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Research Paper

Smoke spread velocity along a corridor induced by an adjacent compartment fire with outdoor wind

S.C. Li [a], D.F. Huang [b], N. Meng [c], L.F. Chen [d], L.H. Hu [d,*]

[a] Department of Fire Command, The Chinese People's Armed Police Force Academy, Langfang, Hebei 065000, China
[b] Public Security and Fire Fighting Forces Academy, Kunming, Yunnan 650208, China
[c] College of Mining and Safety Engineering, Shandong University of Science and Technology, Qingdao, Shandong 266590, China
[d] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, China

HIGHLIGHTS

- Smoke velocity along corridor generated from adjacent fire room with outdoor wind.
- A theoretical model of smoke velocity in the corridor with outdoor wind established.
- Experiments were performed to investigate the velocity of smoke in the corridor.

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ABSTRACT

Outdoor wind is one of the important driving forces of fire smoke movement in high-rise buildings. This paper investigates the smoke spread velocity along a corridor induced by an adjacent compartment fire with outdoor wind. Based on momentum and mass conservation laws, a theoretical model predicting the smoke spread velocity was developed. Reduced-scale experiments were performed for model validation. Correlations for smoke spread velocity in the corridor under the effect of outdoor wind were proposed. It is found that the initial velocity can be very well predicted according to the stratification stability of smoke with the criterion of *Fr*. Moreover, the velocity profiles along the corridor decay exponentially.

1. Introduction

The number of high-rise or super high-rise buildings has been increasing rapidly in recent years. High-rise building fire is a crucial concern of fire safety engineering and has attracted more and more attention due to the large number of casualties, such as the notable Jingan fire in Shanghai on Nov. 15th, 2010, 58 persons were killed in the disaster. Statistics have shown that smoke is the most hazardous factor in fires [1,2] hence it is worthwhile studying its spread. The driving forces of smoke spread include thermal buoyancy, expansion, heat pressure (stack effect), wind effect, mechanical ventilation and so on. The outdoor wind velocity increases exponentially with increase of building height, which has significant influence on the fire smoke spread in high-rise building. Outdoor wind may blow into the fire room from open windows and carry a large amount of smoke into the corridor, which threats the safety evacuation process significantly. Therefore, it is necessary to study the smoke spread velocity in the corridor under the effect of outdoor wind.

There have been numerous studies on smoke velocity in corridor driven by thermal buoyancy. The correlation developed by Hinkley [3] is well-known as

$$V = 0.8\left(\frac{gQT}{C_p\rho_a T_a^2 W}\right)^{1/3} \tag{1}$$

where g is the gravitational acceleration, Q denotes the fire heat release rate, T denotes the absolute temperature of smoke, C_p is the specific heat of smoke at normal pressure, ρ_a is the ambient air density, T_a is the ambient temperature, and W is the width of the corridor. Kim et al. [4] conducted experiments in a corridor with dimensions of 11.83 m long, 2.83 m wide and 2.3 m high and used laser-assisted visualization technology for smoke measurements. It was found that the smoke velocities calculated from Hinkley's formula were 20% greater than the measured values. He [5] further

* Corresponding author.
E-mail address: hlh@ustc.edu.cn (L.H. Hu).

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Nomenclature

C_p	specific heat of air at constant pressure (kJ/kg K)	m_e	mass flow rate of air entrainment (kg/s)
g	gravitational acceleration (m/s^2)	m_s	mass flow rate of smoke entering the corridor from the fire room (kg/s)
Q	fire heat release rate (kW)	m	initial mass flow rate of smoke in the corridor (kg/s)
Q_{cv}	the actual heat flow rate of ceiling jet (kW)	w_e	entrainment rate of fresh air (m/s)
C_{pw}	wind pressure coefficient of the upwind side	A_w	window area (m^2)
C_{pl}	wind pressure coefficient of the leeward side	A_d	door area (m^2)
T	absolute temperature of the smoke (K)	a	back pressure coefficient
T_a	ambient temperature (K)	C_0	transmissibility coefficient, equals 0.7 in this paper
ΔT	temperature rise of fire smoke (K)	τ	frictional resistance between smoke and the wall (Pa)
T_2	temperature in the fire room (K)	λ	friction drag coefficient between smoke layer and the ceiling
T_1	initial temperature in the corridor (K)	h_{fr}	loss of resistance along the path (kg/m s^2)
Fr	Froude number	D	hydraulic diameter of the corridor (m)
u	local horizontal velocity of smoke (m/s)	W	width of corridor (m)
u_0	initial velocity of smoke entering the corridor (m/s)	ρ_s	density of smoke (kg/m^3)
u'_0	velocity of smoke through the doorway under the effect of simple thermal buoyancy (m/s)	ρ_a	density of ambient air (kg/m^3)
h	thickness of smoke layer (m)	$\Delta\rho$	density difference between air and smoke (kg/m^3)
u_w	horizontal velocity of outdoor wind after entering the corridor (m/s)		
v_w	outdoor wind velocity (m/s)	*Subscripts*	
v_{w0}	initial velocity of outdoor wind entering the corridor (m/s)	a	ambient
H	height of doorway (m)	s	smoke
U	velocity difference between the upper smoke and lower air (m/s)	0	the initial value in the corridor
		cv	convective

studied Kim's experiments and found that the smoke flowed at only one direction in Hinkley's assumption; however, the smoke propagated to both two directions of the corridor in Kim's experiments. He [5] assumed the fire smoke as double symmetric flow after entering the corridor and modified the Hinkley's correlation as

$$V = 0.8\left(\frac{0.5gQT}{C_p\rho_a T_a^2 W}\right)^{1/3} \tag{2}$$

Eq. (2) gave better predictions to Kim's experiments compared to Eq. (1). As zone models cannot be applied to tunnels or long corridors, the smoke in the corridor is simplified to a two-dimensional flow by Jones et al. [6] who assumed that the density of smoke maintained constant. A simplified equation for calculating the average velocity of smoke was proposed:

$$V_{mean} = 0.961\left(\frac{\Delta\rho g V_l}{\rho_s W}\right)^{1/3} \tag{3}$$

where V_l denotes the volumetric flow rate of smoke in the corridor, $\Delta\rho$ is the density difference between air and smoke, and ρ_s is the density of smoke.

On the basis of the field model, Baily et al. [7] proposed a sub-model to improve the CFAST zone model, and the horizontal velocity and temperature rise of fire smoke were expressed as:

$$V \approx 0.7\left(gh\frac{\Delta T}{T_0}\right)^{1/2} \tag{4}$$

$$\Delta T = \Delta T_0\left(\frac{1}{2}\right)^{x/16.7} \tag{5}$$

where h denotes the depth of smoke layer, T_0 is the ambient temperature, and ΔT is the temperature rise of smoke.

To validate the model, Baily et al. [7] conducted experiments in a 8.51 m long corridor and the results agreed well with the model predictions. However, actual corridors are much longer than 8.51 m, therefore, further validation is still demanded.

