

Experimental investigation on drag effect of sprinkler spray to adjacent horizontal natural smoke venting

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ABSTRACT

Discharge rate of a horizontal adjacent smoke vent under sprinkler spray is experimentally investigated. Temperature of smoke layer and velocity of smoke venting were measured, under different sprinkler operating pressures and smoke venting areas. CO concentration at the smoke vent center and velocity of vent flow with fresh air outside were recorded in tests under different smoke venting conditions. Experimental results have shown that efficiency of smoke venting is controlled by a combination of smoke buoyancy and drag force of sprinkler spray. Only when buoyancy is greater than drag force the smoke could be extracted by venting. Velocity of smoke venting has shown to decrease as the operating pressure increases. Smoke venting logging, which represents the failure of smoke venting, was experimentally found from certain operating pressure called initial logging pressure. The CO concentration was found to increase after sprinkler was operated as the smoke is constrained in the spray region with horizontal momentum decreased. Negative pressure difference is caused at the vent when there is smoke venting logging, which might practically bring the exterior fresh air into the fire building. Additionally, experiments results have shown that the venting area has little influence on smoke flow under smoke venting logging.

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1. Introduction

Automatic sprinkler systems are required to be installed in buildings such as hotels, factories and shopping malls under prescriptive regulations around the world. The sprinkler systems, which can directly control or suppress the fire, are very reliable in protecting buildings against fires [1–3]. It is also well recognized that smoke and heat vents can play an important role in the fire safety design of buildings besides sprinklers [4,5]. However the buoyancy of the hot smoke layer, which supports the stratification for horizontal natural smoke venting (simply represented by smoke venting), may decrease due to the cooling effect of the water spray. The drag force produced by the water droplets also pulls the stratified smoke layer downward. Both of these two effects might lead to a decrease in smoke venting efficiency, which is a risk to evacuation and fire fighting [6–8].

So far, design codes for sprinklers and roof vents have remained independent and a broadly accepted equivalent design basis for both sprinklers and vents has not been universally recognized [9–11]. However a long-standing debate has been lasted for

decades in the fire protection community about the combined use of smoke and heat vents and sprinklers [7,8]. The reports in favor of combined use of the two systems usually claim that smoke vents can exhaust the combustion product, decrease the number of operating sprinkler, help the fire service identify the fire location and reduce the building temperature while the sprinkler are inoperative. However, others have claimed that smoke vents will enhance burning rate and delay the activated time of the sprinkler; the combined use is cost ineffective as smoke vents may lose its benefits with sprinkler operation.

Even though numerous studies have been conducted over the past few decades, many questions about the interaction of these devices have yet to be resolved. A full scale experimental study was conducted by FMRC in 1956 to investigate the interaction of sprinklers, vents and draft curtains [12]. The tests were conducted in a 36.6 m × 18.3 m test building with a curtained area of 212 m². Sprinklers with 3 m × 3 m spacing were installed. The draft curtains were 1.5 m deep and the roof vents area were 1.5 m² or 3.0 m². The test results showed that draft curtain may reduce the number of operating sprinklers to only those within the curtained space, and smoke vents have little effect on sprinkler operating but they are very important for preventing the smoke flowing out to the adjacent curtained space. In the 1960s, research work by Thomas and Hinkley on performance of roof vents led to a tentative

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Nomenclature

A_f	make-up air intake area (m ²)
A_T	target area (m ²)
A_V	roof vent area (m ²)
C_d	flow coefficient
C_T	resistant coefficient of target
F_d	force on the target element (N)
g	acceleration due to gravity (m s ⁻²)
h	initial thickness of the smoke layer (m)
H	height of the room (m)
H_L	height of the smoke layer interface (m)
H_N	height of the natural plane (m)
\dot{m}_a	mass flow rate of make-up air (kg s ⁻¹)
\dot{m}_V	mass flow rate of smoke venting (kg s ⁻¹)
ΔP_{IN-OUT}	pressure difference at the vent (Pa)
ΔP_{OUT-IN}	pressure difference at the make-up air intake (Pa)
ΔT	average temperature rise of the smoke layer (K)
T_0	standard working temperature of target flowmeter (K)
T_a	ambient temperature (K)
T_g	average smoke layer temperature (K)
T_{gM}	measured temperature at the vent (K)
V_a	velocity of supply air (m s ⁻¹)
V_V	velocity of smoke venting in zone model (m s ⁻¹)
V_{VR}	actual velocity of smoke venting (m s ⁻¹)
V_{VM}	measured velocity of smoke venting (m s ⁻¹)
<i>Greek symbols</i>	
ρ_0	standard working density of target flowmeter (kg m ⁻³)
ρ_a	air density at ambient temperature (kg m ⁻³)
ρ_g	density of the smoke (kg m ⁻³)
ρ_{gM}	density of the smoke at the vent (kg m ⁻³)

recommendation such that the sprinklers should be operated before vents in order to avoid the delay caused by smoke venting [13]. Since then, many large scale experiments were conducted by Suchomel [14], Waterman [15], Hinkley [16], Sheppard [17] and McGrattan [8], respectively to investigate the interaction between the sprinklers system and the vents system. Numerical studies on interaction of roof vents and sprinklers were also carried out by Heselden [18], Hinkley [19,20], Chow [21], McGrattan [8] and Cooper [22,23]. Most of these studies focused on how roof vents affect the activation time, number and location of operating sprinklers; or how the sprinklers affect the activation time and number of automatic roof vents. Little efforts were put to study the effect of sprinklers on smoke venting. The experimental work done at SP [24,25] studied the effect of a single sprinkler on the temperature and velocity of the hot smoke flowing through a 1 m by 2 m center ceiling vent. The tests were carried out in a 7.5 m by 15 m by 6 m high channel test space that was opened on two sides. A single sprinkler with a flow rate of either 80 L/min or 100 L/min was installed at various locations of the ceiling. The conclusions drawn were that when the sprinkler was installed upstream of the vent (between the fire and the vent), it had a “significant” impact on the discharge rate of the vent and when the sprinkler was installed downstream of the vent its influence on vent discharge was regarded as “negligible”. The SP experiment mainly focused on the discharge efficiency of the vent far away from the sprinkler spray which is mainly determined by the thickness and the temperature of the smoke layer beneath the vent rather than the drag force of sprinkler spray. Discharge rate of roof vents adjacent to the sprinkler spray was experimentally studied by McGrattan

[8] with a velocity probe positioned at center of the vents in 1998. Unfortunately, the velocity data was deemed to be unreliable in terms of the statements by McGrattan [8] and there was no means to directly measure the discharge rate of smoke venting in those tests. It should also be noted that before the mathematical model for sprinkler spray was built by Sheppard in 2002, drag force of droplets was hard to be calculated that the interaction of sprinkler spray and smoke layer was absolutely unknown [26,27]. Therefore, effect of sprinkler spray on the behavior of smoke flow could not be analyzed mathematically.

