table 1.

Propane is used as the fuel in the experiments (heat of combustion: 50.35 MJ/kg), which is supplied by a gas burner placed at the compartment floor center. The gas burner used is porous and square with dimension of 0.2 m. A mass flowmeter controls fuel supply flow rate (measurement accuracy: 0.01 dm^3/min). The fuel supply flow rates, hence heat release rates, are controlled to have the compartment fire at under-ventilated condition to have ejected facade flame outside the opening.

Table 1
Summary of Experimental Conditions

Test series	Opening dimensions (m)		Ventilation factor	Wind speed (m/s)				
	Width (W)	Height (H)	($A\sqrt{H}$, m$^{2.5}$)	0	0.5	1.0	1.5	2.0
				Total heat release rate (kW)				
1	0.20	0.10	0.0063	20.9–24.1				
2	0.15	0.15	0.0087	27.8–31.8				
3	0.10	0.20	0.0089	26.9–31.4				

The lateral temperature profiles of the facade fire plume ejected from the opening are measured by two horizontal thermocouple arrays (6 columns, horizontal interval between columns is 0.05 m) installed at 0.75 m and 0.9 m above the compartment top surface in the central plane normal to the facade, as shown in the Fig. 1. The horizontal distance of the nearest thermocouple is 0.5 cm away from the facade wall. The temperature values measured in the experiments are calibrated by radiation correction. Each experimental case is repeated 3 times. The data (temperature value) fluctuation is found to be no more than 5%, and the averaged lateral temperature values are analyzed and discussed in the following section.

3. Results and Discussion

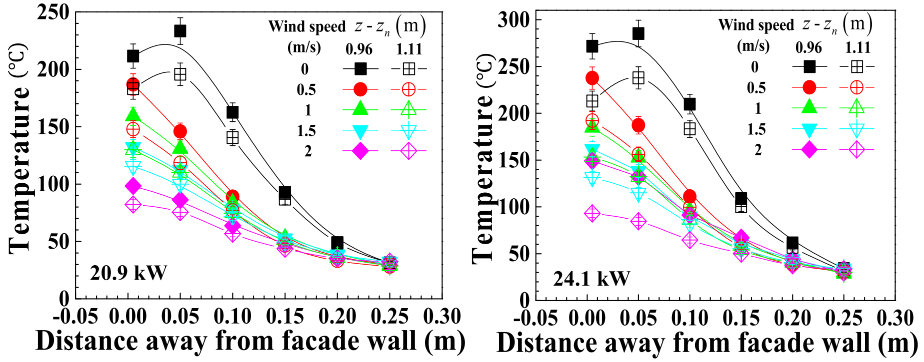
3.1. Measured Lateral Temperature Profile

Figure 2 presents the lateral temperature profiles measured for the window-ejected facade fire plumes under various heat release rates (HRR) and wind speeds for each opening. It is shown that: (1) with increasing of distance from the facade wall, the temperature first increases (0.05 m to the facade wall) then decreases for no wind condition, however, the temperature monotonically decreases under wind conditions; (2) the temperature measured at higher location is lower than that at relative lower location, however, their difference gradually reduces with the increasing of distance away from the facade wall; and (3) at a given distance from the facade, the temperature generally deceases with increasing of wind speed, which is more obvious when the distance from the facade is smaller.

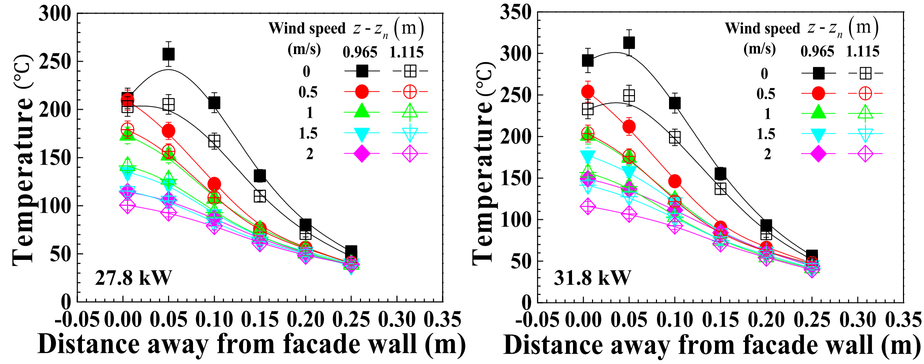
Figure 3 depicts the normalized lateral temperature profiles against the dimensionless lateral distance based on the model of Eq. (1) proposed by Tang [16] for each opening, the temperature rise is normalized by the maximum temperature rise at $x = x_m$ of each height (see the ordinate). Here, the dimensionless lateral distance $(x - x_m)/L$ is used as the abscissa, considering that the maximum temperature value appears in different position under various wind speeds (as shown in Fig. 2). It can be seen that the experimental data of lateral temperature for different wind speeds cannot converge well using the model of Eq. (1). Also, the decay rate of the normalized lateral temperature profile decreases with the increasing of wind speed, which is caused by the enhanced air entrainment under wind condition. The effective characteristic thickness of the facade fire plume L in the Eq. (1) should be re-defined for wind condition.