Hinkley's correlation was further modified by Yang [8] who noted that the heat loss from the smoke layer to boundary walls is very large and the actual heat flow rate of smoke could be significantly lower than the convective heat released from the fire origin. Under such conditions, Hinkley's correlation should be modified by replacing Q with the actual heat flow rate of the ceiling jet, Q_{cv}:

$$V = 0.8\left(\frac{gQ_{cv}T}{C_p\rho_a T_a^2 W}\right)^{1/3} \tag{6}$$

$$Q_{cv} = \frac{\Delta T V_l \rho_a T_a C_p}{T} \tag{7}$$

where V_l denotes the volumetric flow rate of fire smoke.

Yang compared the calculated results of Eqs. (6) and (7) with experimental results and found that the maximum difference was less than 15%, which indicates that Eq. (6) can predict the flow rate of smoke well.

Based on mass, momentum and energy conservation, the distributions of temperature and velocity along the corridor were established by Hu et al. [9]:

$$\frac{\Delta T}{\Delta T_0} = \exp\left[-\frac{\alpha}{\rho hu}(x - x_0)\right] \tag{8}$$

$$\frac{u}{u_0} = \exp\left[-\frac{\lambda}{2h}(x - x_0)\right] \tag{9}$$

where ΔT is the temperature rise of smoke at the location of $x - x_0$ m away from the reference position, u is the local horizontal velocity of smoke, and λ is the friction coefficient usually ranging from 0.0055 to 0.0073. The theoretical model of Hu was validated by the experimental data in a full-scale corridor with a dimension of 88.0 m (length) × 8.0 m (width) × 2.65 m (height). It is noted that the temperature and velocity distributions along the corridor fell into exponential decays.

All the studies above were focused on the velocity of smoke under thermal buoyancy. Few studies were carried out on the fire smoke movement under the combined effects of thermal buoyancy and outdoor wind. The current paper theoretically and experimentally studies the smoke spread velocity in the corridor of high-rise buildings under the effect of outdoor wind.

2. Theoretical analysis

When the outdoor wind blows into the fire room, the smoke in the room is affected by two factors: heat and air. When the thermal buoyancy is dominant, the smoke layer can spread into the corridor maintaining a good stratification. However, when the outdoor wind is dominant, the smoke layer will lose stability and enters the corridor mixed with the outdoor air. Thus the stratification stability of smoke in the corridor can be used to determine whether it is thermal buoyancy or outdoor wind dominant.

Outdoor wind is one kind of forced ventilations. The effect of outdoor wind on the smoke layer is actually a function of the inertia force induced by the forced ventilation. The fire-induced buoyancy tends to maintain the stability of stratification whereas the outdoor wind tends to mix the flows. Therefore, the fire-induced stratification depends upon these two competing mechanisms. Froude number was commonly used to characterize the competition of inertia force and buoyancy force [10]. Newman [11] presented a very simple method to identify the stratification condition in terms of Fr:

$$Fr = \frac{u_{avg}}{\sqrt{gH\Delta T_{cf}/T_{avg}}} \tag{10}$$

where H denotes the height of the corridor, ΔT_{cf} is the temperature difference between ceiling and floor and $u_{avg} = uT_{avg}/T_a$, T_{avg} is the mean temperature of the section at certain place in the corridor and u is the local horizontal velocity of smoke.

Nyman, Ingason and Li [12,13] indicated that: (a) when $Fr < 0.9$, it can be approximated that the smoke layer is affected only by thermal buoyancy and there is noticeable stratification between the smoke layer and ambient air; (b) when $0.9 \leqslant Fr \leqslant 3.2$, there is strong interaction between forced horizontal flow and buoyancy forces; (c) when $Fr > 3.2$, the smoke stratification is destructed and the smoke layer in the corridor loses its stability and flows mixing with the outdoor wind.

Based on the theories of smoke velocity under thermal buoyancy, this paper took into account the effect of outdoor wind, the theory of momentum theorem and Bernoulli principle. Theoretical model of smoke velocity in the corridor under the effect of outdoor wind was developed based on the following assumptions:

(1) The velocity distribution in the smoke layer and the lower air was uniform.
(2) The density of smoke in the corridor was constant.
(3) The smoke flow in the corridor was always in a steady state.

2.1. Velocity model of smoke movement when thermal buoyancy effect was dominant

When the thermal buoyancy effect was dominant, the smoke layer keeps well stratification in the corridor and a section of smoke was selected as control unit (as shown in Fig. 1). According to momentum conservation, the mass flow of the control unit is

$$\frac{d}{dx}(\rho_s h u^2) = \rho_a w_e v_{w0} - \frac{d}{dx}\left[\frac{1}{2}g(\rho_a - \rho_s)h^2\right] - \tau \tag{11}$$

where τ denotes the frictional resistance between smoke and the wall, $\frac{d}{dx}\left[\frac{1}{2}g(\rho_a - \rho_s)h^2\right]$ denotes the resistance of the air, w_e denotes the entrainment rate of the fresh air, $\rho_a w_e v_{w0}$ means the momentum increase induced by the entrainment of the air, u is the horizontal velocity of smoke, and v_{w0} is the horizontal velocity of outdoor wind after entering the corridor.

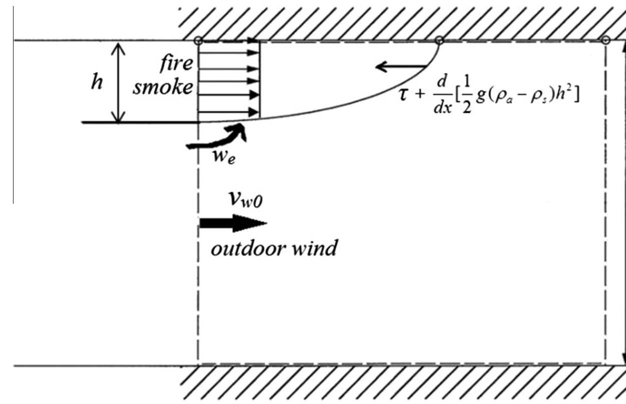


Fig. 1. Schematic of the smoke front when thermal buoyancy effect was dominant.

According to the basic theory of fluid mechanics:

$$\tau = \lambda \rho_s u^2 \tag{12}$$

where λ is the friction drag coefficient between the smoke layer and the ceiling.

Assuming that the smoke layer thickness h is constant, the second term at the right side of Eq. (11) can be approximated as 0. Therefore, Eq. (11) can be rewritten as:

$$\frac{d}{dx}(\rho_s h u^2) = \rho_a w_e v_{w0} - \lambda \rho_s u^2 \tag{13}$$

Eq. (13) will be analyzed in Section 4.1.