Full scale experiments were conducted in this study to investigate the drag effect of sprinkler spray on the efficiency of adjacent smoke venting, where ‘adjacent’ means that the distance between the smoke vent and the sprinkler does not exceed the radius of sprinkler spray coverage area. The velocity of smoke flow through the roof vent, the smoke layer thickness and the temperature, were experimentally measured with various sprinkler operating pressures. The resistant effect of drag force was then analyzed using the experimental results. Additionally, CO concentrations at the vent center were measured in the experiments to analyze the smoke flow states.

2. Measurement of smoke venting velocity*2.1. Velocity of smoke venting without sprinkler spray*

Fire room with a roof vent and a make-up air intake nearby the floor is shown in Fig. 1. The pressure difference at the location of roof vent and make-up air intake are expressed, respectively as [28,29]

$$\Delta P_{IN-OUT} = (H - H_N)(\rho_a - \rho_g)g \quad (1)$$

$$\Delta P_{OUT-IN} = (H_N - H_L)(\rho_a - \rho_g)g \quad (2)$$

Velocities of smoke venting and make-up air are consequently deduced to be

$$V_V = \sqrt{\frac{2\Delta P_{IN-OUT}}{\rho_g}} = \sqrt{\frac{2(H - H_N)(\rho_a - \rho_g)g}{\rho_g}} \quad (3)$$

$$V_a = \sqrt{\frac{2\Delta P_{OUT-IN}}{\rho_a}} = \sqrt{\frac{2(H_N - H_L)(\rho_a - \rho_g)g}{\rho_a}} \quad (4)$$

Thus the mass flow rates are

$$\dot{m}_V = C_d A_V \rho_g V_V = C_d A_V \rho_g \sqrt{\frac{2(H - H_N)(\rho_a - \rho_g)g}{\rho_g}} \quad (5)$$

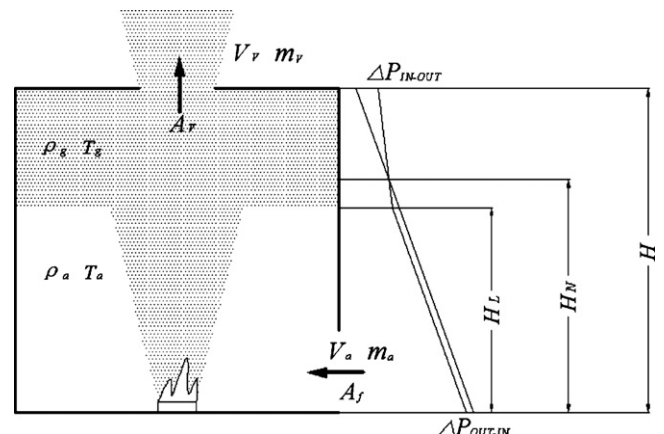


Fig. 1. Schematic drawing of smoke venting without sprinkler spray.

$$\dot{m}_a = C_d A_f \rho_a V_a = C_d A_f \rho_a \sqrt{\frac{2(H_N - H_L)(\rho_a - \rho_g)g}{\rho_a}} \quad (6)$$

where C_d is taken to be 0.61 as recommended by SFPE [5]. Conservation of mass leads to

$$\dot{m}_V = \dot{m}_a \quad (7)$$

Substituting Eq. (7) with Eqs. (5) and (6) gives

$$A_V \sqrt{\rho_g(H - H_N)} = A_f \sqrt{\rho_a(H_N - H_L)} \quad (8)$$

The height of natural plane is then deduced to be

$$H_N = \frac{A_V^2 \rho_g H + A_f^2 \rho_a H_L}{A_V^2 \rho_g + A_f^2 \rho_a} \quad (9)$$

From this equation, H_N equals approximately to H_L when $A_V \ll A_f$, which is referred to as the condition where the make-up area is much larger than the venting area. As a result, the velocity of smoke venting is expressed as

$$V_V = \sqrt{\frac{2h(\rho_a - \rho_g)g}{\rho_g}} \quad (10)$$

Since the smoke could be assumed to be ideal gas, Eq. (10) is converted to

$$V_V = \sqrt{\frac{2h(T_g - T_a)g}{T_a}} = \sqrt{\frac{2h\Delta T g}{T_a}} \quad (11)$$

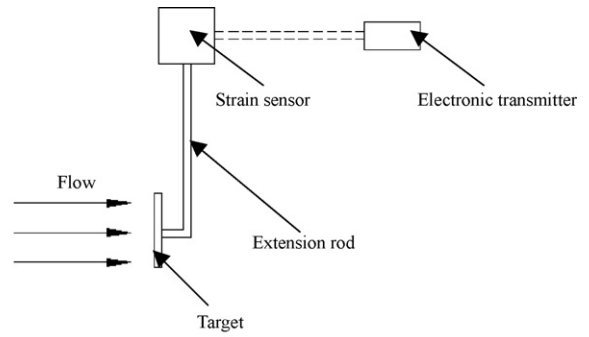
2.2. Measurement of smoke venting velocity with target flowmeter

Right side of Eq. (10) represents the effect of layer buoyancy on smoke venting when the make-up area is much greater than the venting area on the roof. However drag and cooling effect might mainly reduce the buoyancy rather than changing the product concentrations while the water droplets did not act on combustion [24,25]. Thus the flow velocity which represents the efficiency of smoke venting might change as drag and cooling effect were brought by sprinkler spray into the smoke layer. There are different sorts of instruments such as pitot, bidirectional micro-pressure probe and hot-wire anemometer available for recording the velocity of smoke venting. Unfortunately, high humidity of the smoke would produce condensed water when the smoke flow was cooled by the instrument. The condensed water will block the measuring tube (pitot, bidirectional micro-pressure probe) or cover mesh (hot-wire anemometer) and therefore leads to false results. In order to resolve this problem, new measuring device must be incorporated in the experiment. In this experiment, a target flowmeter, which has been widely used to measure velocity or volumetric flow rate of dirty liquid or gas (wet smoke is regarded as dirty gas) [30,31], was used.