3.2. Analysis and a New Formula Including Wind Effect

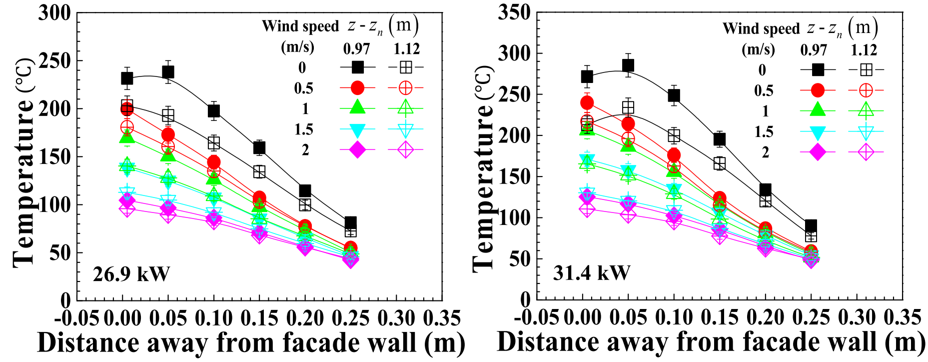
The entrainment and diffusion of air into the buoyant plume makes its horizontal thickness (L) to increase with vertical height [16], which accounts for basically the lateral temperature decay as shown in Eq. (2). The ambient wind will significantly influent the air entrainment and diffusion. As found recently [9] for the window-ejected facade flame height under external wind normal to the facade, this change can be represented by a modification of the two characteristic length scales, ℓ_1 and



(a) 0.20 (*W*)×0.10 (*H*)



(b) 0.15 (*W*)×0.15 (*H*)



(c) 0.10 (*W*)×0.20 (*H*)

Figure 2. Lateral temperature profiles of the facade buoyant plume for various heat release rates and opening sizes under different wind speeds.

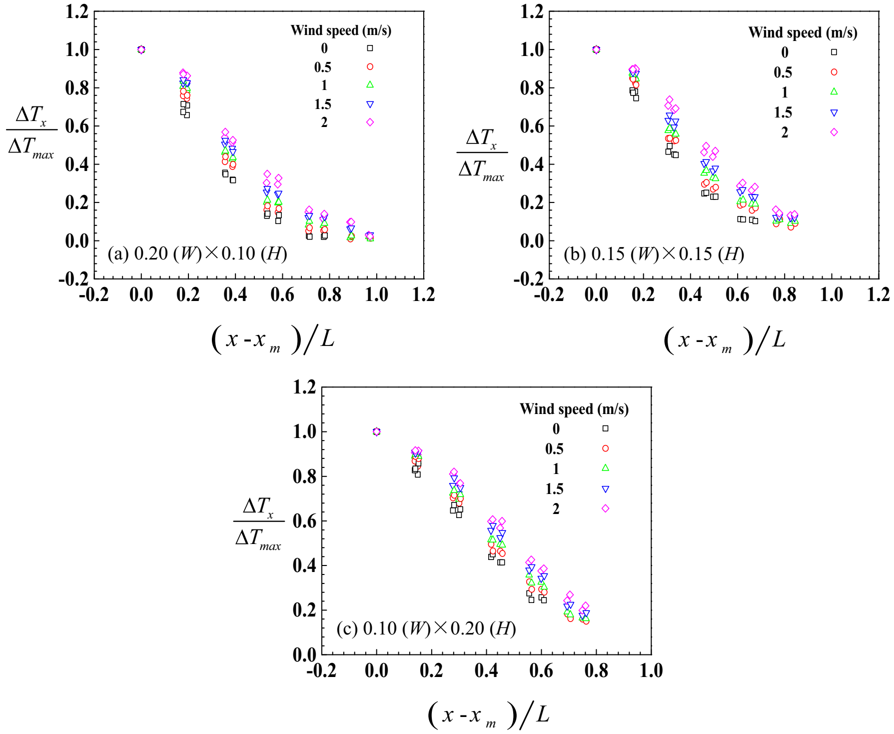


Figure 3. Collapse of experimental data by the model of Eq. (1) for various wind speeds of each opening.