2.2. Velocity model of smoke movement when outdoor wind effect was dominant

When outdoor wind effect was dominant (as shown in Fig. 2), the smoke in the fire room would become instable and enter the corridor mixed with outdoor wind. Stratification in the corridor would disappear and according to Bernoulli equation, the following equations are obtained:

$$\frac{1}{2}\rho u_0^2 = \frac{1}{2}\rho u^2 + h_{fr} \tag{14}$$

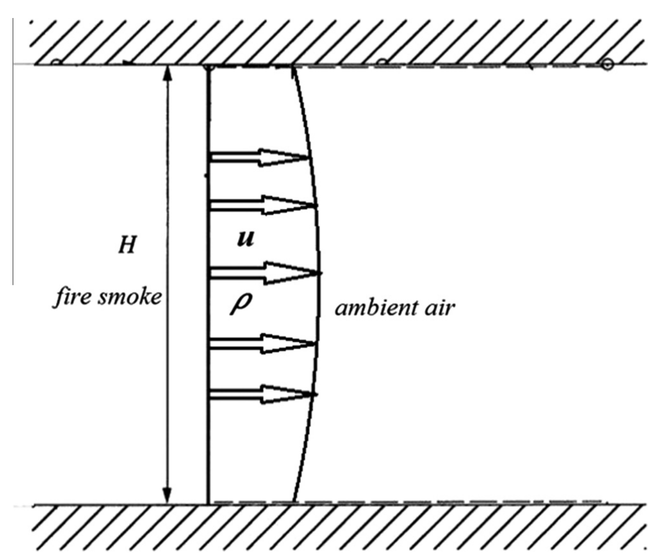


Fig. 2. Schematic of the smoke front when outdoor wind effect was dominant.

with

$$h_{fr} = \int_0^x \frac{\lambda\rho}{2D} u^2 \, dx \tag{15}$$

where h_{fr} is the loss of resistance along the path, and D is the hydraulic diameter of the corridor. Substituting Eq. (15) into (14) and differentiating Eq. (14) with respect to x, getting

$$\rho u \frac{du}{dx} = -\frac{\lambda \rho u^2}{2D} \tag{16}$$

Integrating both sides of Eq. (16) and substituting the initial condition, $x = x_0$ and $u = u_0$, into it, getting

$$\frac{u}{u_0} = e^{-k_2(x-x_0)} \tag{17}$$

where $k_2 = \lambda/2D$.

2.3. Initial solution and determination of undetermined parameters

To obtain the distribution of horizontal smoke velocity along the corridor, the entrainment rate w_e, smoke layer thickness h and initial velocity of smoke entering the corridor u_0 need to be determined.

When the thermal buoyancy effect is dominant, the smoke near the door of the fire room can be assumed as edge wall plume [14]. Fresh air in the lower part would be entrained into the smoke plume near the door. As outdoor wind velocity was much bigger than that of smoke, the velocity of smoke in the upper part of the room would increase with the entrainment of air. Momentum conservation equation near the door of the fire room was:

$$m_e v_{w0} + m_s u'_0 = m u_0 \tag{18}$$

$$u_0 = \frac{1}{m}(m_e v_{w0} + m_s u'_0) \tag{19}$$

with

$$m_s = 0.09 Q_{cv}^{1/3} W^{2/3} H \tag{20}$$

$$m = 1.6 m_s \tag{21}$$

where m_e is the mass flow rate of air entrainment, m_s is the mass flow rate of smoke entering the corridor from the fire room, m is the initial mass flow rate of smoke in the corridor, m equals to the sum of m_s and m_e [15], u'_0 is the velocity of smoke through the doorway under the effect of only thermal buoyancy, u_0 is the initial velocity of smoke entering the corridor, and v_{w0} is the initial velocity of outdoor wind entering the corridor.

Owing to mass conservation, the mass flow of outdoor wind entering the fire room equals to the mass flow out of the room. Then the initial velocity of outdoor wind entering the corridor can be expressed as follows:

$$v_{w0} = \frac{a A_w v_w}{A_d} \tag{22}$$

Here, a is the back pressure coefficient ranging from 0.6 to 1.0 [16]. It is suggested [16] that $a = 0.9$ when the outdoor wind is relatively weak and $a = 0.7$ when the outdoor wind is relatively strong. This is because most of the wind flowed through the door into the corridor when the wind is weak and the stratification was strong. However when the wind was strong and the stratification became disordered, part of the wind would be mixed with the smoke in the fire room and the proportion of the wind entering the corridor would be lower. A_w is the window area, A_d is the door area, and v_w is the outdoor wind velocity.

Then, the outdoor wind is considered to have no effect on the smoke movement in the fire room, the smoke can be considered as entering the corridor only with deriving force of thermal buoyancy. Thus, the velocity of smoke through the doorway only under the effect of thermal buoyancy can be expressed as follows [17]:

$$u'_0 = C_0 \sqrt{2gH} \left[\frac{1-d}{d(1+d^{1/3})}\right]^{1/2} \tag{23}$$

where $d = T_1/T_2$, T_1 is the initial temperature in the corridor, T_2 is the temperature in the fire room; H is the height of doorway; and C_0 is the transmissibility coefficient, in generally $C_0 = 0.7$.

Substituting Eqs. (20)–(23) into Eq. (19), when the thermal buoyancy is dominant, the initial velocity of the smoke entering the corridor can be expressed as follows:

$$u_0 = \frac{1}{1.6}\left[\frac{0.54 A_w v_w}{A_d} + 0.7\sqrt{2gH}\left(\frac{1-d}{d(1+d^{1/3})}\right)^{1/2}\right] \tag{24}$$

When the outdoor wind effect is dominant, it is assumed that the smoke layer was instable. The momentum conservation equation near the door of the fire room is:

$$\rho_a A_d v_{w0}^2 + m_s u'_0 = m u_0 \tag{25}$$

$$u_0 = \frac{1}{m}(\rho_a A_d v_{w0}^2 + m_s u'_0) \tag{26}$$

where $m = m_s + \rho_a A_d v_{w0}$.

Substituting Eqs. (20)–(23) into Eq. (26), when the outdoor wind effect is dominant, the initial velocity of smoke entering the corridor can be expressed as