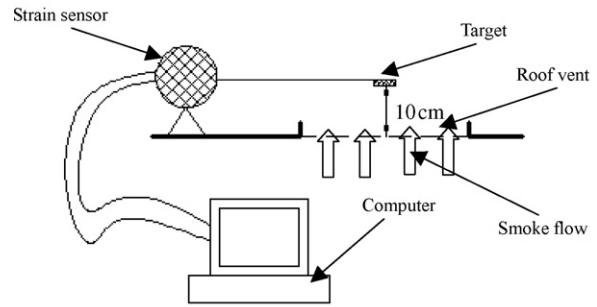
The target flowmeter determine the smoke velocity by measuring the amount of force exerted by the fluid on a target suspended in the flow stream. As shown in Fig. 2(a), for smoke flow with velocity, V_V , the force, F_d , is given by force equation of incompressible flow [31]

$$F_d = C_T A_T \frac{\rho_g V_V^2}{2} \quad (12)$$

where C_T is the resistant coefficient to be determined experimentally based on the flow conditions and the geometry of the target element. For flat plate, C_T is typically 1.28 [31]. For a given design, A and C_T are constant. If the fluid density, ρ_g , is also constant, the velocity V_V is solely a function of F_d to the power of 0.5, which is



(a) Sketch drawing of structure of target flowmeter



(b) Installation of target flowmeter

Fig. 2. Target flowmeter. (a) Sketch drawing of structure of target flowmeter. (b) Installation of target flowmeter.

expressed as

$$V_V = \sqrt{\frac{2F_d}{C_T A_T \rho_g}} \quad (13)$$

However the density of smoke flow may not be constant as the smoke temperature varies in different tests. On the other hand, density of smoke is not uniform in the depth direction of smoke layer. Therefore, the measured velocity should be revised to comply with the density of smoke flowing out whose temperature is measured with thermocouple at the vent plane. As the standard working temperature of the target flowmeter is 298 K, the density of smoke is deduced with the assumption of incompatible ideal gas

$$\rho_{gM} = \frac{T_0}{T_{gM}} \rho_0 \quad (14)$$

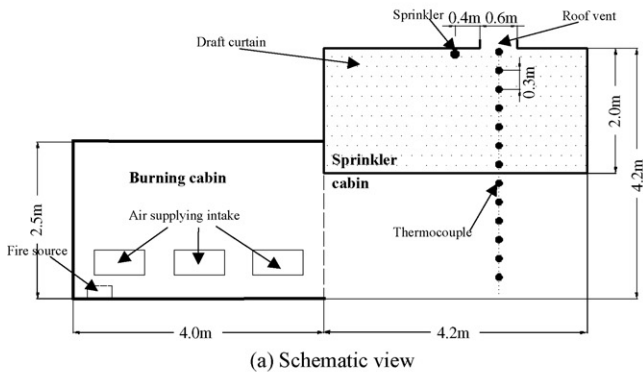
As a result, the revised (or actual) velocity can be calculated with the measured velocity using Eq. (15) by combining in terms of Eqs. (13) and (14)

$$V_{RV} = \sqrt{\frac{2T_{gM}F_d}{C_T A_T T_0 \rho_0}} = \sqrt{\frac{T_{gM}}{T_0}} V_{VM} \quad (15)$$

As shown in Fig. 2(a), the electronic transmitter converts the force to the velocity of fluid flow [30,31]. The target flowmeter was installed on the roof with the target located at the center of the smoke vent as shown in Fig. 2(b). To avoid the impact of upward moving droplets, the target was elevated 10 cm vertically from the vent plane.

3. Experimental

The experimental set up is shown in Fig. 3. It consists of two parts, the burning cabin and the sprinkler cabin. As shown in Fig. 3, pool fires are burned in the burning cabin to generate an initial stable smoke layer in the upper part of the sprinkler cabin. The burning cabin is 4 m long, 2 m wide and 2.5 m high. Six air supplying



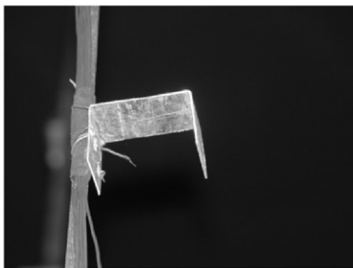
(a) Schematic view



(b) Photo



(c) Photo of the sprinkler

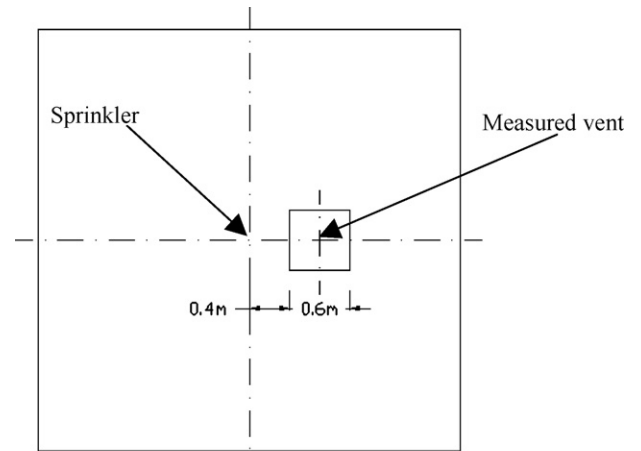


(d) Photo of thermocouple with the waterproofing cap

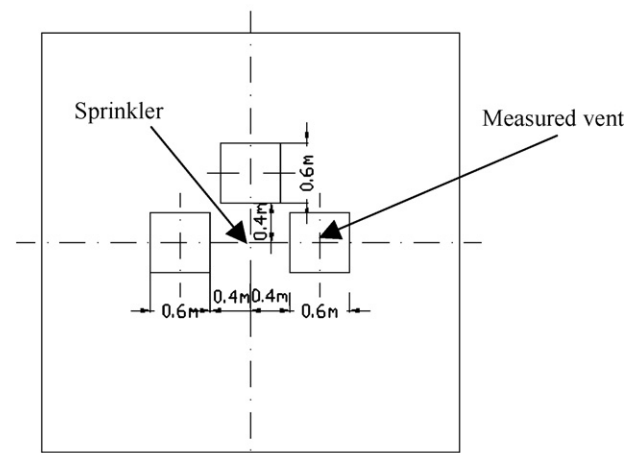
Fig. 3. Experimental rig. (a) Schematic view. (b) Photo. (c) Photo of the sprinkler. (d) Photo of thermocouple with the waterproofing cap.

intakes with $0.8\text{ m} \times 0.4\text{ m}$ opening are located on both sides of the cabin. The sprinkler cabin is a cube with identical length, width and height of 4.2 m. Smoke curtains with height of 2.0 m are installed below the top of the cabin to maintain an initial stable smoke layer. A gauge with height of 4.2 m is inserted in front of the cabin to measure the length of the downward smoke plume as shown in Fig. 3(b).

As shown in Fig. 3(c), ZSTP-15 Sprinkler with nozzle diameter of 12.7 mm is used for the tests. The sprinkler with the flow rate coefficient of 80 is made by copper alloys. The sprinkler is installed in the central of the sprinkler cabin roof with installation type of standard pendant. Pressure reducing valve and pressure transmit-



(a) Single roof vent



(b) Three roof vents

Fig. 4. Configuration of smoke vents. (a) Single roof vent. (b) Three roof vents.

ter are installed on the pipeline to control the sprinkler operating pressure with an accuracy of 0.002 MPa. A digital video camera is used to record the tests.