ℓ_2 to be $\ell_1(1 + \lambda U_w/\sqrt{gH})$ and $\ell_2(1 - \lambda U_w/\sqrt{gH})$, respectively; where $U_w/\sqrt{gH}$ is a Froude number representing the competition of wind inertial to the buoyancy of the window-ejected facade fire at the opening. One notes that these two characteristic length scales determines the "rectangular source" [12, 21] dimensions, as well as the entrainment and diffusion of air from surroundings into the facade fire plume. So, the coefficient K in Eq. (3) should be modified to be

$$K_w = \frac{\ell_x}{\ell_y} \approx \frac{\ell_2}{\ell_1} \cdot \frac{1 + \lambda U_w/\sqrt{gH}}{1 - \lambda U_w/\sqrt{gH}} \tag{4}$$

Besides, the virtual origin height z_0 in Eq. (2) was found to change little with wind speed [11]. Thus, the effective plume thickness length scale under wind condition can be expressed as,

$$L_w = \ell_2 + \alpha\left(\frac{2K_w + 1}{2}\right)(z - z_n - z_0) \tag{5}$$

The coefficient λ in Eq. (4), which describes the ambient wind effect on air entrainment, was found to be a function of $\dot{Q}_{ex}^{*\,2/5}$ (non-dimensional excess heat release rate) [9]:

$$\lambda = 0.8\dot{Q}_{ex}^{*\,2/5} - 0.76 \tag{6}$$

Applying the new effective plume thickness length scale under wind conditions, the experimental data of lateral temperature data are presented in Fig. 4. It is shown that the experimental data of various wind speeds are well collapsed for each opening. However, it should be noted that the value of constant (β) in Gaussian profile function decreases with increasing of opening aspect ratio (H/W).

Figure 5 correlates the value of $\beta^{-1/2}$ (obtained in Fig. 4) against the opening aspect ratio of openings by an exponential function proposed by Tang [16]. The following formula (Eq. 7) was found to characterize the opening aspect ratio effect on the value of β, a basic parameter for describing the lateral temperature profile based on Gaussian function:

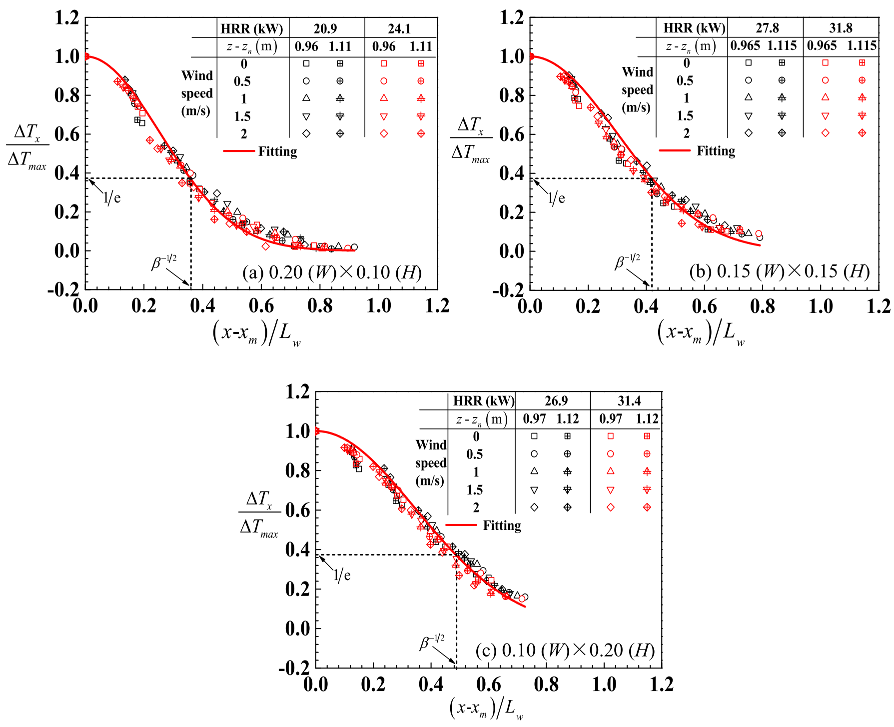


Figure 4. Collapse of experimental lateral temperature by Gaussian function for each opening showing that the newly defined effective plume thickness length scale L_w [Eq. (5)] can correlate the experimental data for different wind speeds.