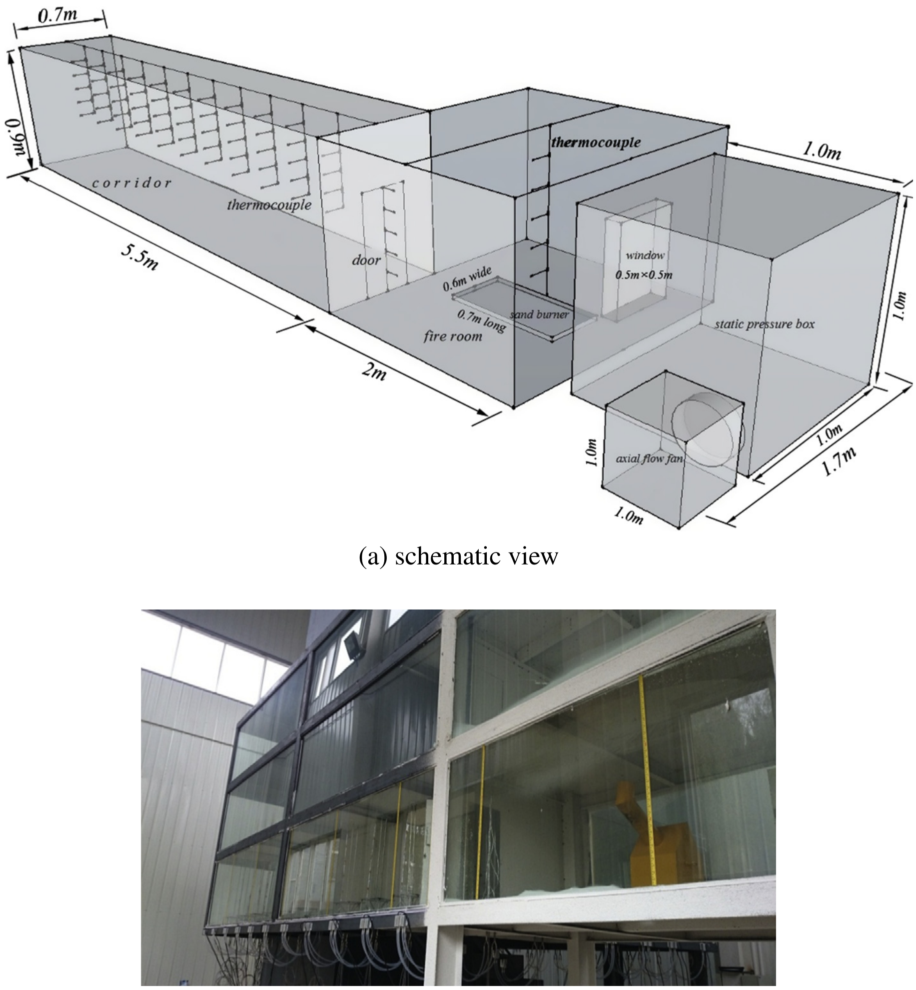
$$u_0 = \frac{0.49\rho_a (A_w v_w)^2 + 0.063 Q_{cv}^{1/3} W^{2/3} H A_d \sqrt{2gH}\left[\frac{1-d}{d(1+d^{1/3})}\right]^{1/2}}{0.09 Q_{cv}^{1/3} W^{2/3} H A_d + \rho_a A_w A_d v_w} \tag{27}$$

3. Experiments

Experiments were conducted in a 1/3 scale horizontal corridor with an internal dimension of 5.5 m (length) × 0.7 m (width) × 0.9 m (height). The schematic view of the experimental corridor and the fire room and the experimental setup are shown in Fig. 3. The fire source was set in the room with a dimension of 2.0 m (length) × 1.7 m (width) × 1.0 m (height) and the dimension of the door connecting the room and the corridor was 0.7 m long by 0.3 m wide. Dimension of the window opposite to the door was 0.5 m (width) × 0.5 m (height). The ceilings and floors of the corridor and fire room were made of steel plate with a thickness of 2.5 mm. The side walls of corridor and fire room were made of fire-resistant glass with a thickness of 10 mm for observation. The ceiling of the room and the corridor were coated with fireproof paint to avoid the damage of high temperature. Sealing treatment was made at each joint.

Fan and static pressure box were used to generate the outdoor wind (as shown in Fig. 3(a)). A frequency converter was used to adjust the velocity of outdoor wind by changing the AC frequency. The flow rate of the axial flow fan was 3740–5029 m^3/h and the rated speed was 2800 r/min. An opening was made with the same dimension as the window to blow air into the fire room.

The gas temperatures in the corridor were measured using K-type shielded thermocouples with a diameter of 1 mm. The measurable temperature range was −50 to +800 °C with an accuracy of ±1 °C. And the response time was on the order of 1 s. The gas temperatures in the fire room were measured using K-type shielded thermocouples with a diameter of 2 mm and a measurable temperature range of −50 to +1200 °C. There were 11 thermocouple trees at the centerline of the corridor with a horizontal interval of 0.5 m. Each thermocouple tree consisted of



(a) schematic view

(b) photo of the experimental facility

Fig. 3. Schematic view of the experimental corridor and room and photo of the experimental facility.

Table 1
Summary of experimental conditions.

Test No.	Heat release rate (kW)	Velocity of outdoor wind (m/s)	Test No.	Heat release rate (kW)	Velocity of outdoor wind (m/s)
1	32.1	0	19	64.2	7.0
2	32.1	1.0	20	80.2	0
3	32.1	2.0	21	80.2	1.0
4	32.1	3.0	22	80.2	2.0
5	32.1	4.0	23	80.2	3.0
6	48.1	0	24	80.2	4.0
7	48.1	1.0	25	80.2	5.0
8	48.1	2.0	26	80.2	6.0
9	48.1	3.0	27	80.2	7.0
10	48.1	4.0	28	96.2	0
11	48.1	5.0	29	96.2	1.0
12	64.2	0	30	96.2	2.0
13	64.2	1.0	31	96.2	3.0
14	64.2	2.0	32	96.2	4.0
15	64.2	3.0	33	96.2	5.0
16	64.2	4.0	34	96.2	6.0
17	64.2	5.0	35	96.2	7.0
18	64.2	6.0			