As shown in Fig. 4, two different adjacent roof vent configurations are used in tests. Tests with one roof vent are conducted to investigate the impact of sprinkler spray on smoke venting. Tests with three adjacent roof vents are conducted to investigate the effect of smoke venting area. Temperature of smoke is measured by the thermocouples trees installed under the center of each vent. The vertical interval of the thermocouples is 0.3 m. The thermocouples are covered by saddle steel waterproofing caps which are used to prevent the water droplets from hitting the thermocouples directly, as shown in Fig. 3(d). Experiments with and without these caps have been conducted to investigate the influence of the caps under the absence of sprinkler spray. The result shows there is no impact on the measured temperature since the caps are very small. A flat target element with length of 10 cm, width of 10 cm and thickness of 0.3 mm is installed on the target flowmeter to measure the velocity of smoke venting. The experimental results must be revised manually by using Eq. (15) as there is not temperature sensor in the target flowmeter for self-calibration. In this paper a Testo350XL gas concentration analyzer as well as a KANOMAX hot-wire anemometer are applied in the test with different smoke venting conditions in addition to the target flowmeter to investigate the variation of CO concentration at the vent center and vent flow velocity. The

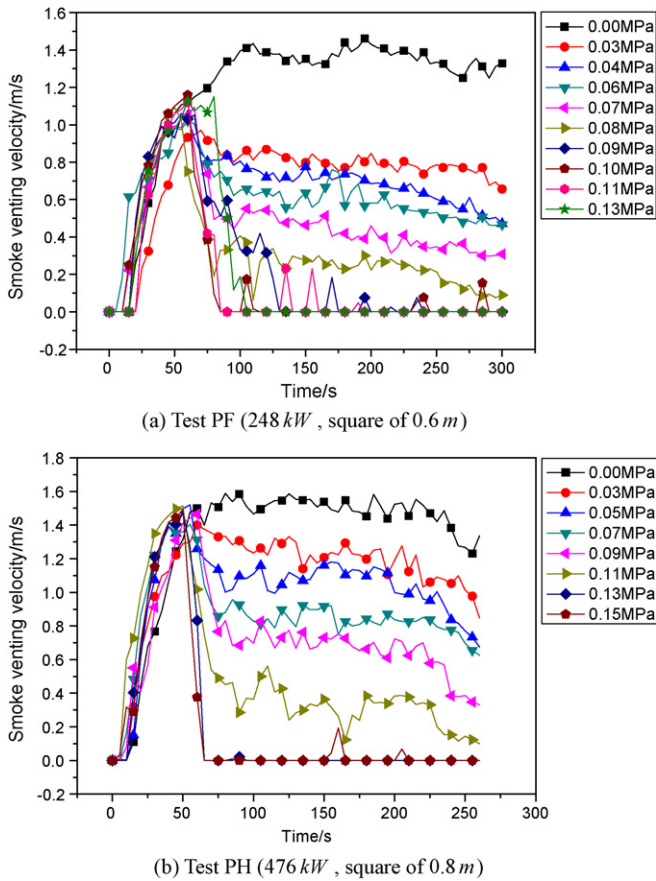


Fig. 5. Smoke venting velocities measured in Tests PF and PH. (a) Test PF (248 kW, square of 0.6 m). (b) Test PH (476 kW, square of 0.8 m).

results are applied to analyze the smoke flow field under different spray conditions. The target flowmeter, the gas analyzer and the anemometer have been installed at the vent on the right of sprinkler, which has been labeled as “Measured vent” as shown in Fig. 4.

A total of 36 tests were conducted with two different fire heat release rates. Diesel was used as the burned material of the pool fires. Heat release rate of the pool fires is determined by the mass loss rate measured by an electronic balance and the heat value of the diesel which is taken to be 42,000 kJ/kg. Factor of the burning efficiency is 0.8 in terms of the researches in cabin [32]. As a result, heat release rates used in experiment are calculated to be 248 kW and 476 kW for different pool fires. In test, the sprinkler spray is activated when the upper part of the sprinkler cabin is filled with a stable smoke layer. The total burning time of each test was about 300 s. Operating pressure of the sprinkler varied from 0.03 MPa to 0.15 MPa.

4. Results and discussion

4.1. Velocity of smoke venting under sprinkler spray

Upper part of the sprinkler cabin was filled with smoke after ignition without sprinkler spray for 50–60 s. After which the smoke started to flow out of the cabin through the bottom edge of the draft curtain. The velocity of smoke venting, which can be calculated by Eq. (11) with smoke layer height of 2 m, would reach its peak at this moment (476 kW, whereas the peak time for 248 kW is around 80 s). The velocity of smoke venting is measured by target flowmeter, which are plotted in Fig. 5. As shown in Fig. 5, the measured

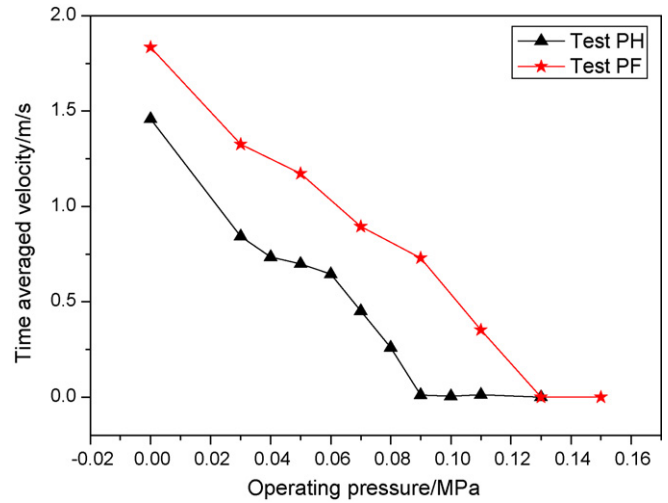


Fig. 6. Revised velocity of smoke venting with increase of operating pressure.

peak velocity is 1.36 m s^{-1} and 1.52 m s^{-1} for heat release rate of 248 kW and 476 kW, respectively. If there was no sprinkler spray, velocity would not change significantly in the test.