$$\beta^{-1/2} = 1 - 0.7e^{-0.25\,(H/W)} \tag{7}$$

Substituting Eq. (5) and Eq. (7) into Eq. (1), a new non-dimensional formula including wind effect on lateral temperature profile of window-ejected facade fire plume can be expressed as below:

$$\frac{\Delta T_x}{\Delta T_{max}} = \exp\left\{-\left[\frac{x/\left(1-0.7e^{-0.25(H/W)}\right)}{\ell_2 + \alpha\left(\frac{2K_w+1}{2}\right)(z - z_n - z_0)}\right]^2\right\} \tag{8}$$

Figure 6 compares the proposed model [Eq. (8)] with experimental data of the lateral temperature profiles for all wind speeds, heat release rates and opening sizes. It is shown that all the experimental data can be well represented by the proposed model.

4. Conclusions

This work studied the effect of ambient wind on lateral temperature profiles of buoyant fire plume issued from a fire compartment through its opening (window). Lateral temperature profiles were obtained experimentally and analyzed for different opening sizes (ventilation factor), heat release rates and wind speeds. This study provides a basic understanding for the window-ejected facade fire plume characteristics with ambient wind. Major findings include:

(1) The lateral temperature at a fixed position decreased with wind speed for all heat release rates and opening sizes, especially at those positions near the facade wall (Fig. 2).
(2) The lateral temperature profile for a given opening size can be well correlated by using the new proposed effective characteristic thickness of facade buoyant

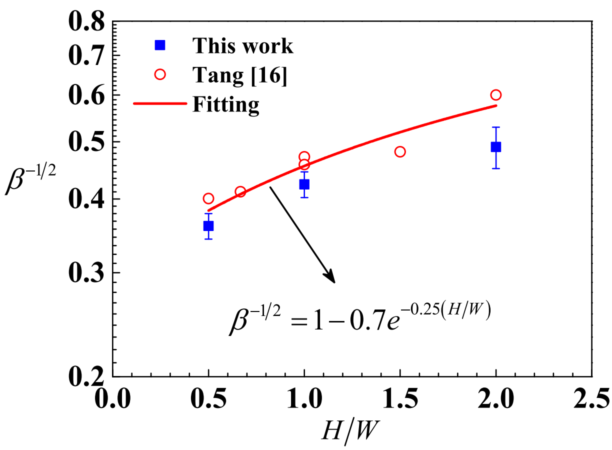


Figure 5. Correlation of value β with opening aspect ratio.

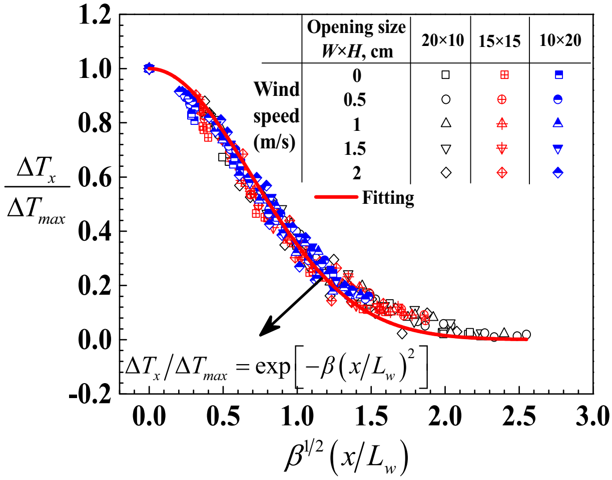


Figure 6. Comparison of the predictions of the proposed model [Eq. (8)] with experimental data for all wind speeds and opening sizes.

plume under wind condition [Eq. (5); Fig. 4]. However, the Gaussian profile constant (β) obtained of each opening was higher as opening size is large, which was found to correlate with the aspect ratio (H/W) (Fig. 5).

(3) A new formula is put forward to describe the lateral temperature profiles of facade buoyant fire plumes including ambient wind effect [Eq. (8); Fig. 6].Publisher's NoteSpringer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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