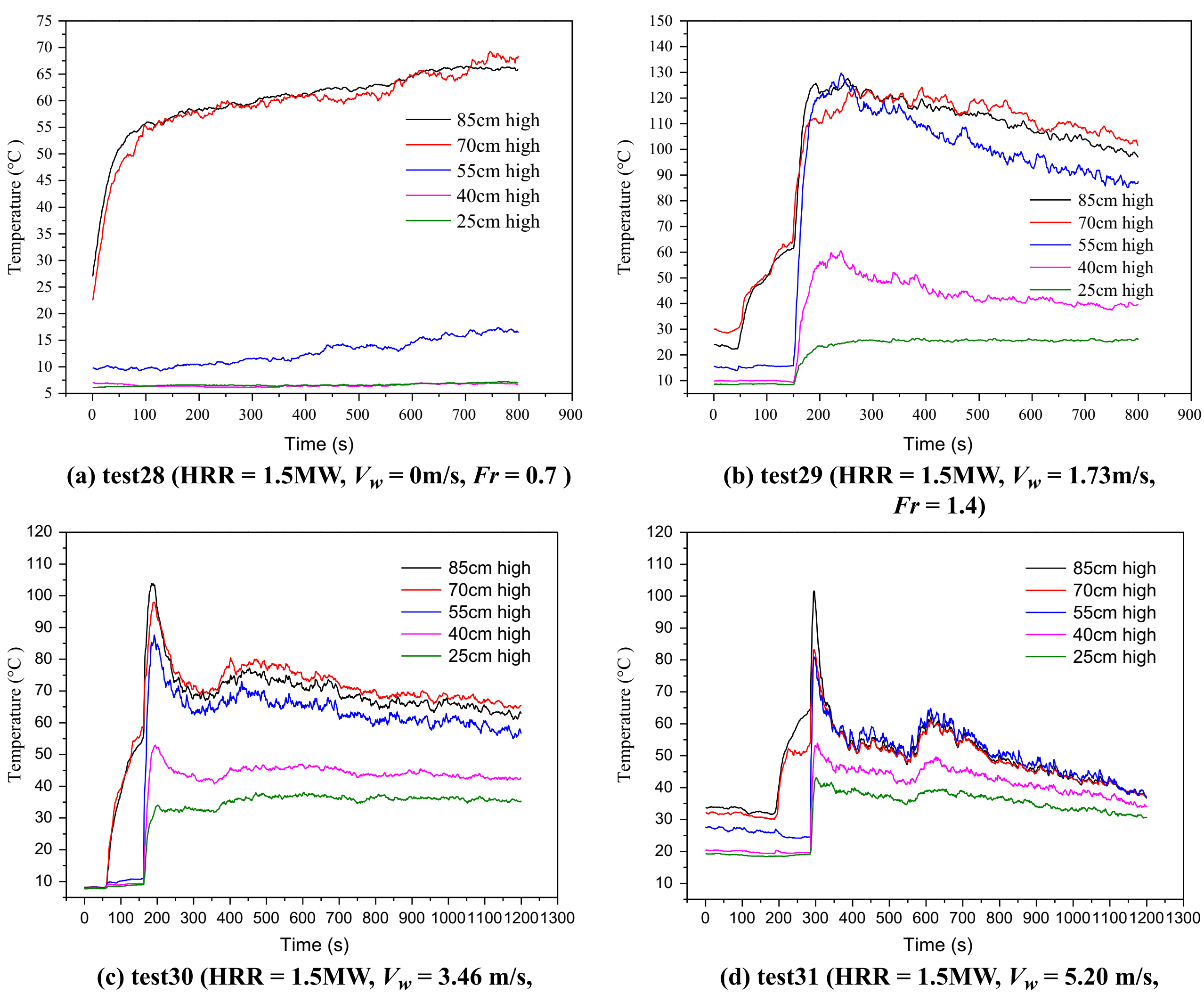
5 thermocouples with a vertical interval of 0.15 m. There were also two thermocouple trees located in the fire room. Each thermocouple tree is consisted of 5 thermocouples with a vertical interval of 0.1 m.

The velocity of smoke was measures by hot wire wind speed meter that can be used within the temperature range of −20 °C to 120 °C. The accuracy was 0.01 m/s when the wind speed meter was 0–9.99 m/s and 0.1 m/s when the wind speed meter was 10.0–50.0 m/s.

A gas burner was used to simulate the fire source. The dimension of the burner was 0.7 m (length) × 0.6 m (width) × 0.1 m (height). The burner was located in the middle of the fire room.

Table 2
Value of parameters of each test.

Test No.	Outdoor wind velocity V (m/s)	Initial velocity u_0 (m/s)	Temperature of smoke T_s (K)	Ambient temperature T_a (K)	Fr	Test No.	Outdoor wind velocity V (m/s)	Initial velocity u_0 (m/s)	Temperature of smoke T_g (K)	Ambient temperature T_a (K)	Fr
1	0	0.99	333.72	285.15	0.59	19	12.12	10.06	283.41	287.15	70.22
2	1.73	1.64	311.57	285.15	1.63	20	0	1.61	339.23	279.15	0.78
3	3.46	2.62	302.25	285.15	4.57	21	1.73	2.65	383.52	279.15	1.33
4	5.20	3.60	298.29	285.15	17.38	22	3.46	3.18	336.35	279.15	2.50
5	6.93	4.78	299.76	285.15	5.36	23	5.20	4.56	313.96	279.15	5.94
6	0	1.26	323.15	289.15	0.98	24	6.93	6.46	307.84	279.15	17.79
7	1.73	1.93	352.99	289.15	1.09	25	8.66	7.53	306.94	279.15	65.27
8	3.46	2.70	320.37	289.15	2.26	26	10.39	9.27	297.55	279.15	39.25
9	5.20	3.76	306.36	289.15	5.65	27	12.12	10.83	302.16	279.15	95.04
10	6.93	5.23	301.21	289.15	20.57	28	0	1.75	403.62	288.15	0.70
11	8.66	5.99	300.15	289.15	18.50	29	1.73	3.01	454.26	288.15	1.40
12	0	1.51	360.53	287.15	0.70	30	3.46	3.69	410.45	288.15	1.96
13	1.73	2.27	378.38	287.15	1.06	31	5.20	5.08	368.25	288.15	3.56
14	3.46	2.23	356.02	287.15	1.40	32	6.93	7.03	339.43	288.15	7.28
15	5.20	4.14	323.84	287.15	3.83	33	8.66	8.35	309.68	288.15	27.69
16	6.93	5.51	305.67	287.15	11.71	34	10.39	9.72	311.62	288.15	39.67
17	8.66	7.02	304.43	287.15	38.92	35	12.12	11.59	310.52	288.15	79.46
18	10.39	8.38	297.32	287.15	39.69						



(a) test28 (HRR = 1.5MW, V_w = 0m/s, Fr = 0.7)

(b) test29 (HRR = 1.5MW, V_w = 1.73m/s, Fr = 1.4)

(c) test30 (HRR = 1.5MW, V_w = 3.46 m/s, Fr = 1.96)

(d) test31 (HRR = 1.5MW, V_w = 5.20 m/s, Fr = 3.56)

Fig. 4. Development of temperature stratification with the increase of outdoor wind velocity.

Table 3
Parameters' calculation results when $Fr < 3.2$.

Test No.	Fire power (kW)	Velocity of outdoor wind (m/s)	Entrainment coefficient E of the point 8.4 m away from the door	Smoke layer height h (m)	Fr
1	500	0		0.83	0.59
2	500	1.73	1.80E−10	1.79	1.63
6	750	0		0.96	0.98
7	750	1.73	3.14E−28	1.07	1.09
8	750	3.46	3.72E−37	2.00	2.26
12	1000	0		0.92	0.70
13	1000	1.73	6.11E−06	1.08	1.06
14	1000	3.46	7.42E−26	1.66	1.40
20	1250	0		0.96	0.78
21	1250	1.73	7.35E−04	1.02	1.33
22	1250	3.46	0	1.68	2.50
28	1500	0		0.93	0.70
29	1500	1.73	8.11E−34	1.29	1.40
30	1500	3.46	0	1.73	1.96

The fuel was liquefied petroleum gas. The measuring ranges of two rotor flow-meters were 0–2.5 m^3/h and 2.5–25 m^3/h with the accuracy of 0.05 m^3/h and 0.5 m^3/h respectively. The fuel supply rates can be controlled and monitored by the flow-meter, and the corresponding heat release rate was determined by the flow rate and heat value of liquefied petroleum gas.