Droplets of sprinkler spray might cool the smoke layer and decrease its buoyancy by drag force. Consequently, sprinkler operating would lead to a decrease of smoke venting velocity. As shown in Fig. 5, velocity reached around 1.15 m s^{-1} and 1.50 m s^{-1} before sprinkler was operated when heat release rate was 248 kW and 476 kW, respectively. The velocity decreased sharply within half a minute after sprinkler was being operated. After this period, the velocity remained relatively stable. This period could be regarded as the steady state of smoke venting under sprinkler spray. When the fuel was running out, smoke venting velocity began to decrease till zero velocity; the start of running out was about 250 s in 248 kW tests and 200 s in 476 kW tests. The velocity of steady state was found to decrease as the sprinkler operating pressure increases. For 248 kW tests, the steady state velocity was about 0.8 m s^{-1} when the operating pressure was 0.03 MPa. The velocity decreased to around 0 m s^{-1} as operating pressure increased to 0.09 MPa. As shown in Fig. 5(a), when the operating pressure is higher than 0.09 MPa, the velocity of smoke venting remains 0 m s^{-1} and no smoke was going to be vent extracted at steady state. This is named as “smoke venting logging”. The smoke could not flow out of the building through vents under “smoke venting logging”, which is practically dangerous to the evacuating people in fire. The operating pressure at which smoke venting logging started was named as “initial logging pressure”. Therefore, the initial logging pressures in 248 kW and 476 kW tests are 0.09 MPa and 0.13 MPa, respectively as seen in Fig. 5.

Experimentally measured data are summarized in Table 1. Time average was made for steady state velocity and is labeled as V_{VM} in Table 1 so that the revised velocity, V_{VR} , can be calculated by Eq. (15). Temperature measured by the top thermocouple shown in Fig. 3(a) is applied to be T_{gM} . It can be seen that as the operating pressure increases, cooling and drag effect of the sprinkler spray increase. As a result, the pressure difference decreases at the vent plane and therefore the smoke venting velocity decreases. This trend can be observed in Fig. 6. As shown in the figure, the revised velocity decreases as the operating pressure increases. As the heat release rate is higher, the velocity in Tests PH is greater than that in Tests PF. As shown in Table 1, temperature rise of smoke layer below the vent does not equal to 0 K under initial logging pressure or even higher ones. For example in Test PF7, PH6, and PH7, the temperature rise is 6.0 K, 9.9 K, and 10.3 K, respectively. This implies that buoyancy of smoke layer can occur while smoke vent-

Table 1
Summary of tests.

Index of test	Pool size (m ²)	Number of vents	Test no.	HRR (kW)	Sprinkler operating pressure (MPa)	Ambient temperature (K)	Average temperature rise of the smoke layer (K)	Temperature rise of smoke at the vent (K)	V_{VM} (m s ⁻¹)	V_{VR} (m s ⁻¹)	CO (PPM)	Vent flow velocity (m s ⁻¹)
PF	0.36	1	PF0	248	None	304	32.3	39.1	1.359	1.458	28	–
			PF1	248	0.03	304	13.6	18.8	0.810	0.843	–	–
			PF2	248	0.04	304	10.2	15.3	0.710	0.734	–	–
			PF3	248	0.05	304	10.05	13.5	0.676	0.698	–	–
			PF4	248	0.06	304	8.5	12.0	0.626	0.645	–	–
			PF5	248	0.07	304	7.7	10.8	0.440	0.452	46	–
			PF6	248	0.08	304	7.2	9.5	0.254	0.260	–	–
			PF7	248	0.09	304	6.0	6.6	0.010	0.011	–	–
			PF8	248	0.10	304	5.8	6.3	0.005	0.005	–	–
			PF9	248	0.11	304	5.3	5.8	0.012	0.012	–	–
			PF10	248	0.13	304	4.88	6.0	0	0	5	–
PG	0.36	3	PG1	248	0.03	301	12.3	15.5	0.637	0.656	–	–
			PG2	248	0.04	301	9.5	11.8	0.623	0.638	–	–
			PG3	248	0.05	301	8.37	11.5	0.618	0.633	–	–
			PG4	248	0.06	301	6.8	7.3	0.588	0.598	–	–
			PG5	248	0.07	301	6.5	7.5	0.423	0.430	–	–
			PG6	248	0.08	301	6.6	8.2	0.250	0.254	–	–
			PG7	248	0.09	301	5.87	7.0	0.092	0.094	–	–
			PG8	248	0.10	301	5.5	6.2	0.017	0.018	–	–
			PG9	248	0.11	301	5.35	5.9	0	0	–	–
						PG10	248	0.13	301	4.8	5.0	0
PH	0.64	1	PH0	476	None	303	80.9	130.8	1.520	1.834	–	–
			PH1	476	0.03	303	30.0	42.3	1.231	1.325	–	Blocked
			PH2	476	0.05	303	25.9	33.1	1.104	1.172	–	–
			PH3	476	0.07	303	16.45	25.6	0.852	0.894	–	–
			PH4	476	0.09	303	12.8	20.5	0.701	0.730	–	–
			PH5	476	0.11	303	11.2	15.0	0.341	0.352	–	–
			PH6	476	0.13	303	9.9	13.0	0	0	–	0.61
			PH7	476	0.15	303	10.3	12.8	0	0	–	0.82
PI	0.64	3	PI1	476	0.03	300	16.77	23.1	1.031	1.073	–	–
			PI2	476	0.05	300	13.3	20.5	0.893	0.926	–	–
			PI3	476	0.07	300	12.5	17.7	0.732	0.755	–	–
			PI4	476	0.09	300	12.0	15.5	0.598	0.615	–	–
			PI5	476	0.11	300	11.0	12.0	0.330	0.338	–	–
			PI6	476	0.13	300	10.2	10.5	0.025	0.026	–	–
						PI7	476	0.15	300	9.84	10.1	0

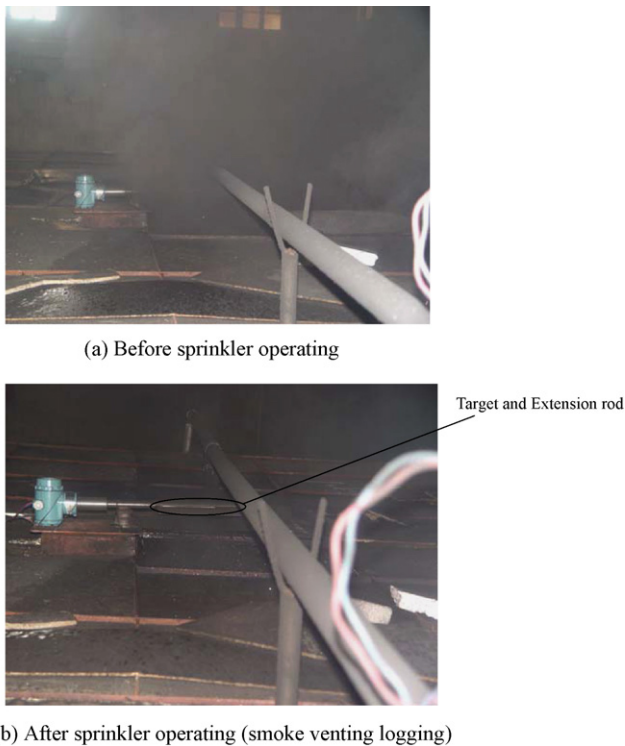


Fig. 7. Photograph of smoke venting state change under smoke venting failure (Test PF10). (a) Before sprinkler operating. (b) After sprinkler operating (smoke venting logging).

ing logging in these tests. Therefore, it can be concluded that drag force may play an important role in adjacent smoke venting logging besides cooling effect. As the operating pressure increases to the initial logging pressure, drag effect exceeds the buoyancy, which leads to smoke venting logging. As seen in the experiment PF10 which had been shown with smoke venting logging, smoke venting without sprinkler spray causes a plume above the vent such that the target flowmeter could not be visual under this condition as shown in Fig. 7(a). After sprinkler was operated and smoke venting logging occurred, the target and the extension rod could be seen very clearly, as shown in Fig. 7(b).