The velocity of the outdoor wind varied from 0 to 7.0 m/s and the corresponding full-scale outdoor wind velocity range was 0–12.12 m/s according to the scaling law of Froude modelling [18]. The heat release rate (HRR) in the experiments were 32.1 kW, 48.1 kW, 64.2 kW, 80.2 kW and 96.2 kW, which correspond to full-scale HRR of 0.5 MW, 0.75 MW, 1.0 MW, 1.25 MW and 1.5 MW. A total of 35 experiments were carried out and the experimental conditions were listed in Table 1.

During the experiments, it was found that for the HRR of 32.1 kW, the fire would extinguish when the velocity exceeded 4 m/s. For the HRR of 48.1 kW, the fire would extinguish when the velocity exceeded 5 m/s. Thus, there was no experiment under these two HRR when the wind velocity exceeded the extinguishing velocity.

The ambient temperature was associated with the Froude number and the ambient temperatures of these tests varies from 6 °C to 16 °C, as shown in Table 2.

4. Results and discussion

4.1. The determination of undetermined parameters

To make the research results applicable to actual working conditions, the experimental results were firstly scaled up according to the Froude modelling. Therefore, the parameters and results used in this section were all full-scale values.

In order to determine which one is dominant, outdoor wind effect or thermal buoyancy effect, Fr of the 35 tests were calculated according to Eq. (10) and shown in Table 2.

The vertical temperature profiles at 0.9 m from the doorway in the corridor of tests 28–31 are shown in Fig. 4(a)–(d). It can be seen that when the outdoor wind velocity reaches 3.46 m/s, the corresponding Fr increases from 1.96 to 3.56 and the stratification denoted by temperature becomes disorder. Similar outcomes always showed in other heat release rates: vertical temperature profiles lose stable stratification when Fr rises above 3.2 with increasing outdoor air velocity. Thus, when $F_r < 3.2$, it can be considered that the smoke enters the corridor stratified and the velocity decay should comply with Eq. (13) while the initial velocity of smoke at the door can be calculated using Eq. (24). When $F_r > 3.2$, smoke entering the corridor completely mixed with the air and the velocity decay should comply with Eq. (17) while the initial velocity of smoke at the door can be calculated by Eq. (27). In Table 1, it can be seen that the velocity of test 1, 2, 6, 7, 8, 12, 13, 14, 20, 21, 22, 28, 29 and 30 could be determined by Eqs. (13) and (24) while other tests could be determined by Eqs. (17) and (27).

The thickness of smoke layer in this paper was calculated by N-percentage rule [19]. As the corridor and fire room were enclosed by steel plate and fireproof glass, coefficients of heat conduction and convection heat transfer were much bigger than those of concrete. The deviation between the calculated value and actual value would be too great if N was too small, thus N = 40 was used in calculating the thickness of the smoke layer and the stratification height.

The entrainment coefficient E is the function of Richardson number R_i. R_i and E were calculated by the following equations [20]:

$$E = 0.13\exp(-3.9Ri) \tag{28}$$

$$Ri = \frac{\Delta bh}{U^2} \tag{29}$$

where $\Delta b = g\Delta\rho/\rho_0$, h is the thickness of smoke layer, and U denotes the velocity difference between the upper smoke and lower air.

Various parameters of the working conditions when $Fr < 3.2$ were calculated and shown in Table 3. The fourth column of Table 3 was the entrainment coefficient E of the measuring point 8.4 m from the doorway.

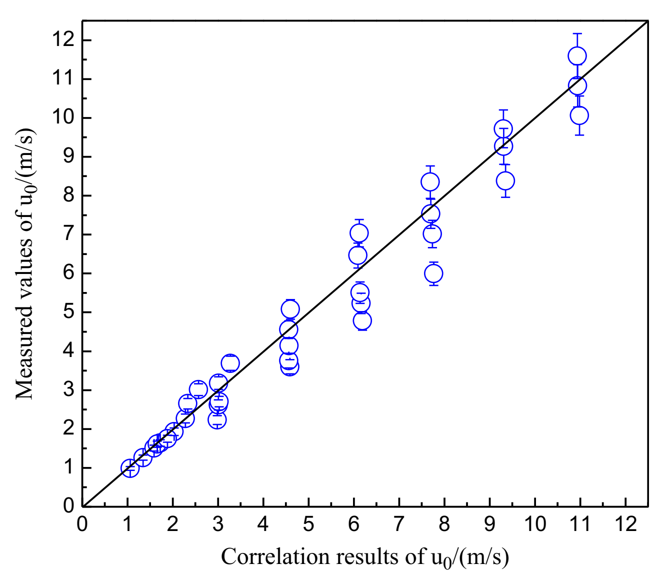


Fig. 5. Comparison between measured values and correlation results of smoke initial velocity u_0.

4.2. Validation of the theoretical model

It can be seen in Table 3 that the entrainment coefficients E of 14 tests were very small when the thermal buoyancy effect was dominant. Thus, the entrainment can be ignored and the decrease of smoke velocity was mainly caused by friction between the smoke layer and ceiling. Thus, Eq. (13) can be simplified as:

$$2\rho hu\frac{du}{dx} = -\lambda\rho u^2 \tag{30}$$

Integrating both sides of Eq. (30), and substituting the initial condition, $x = 0$, $u = u_0$, into it,

$$\frac{u}{u_0} = e^{-k_1(x-x_0)} \tag{31}$$

where $k_1 = \lambda/2h$.

Eqs. (17) and (31) can be unified as

$$\frac{u}{u_0} = e^{-k(x-x_0)} \tag{32}$$

where

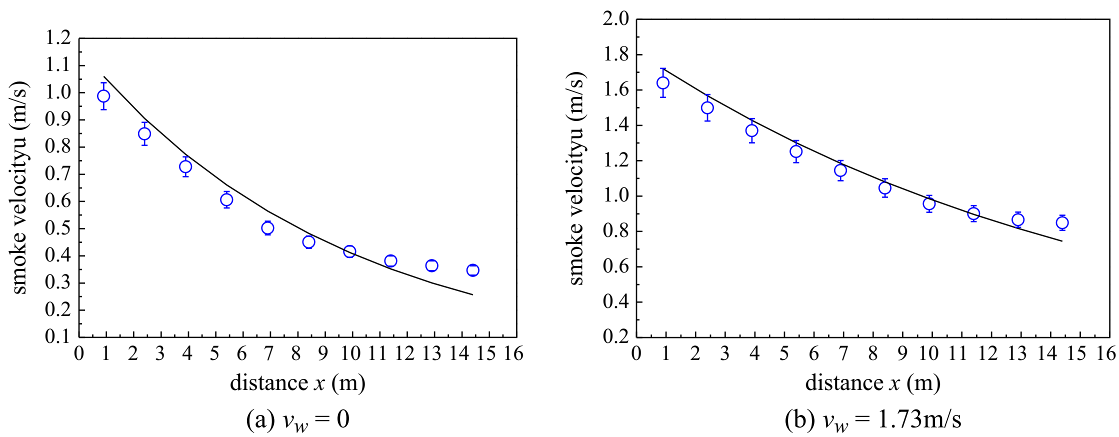


Fig. 6. Comparison of predicted smoke velocities obtained from Eq. (32) with the experimental results when HRR = 0.5 MW.

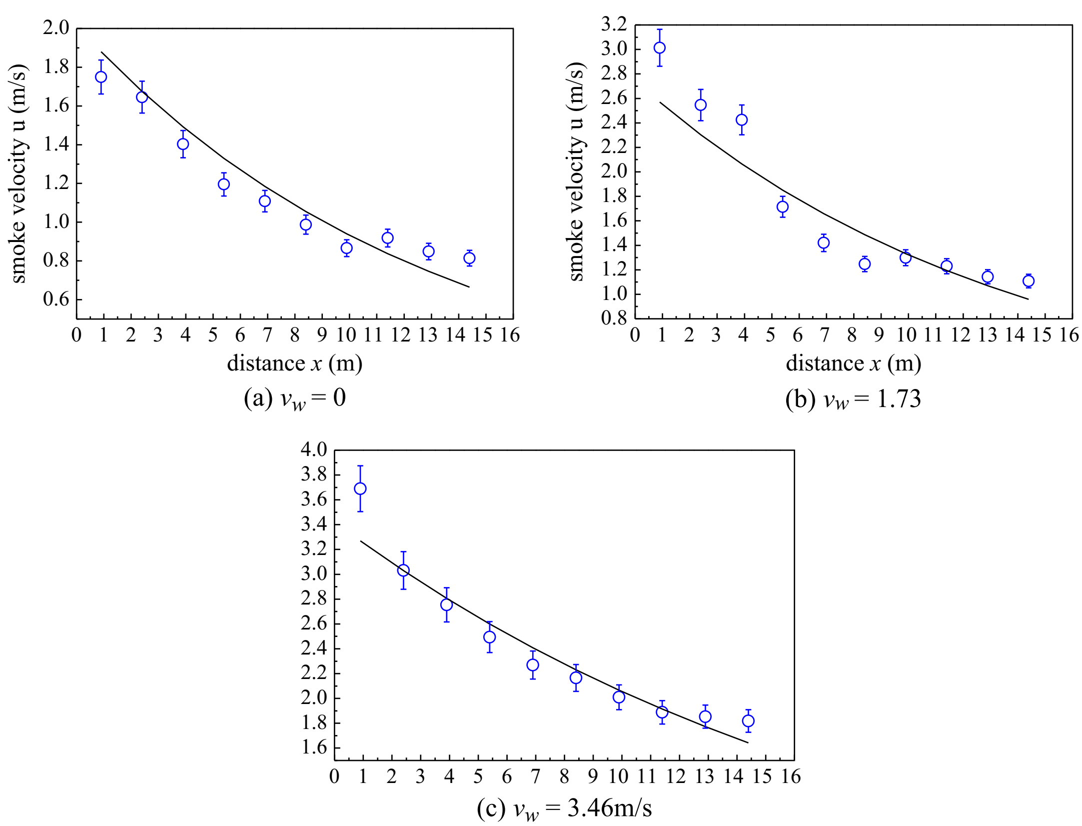


Fig. 7. Comparison of predicted smoke velocities obtained from Eq. (32) with the experimental results when HRR = 1.5 MW.

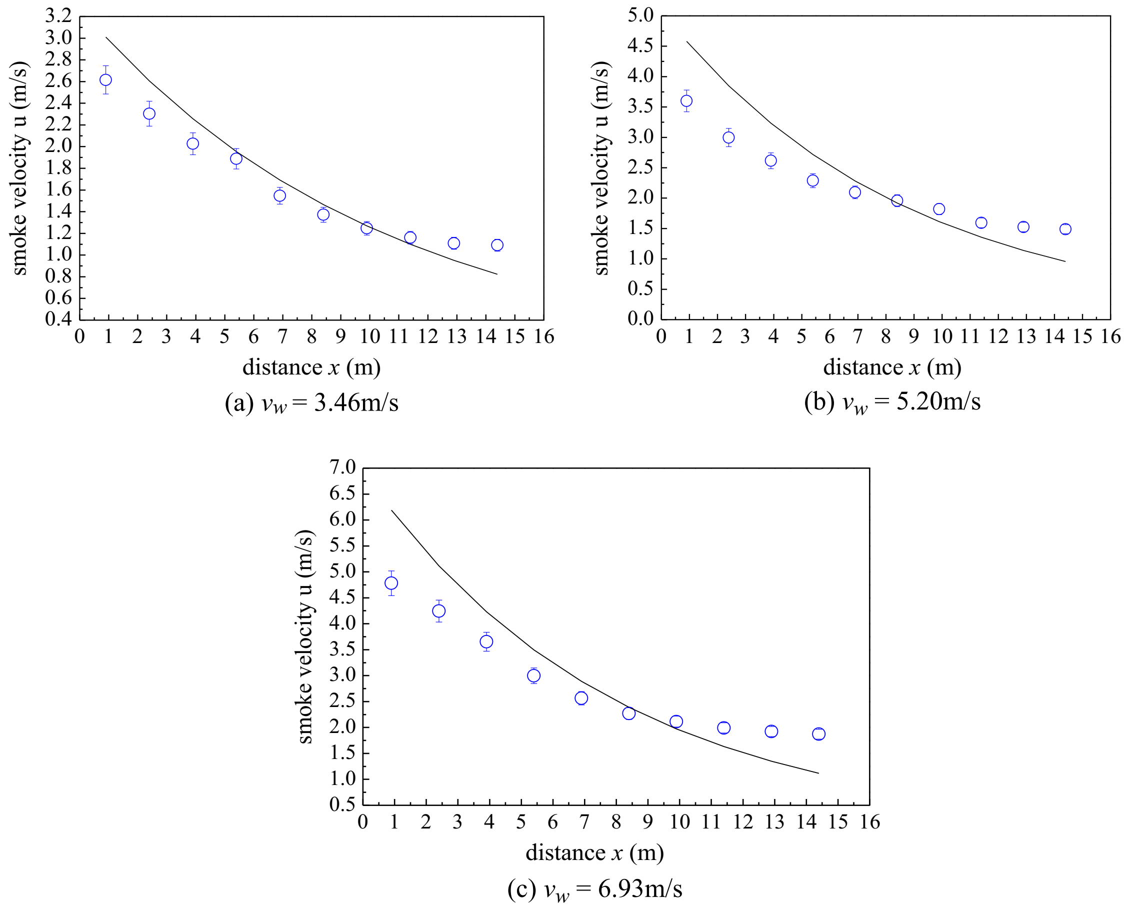


Fig. 8. Comparison of predicted smoke velocities obtained from Eq. (32) with the experimental results when HRR = 0.5 MW.