In theory, the pressure difference at the roof vent, which is caused by the buoyancy smoke layer, may push the smoke to flow upward and eventually lead to smoke venting. However the spray

drag force will pull the smoke down and reduce the buoyant effect of the smoke layer. Therefore the pressure difference drops down whenever the sprinkler is operated to a certain smoke layer. On the other hand, the spray drag force is determined by both of the velocity and the quantity of the droplets which increase as the operating pressure increases. So, as to a certain smoke layer, the pressure difference at the vent decreases while the operating pressure increases. Consequently, as the operating pressure keeps increasing, the drag force is eventually greater than the buoyancy, which leads the smoke to flow downward rather than venting. A similar result that the mass flow rate decreased under sprinkler spray was found by McGrattan [8] from his simulations. Therefore the experimental result seems to be reasonable. Compared to previous research, this study increases the operating pressure up to a higher value causing smoke venting logging, which have not been investigated before.

4.2. CO concentration in typical experiments

The carbon monoxide concentrations at the center of the Measured vent in Test PF0, PF5, and PF10, which represent the states of “no sprinkler spray”, “no smoke venting logging under sprinkler spray” and “smoke venting logging” respectively, were measured by the gas analyzer. The data were recorded in Fig. 8 as well as in Table 1. It is interesting to note that the CO concentration of smoke increased after sprinkler is operated. As shown in Fig. 8, the measured CO concentration of the smoke venting flow is approximately 28 PPM for Test PF0. The value drops sharply after sprinkler is operated during Test PF5 then suddenly increased to a higher value of 46 PPM which is about 1.5 times of Test PF0. The water spray, which has prevented the smoke from flowing out of the sprinkler cabin through the bottom edge of smoke curtain by decreasing its horizontal velocity, is analytically attributed to be the main reason of the CO increase. Actually when smoke is downward dragged by the water spray with vertical momentum decrease, its horizontal momentum might be reduced as well with “smoke logging” in the spray region [22,27]. At this moment the lower part of sprinkler cabin is filled with smoke under sprinkler spray, which might weaken the entrainment of fresh air outside and thus lead to an increase of carbon monoxide. CO concentration in Test PF10 drops to 5 PPM after sprinkler operation. The smoke venting logging in this test prevented smoke from flowing out through roof vent, which caused a major decrease of CO concentration in gas analyzer as no smoke flowed through the measuring probe. Time average is made between 100 s and 200 s which is considered as

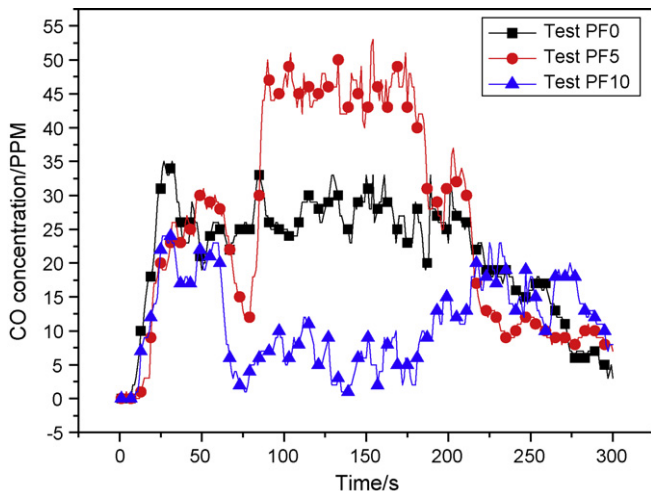


Fig. 8. CO concentration in Tests PF.

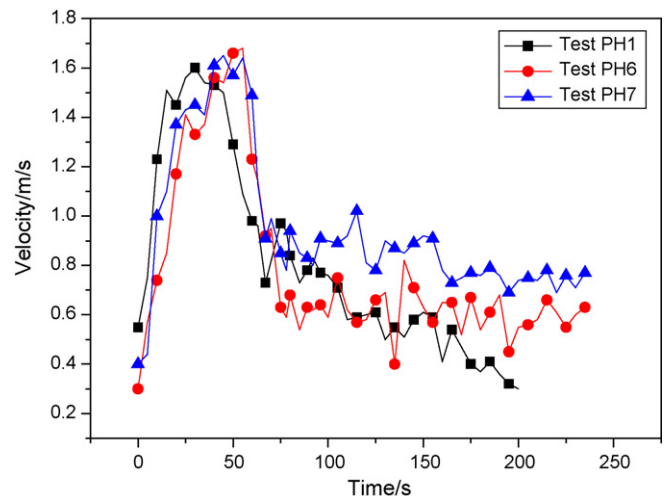


Fig. 9. Velocity of vent flow in Tests PH.

the steady state as shown in Fig. 8. The results are recorded in Table 1.

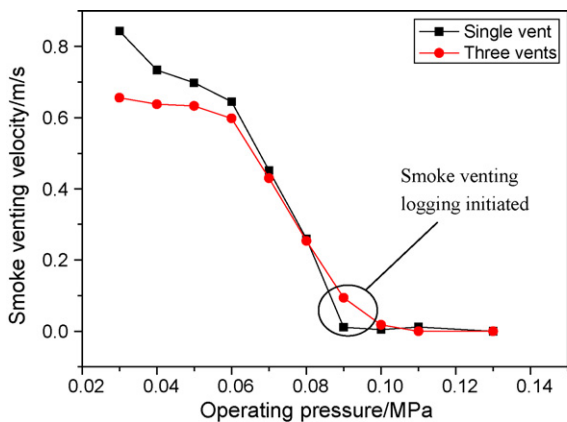
4.3. Character of venting flow under smoke venting logging