$$u_0 = \begin{cases} \frac{1}{1.6}\left(\frac{0.54A_w v_w}{A_d} + 0.7\sqrt{2gH}\left[\frac{1-d}{d(1+d^{1/3})}\right]^{1/2}\right) & (Fr < 3.2) \\ \frac{0.49\rho_a (A_w v_w)^2 + 0.063Q_c^{1/3}W^{2/3}HA_d\sqrt{2gH}\left[\frac{1-d}{d(1+d^{1/3})}\right]^{1/2}}{0.09Q_c^{1/3}W^{2/3}HA_d + \rho_a A_w A_d v_w} & (Fr > 3.2) \end{cases}$$

According to the equations above, the initial velocity of smoke entering the corridor of each test u_0 was calculated (choosing the reference position at 0.9 m from the doorway in order to ensure that the flow has reached steady one-dimensional flow condition, which is the base for normalization of the velocity decay along the corridor. There should be larger turbulence and mixing, and thus the uncertainty for the flow just spilling out of the doorway should be larger). Fig. 5 is the comparison between measured values and calculation results of smoke initial velocity u_0. It can be seen from Fig. 5 that the calculation results agree well with the measured values with the correlation coefficient R^2 of 0.9578 indicating that the model can predict the initial velocity u_0 well.

With the experimental data and Eq. (32), nonlinear fitting of smoke velocity decay of the 35 tests were performed. The velocity at 0.5 MW is defined as u. Velocity u against the distance x (distance from the doorway) is shown in Fig. 6. Fig. 7 shows the results when HRR were 1.5 MW and the outdoor wind speed is low. The reference position was 0.9 m away from the doorway according to the Froude modelling. Both the two figures show the results of tests of $Fr < 3.2$ where velocity of outdoor wind is low and the thermal buoyancy effect was dominant. From Figs. 6 and 7, it can be seen that experimental results were lower than the calculation results. It may because that the experimental rig was mainly made of steel material and the heat loss was too large. When the outdoor wind effect was dominant, all the correlation coefficients were larger than 0.9, indicating that the theoretical model can predict the changing rule of smoke velocity under such conditions well.

Figs. 8 and 9 present the velocity decays when the outdoor wind speed is high and $Fr > 3.2$. It can be seen that the results predicted by Eq. (32) are similar to the full-scale data. When the outdoor wind effect was dominant, most of the correlation coefficients exceed 0.95. Thus, the velocity decay model proposed in this paper was verified by the experiments well.

5. Conclusions

Based on momentum and mass conservations, theoretical models of smoke velocity in the corridor under the effect of outdoor wind were developed. Reduced-scale experiments were performed to validate the models. The experimental results were converted into full-scale data according to the Froude modelling. It was found that the initial velocity can be predicted very well according to the flow state of smoke with the criterion of Fr. The velocity distribution along the corridor falls into exponential decays in spite of the influence of thermal buoyancy and outdoor wind.

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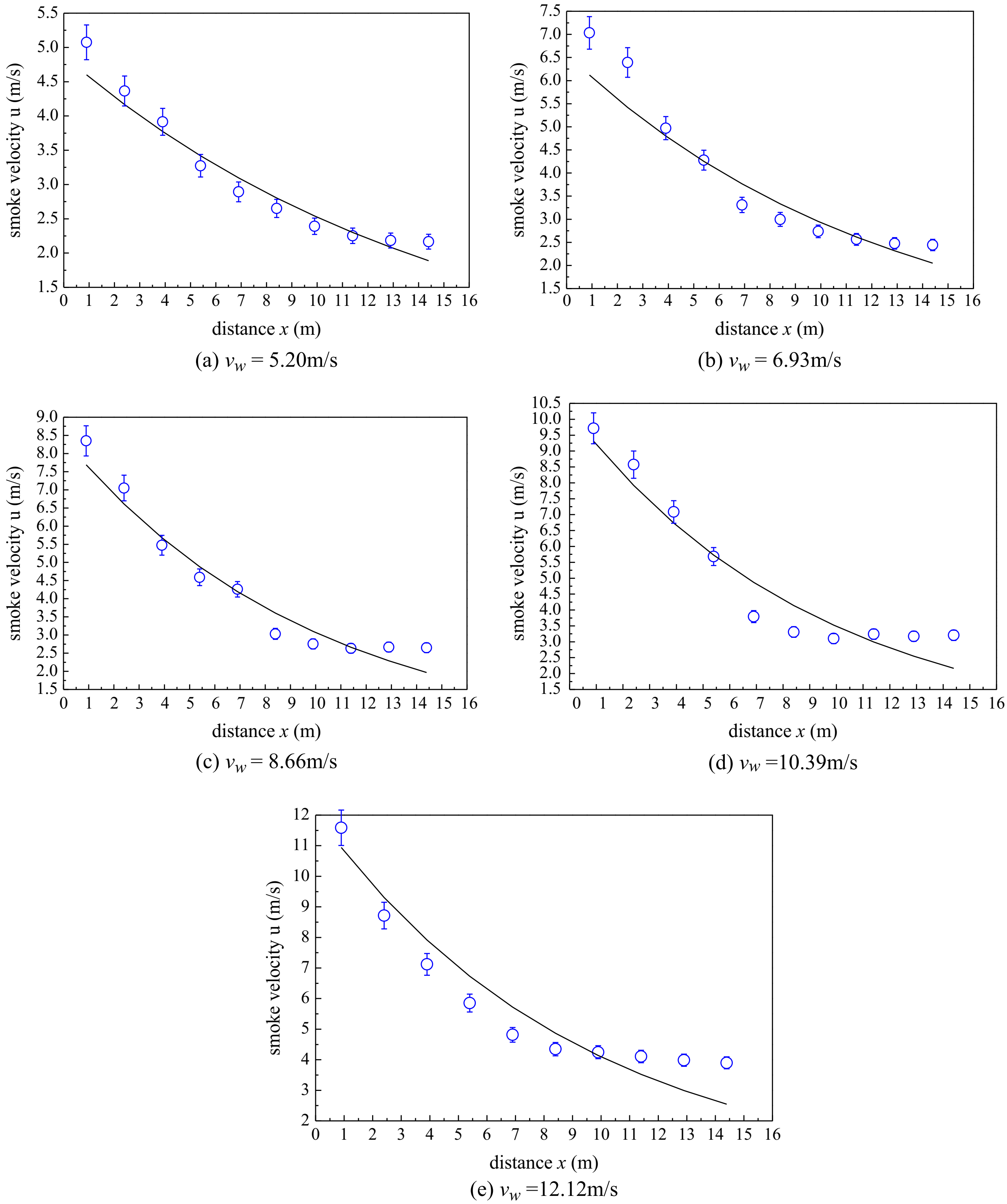

Fig. 9. Comparison of predicted smoke velocities obtained from Eq. (32) with the experimental results when HRR = 1.5 MW.

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