Above statements presents that when wet smoke flowed through the hot-wire anemometer, the condensed water would block the cover mesh of its probe, which then causes a decrease of measured velocity since the smoke flowing through the probe is reduced. However the hot-wire anemometer could still be used to measure the flow velocity if the flowing gas was clean air rather than smoke. So the KANOMAX hot-wire anemometer is applied in typical experiments to study the character of venting flow under smoke venting logging. As shown in Fig. 9, for Test PH1 with operating pressure of 0.03 MPa, the measured velocity decreases after sprinkler being operated and no steady state is found in the experiment. However this was not observed in Fig. 5. In Test PH6 and PH7, since there is smoke venting logging and no smoke flows through the probe, the measured velocities in Fig. 5 should drop to zero. However the measured velocity does not drop to zero in these two experiments as seen in Fig. 9. This is because the hot-wire anemometer can measured bidirectional flow velocity. So the anemometer can measure the velocity if the venting flow is formed by the fresh air outside. Consequently, it is deduced that the vent flow under smoke venting logging is caused by the fresh air outside of the sprinkler cabin being sucked into the vent due to the negative pressure difference which is resulted from the drag force being greater than the buoyancy. This negative air flow is a concern in

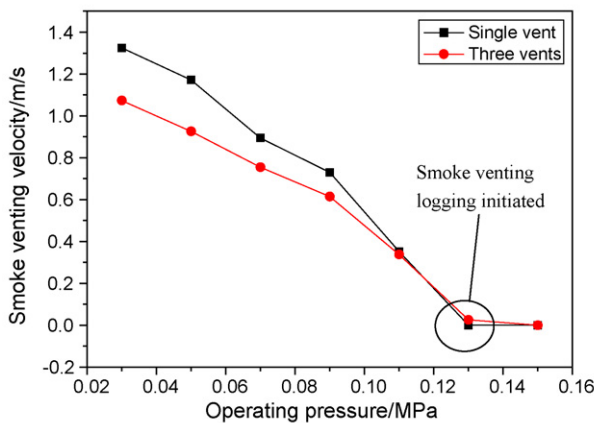
actual fire as it might benefit the combustion and the smoke spread. Theoretically, as the smoke moves downwardly under smoke venting logging condition, the outside air also flows downwardly due to the continuity. As the operating pressure increases, the effect of downward movement increases. Therefore more fresh air is sucked into the sprinkler cabin. As shown in Fig. 9, velocity of Test PF7 is greater than that in Test PF6 due to the higher operating pressure which enhances the downward trend of the smoke flow. Thus, it can be concluded that the flow rate of sucked air increases if the operating pressure increases under smoke venting logging, which is likely to increase the risk of fire.

4.4. Comparison of different smoke venting conditions

The number of adjacent roof vents at the same distance from sprinkler is increased to 3 in Tests PG and PI as shown in Fig. 4(b). Velocity of smoke venting is recorded at the Measured vent. The velocity was compared in Fig. 10. It was found that the velocity with three vents is relatively lower than the velocity with a single vent before smoke venting logging initiate. While the operating pressure increases, difference between the two velocities decreases. It

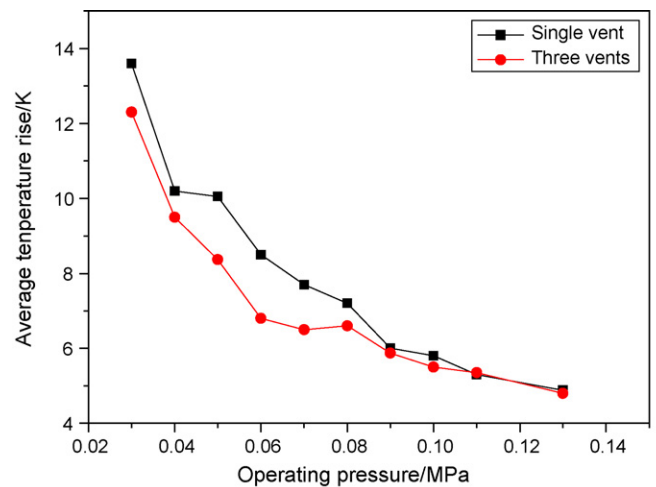


(a) Comparison of velocity in Tests PF and PG with low HRR

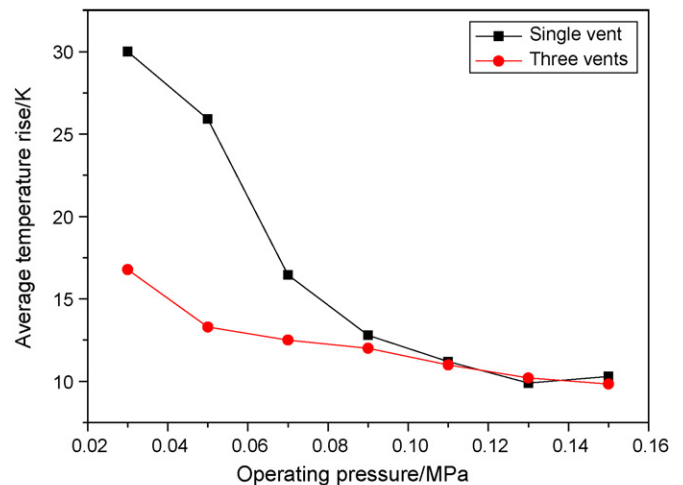


(b) Comparison of velocity in Tests PH and PI with high HRR

Fig. 10. Volumetric flow rate of smoke venting under different smoke venting conditions. (a) Comparison of velocity in Tests PF and PG with low HRR. (b) Comparison of velocity in Tests PH and PI with high HRR.

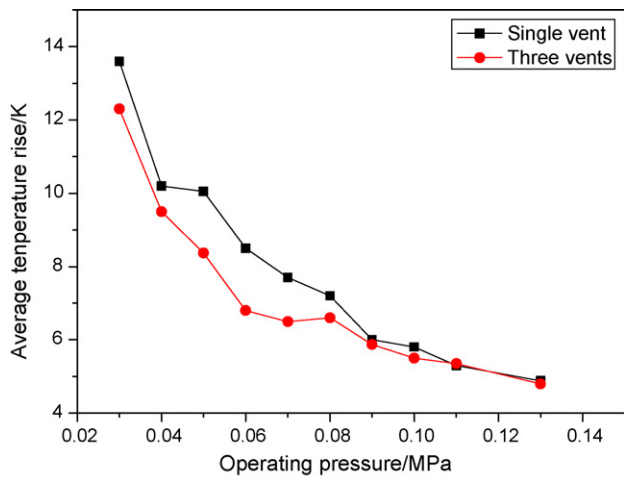


(a) Comparison of smoke layer temperature rise in Tests PF and PG with low HRR

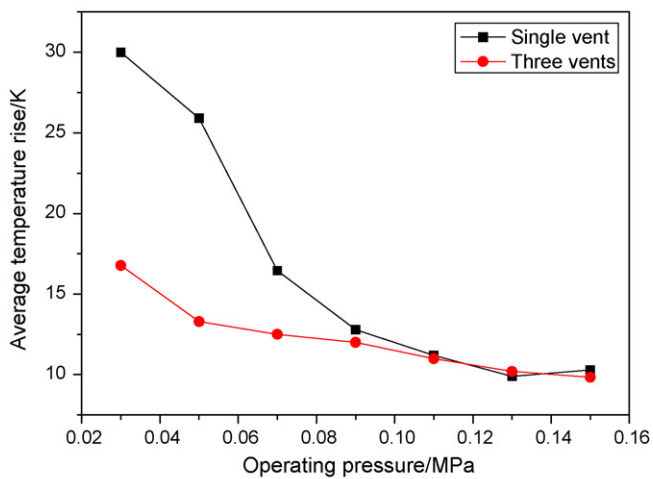


(b) Comparison of smoke layer temperature rise in Tests PH and PI with high HRR

Fig. 11. Smoke temperature rise under different smoke venting conditions. (a) Comparison of smoke layer temperature rise in Tests PF and PG with low HRR. (b) Comparison of smoke layer temperature rise in Tests PH and PI with high HRR.



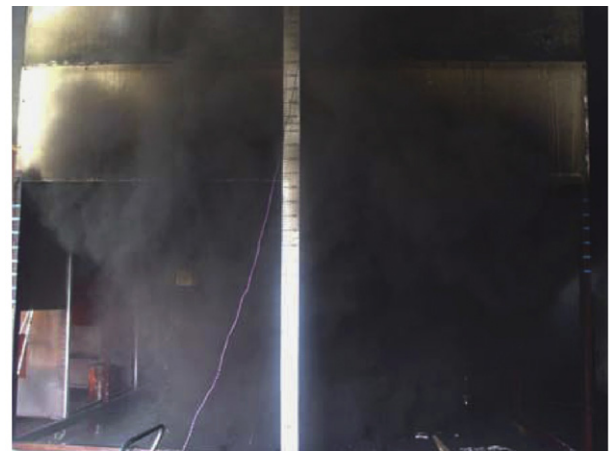
(a) Comparison of smoke layer temperature rise in Tests PF and PG with low HRR



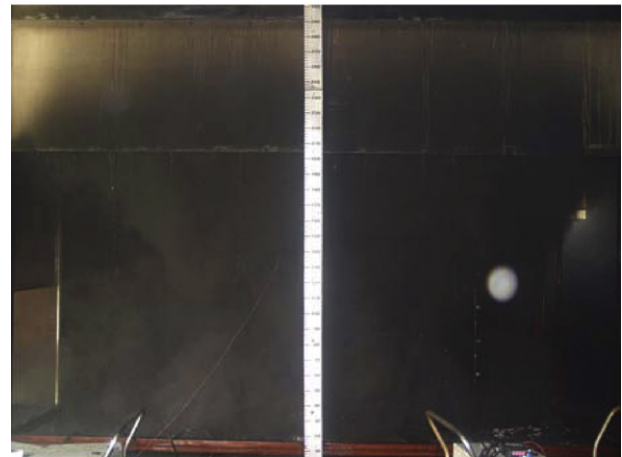
(b) Comparison of smoke layer temperature rise in Tests PH and PI with high HRR

Fig. 12. Total volumetric flow rates under different smoke venting conditions. (a) Volumetric flow rates of smoke venting in Tests PF and PG with low HRR. (b) Comparison of smoke layer temperature rise in Tests PH and PI with high HRR.

was also found that the velocity decreases as the operating pressure increases under both smoke venting conditions. Smoke venting logging occurs under the same operating pressure which is determined by the heat release rate. Initial logging pressure are highlighted by the circles in Fig. 10, which is 0.09 MPa for tests with heat release rate of 248 kW and 0.13 MPa for tests with heat release rate of 476 kW. Fig. 11 presents the average temperature rise of the smoke layer beneath the Measured vent. It can be seen that the average temperature rise beneath the vent is different when smoke venting is not logging. This is because that before smoke venting logging occurs, as the smoke venting area increases, total volumetric flow rate of smoke venting increases. As shown in Fig. 12, single vent, under which total volumetric flow is less because of less smoke venting area, would lead to less heat loss from the sprinkler cabin and thus higher temperature rise of smoke layer. The temperature rise difference decreases while the operating pressure increases and becomes almost zero when smoke venting logging initiates. Intuitively, it is expected that the smoke venting area can affect the efficiency when there is no logging, which would lead to different velocity and temperature rises. When smoke venting is logged, the roof vents would not affect the smoke flow dragged down by the



(a) Test PH7



(b) Test PI7

Fig. 13. Smoke flow field under smoke venting logging. (a) Test PH7. (b) Test PI7.

sprinkler spray, which leads to the same initial logging pressure and temperature rise. So, it can be concluded that smoke venting condition would have insignificant impact on the smoke flow field under smoke venting logging condition as the vents have lose its venting function already. No matter how large the smoke venting area is, the flow fields of smoke would be very similar under smoke venting logging condition. Fig. 13 shows the smoke flow field in Test PH7 and PI7 which were under smoke venting logging. It can be seen from Fig. 13 that the smoke is pulled down and flows out from the lower part of sprinkler cabin. No smoke has flowed out through the roof vents in these two tests. Therefore, smoke venting area has no significant effect on the smoke flow.

5. Conclusions

Effect of adjacent smoke venting under sprinkler spray was experimentally studied in this paper. Full scale experiments were carried out to investigate the variation of smoke venting velocity under different operating pressures of a sprinkler. With the increase of the sprinkler operating pressure, the velocity of smoke venting decreases. Smoke venting function of the roof vent is going to be lost from certain operating pressure called “initial logging pressure”, which might cause “smoke venting logging”. The smoke venting logging would lead to measured velocity by target flowmeter of 0 m s^{-1} ; then no smoke flowed out through the roof vents. Drag effect of the sprinkler spray was found to have a significant

impact on discharge rate of smoke venting since the temperature rise of the smoke layer beneath the roof vent was not zero under smoke venting logging. Drag force pulls the smoke down while buoyancy pushes it up; and smoke venting logging might happen when the drag force was greater than the buoyancy. The sprinkler spray decreases the horizontal momentum of the smoke flow therefore prevent it from flowing out of the spray region, which leads to an increase of CO concentration. When there is no smoke venting logging, the increase could be recorded by measuring the smoke at the roof vent. Actually, the vent flow velocity is not zero under smoke venting logging condition. Fresh air outside will be sucked into the vent whenever there is negative pressure difference caused by smoke venting logging. Different smoke venting areas are also considered in the experiment. Results show that the smoke venting areas would lead to difference of velocities and smoke layer temperature rises when smoke venting is not logged and would have no significant effect on the smoke flow state under smoke venting logging.

Current research reveals the mechanism of adjacent smoke venting under sprinkler spray. Practically combination of sprinkler and smoke venting systems in building should be aware with the smoke venting logging problem which might happen in actual fires. Further works, which focus on the regulation of CO concentration variation, the cooling effect and predicting the temperature distribution of the smoke layer in spray region, are ongoing and will be reported later.

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