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Influence of fire source locations on the actuation of wet-type sprinklers in an office fire

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ABSTRACT

An experiment is conducted on a full-scale model office and an actual sprinkler system to explore the influence of fire source locations on sprinkler actuation. The office space is a brick structure that measures 5.7 m in interior length, 4.7 m in width and 2.4 m in ceiling height, and equipped with a sprinkler system. The investigated fire source (100 kW LPG burner) locations include the room center, wall centers, room corner, and other locations at different distances from sprinklers. The results show that actuation of the sprinklers is affected by the fire source locations and the heat conduction properties of the glass temperature-sensing bulb. Average actuation time of all the tests is 102 s, around 40 s faster than if the fire source is located in the room center. For fire sources in corners, sprinklers are quickly activated at the experimental time 75 s, showing concentrated hot gas flow.

1. Introduction

At a fire scene, the phase change of water from liquid to steam effectively removes heat directly from flames, slows high temperature combustion, and cools the fuel surface directly via the latent heat of evaporation. Large amounts of steam can also reduce the oxygen concentration (particularly effective in enclosed spaces) to extinguish fire [1]. Such characteristics make water a preferred extinguishing agent. Inside buildings, automatic sprinklers deliver water drops in the fire protection area to restrain, control, and extinguish fires. When heat initiates the detection component of the sprinkler system, the system discharges water into the activated sprinklers to extinguish the fire. Sprinkler systems are classified as wet pipe, dry pipe, pre-action and the deluge. Which type of system is utilized depends on climate conditions, ambient temperature, protection objectives, burning style and local regulations. Wet pipe sprinkler systems are highly recommended since they have a simple structure, low maintenance cost, high reliability, and fast response.

With regard to the mutual influence of fire scene characteristics and sprinkler actuation, Cooper [2] analyzed a two-layer-type model to explore different interactions, including upper-layer entrainment into the sprinkler spray, momentum and mass exchange between drops and entrained gas, gas cooling by evaporation, buoyancy effects, and others. Ingason [3] used a heated wind tunnel to observe the thermal response of the glass temperature-sensing bulb used in the sprinklers. Different combinations of the parameters, including the response time index (RTI), the conduction parameter (C), and the change of phase parameter (CHP), were used to predict the response times of various test conditions, including different fire growth rates. Hua et al. [4] developed a numerical simulation method to investigate the interaction between the fire plume and the water spray. Ruffino and diMarzo [5] investigated the evaporative cooling and actuation delay of the sprinkler adjacent to the one activated by releasing water droplets into the fire plume of hot gases. Schwille and Lueptow [6] conducted experiments where 5, 15, and 50 kW gas burner fires were exposed to a spray from one of three spray sources with 6–106 L/min water flow rates.

Regarding the effect of fire location on the actuation of sprinklers, Wade et al. [7] conducted a set of 22 fire/sprinkler experiments to investigate the sprinkler response times and to predictive capability of the BRANZFIRE fire model. The results showed that, when using the BRANZFIRE model for predicting sprinkler response times, incorporating the NIST/JET ceiling jet algorithm, gave a closer prediction of the sprinkler response time in a small room than

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Alpert's correlation. It was also found that the position of the sprinkler head beneath the ceiling is an important parameter and has a strong influence on the response time of the sprinkler; values for the RTI and C-factor were found to be not so critical. Bennetts et al. [8] indicated data relating to the performance of sprinklers, including the times for activation of various types of sprinkler heads (normal and fast response), and the efficacy of the systems as far as extinguishment is concerned, in real office fire situations. It has been observed that for a 4 m × 4 m office, a fire size of 300 kW (midway between the sprinkler head and the wall) was required to actuate the sprinkler head, located at the room center. Tests also showed that Quick Response sprinklers were generally activated before the Standard Response sprinklers. The former were in most cases activated when the adjacent air temperature was between 90 and 130 °C while the latter were activated at air temperatures between 180 and 210 °C.

In this study, an experiment is conducted on a full-scale model office space and an actual sprinkler system to explore the influence of fire source locations, include the room center, wall centers, room corner, and other locations at different distances from sprinklers, on sprinkler actuation.

2. Research method

2.1. 10 MW fire test facility

A full-scale fire experiment was done using the 10 MW fire test facility and a combustion gas continuous online analysis system. The device is in the Fire Experiment Center, Architecture & Building Research Institute, Ministry of Interior, located on the Gueiren Campus of National Cheng-Kung University.

The 10 MW fire test facility consists of a smoke collection hood, smoke collection bend, mixture tube, measurement section, exhaust bend, and exhaust pipe, as in Figs. 1 and 2. Large objects or structures can be placed on the platform under the hood ❶ for testing. Hot gas, smoke, and combustion products are collected with the smoke collection hood, flow vertically through the smoke collection bend❷, are transferred horizontally into the mixture tube❸, go through the measurement section, and exit through the exhaust bend❹ and exhaust pipe❺ . The end of the exhaust pipe is finally connected to a waste gas treatment system❻. A large exhaust fan in the waste gas treatment system offers a maximum 30 m^3/s fire gas flow.

The combustion gas continuous online analysis system consists of (1) the gas analysis system (including O_2, CO, CO_2, NO_x, and HC analyzers, as well as a gas sampling/calibration system), (2) an optical density analyzer, (3) a flow rate/temperature monitor, and (4) a data processing system.

Fig. 1. 10 MW fire test facility.

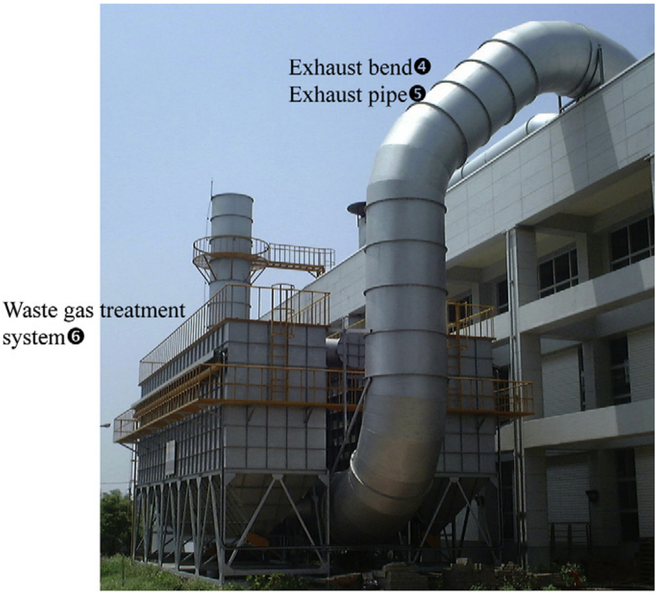


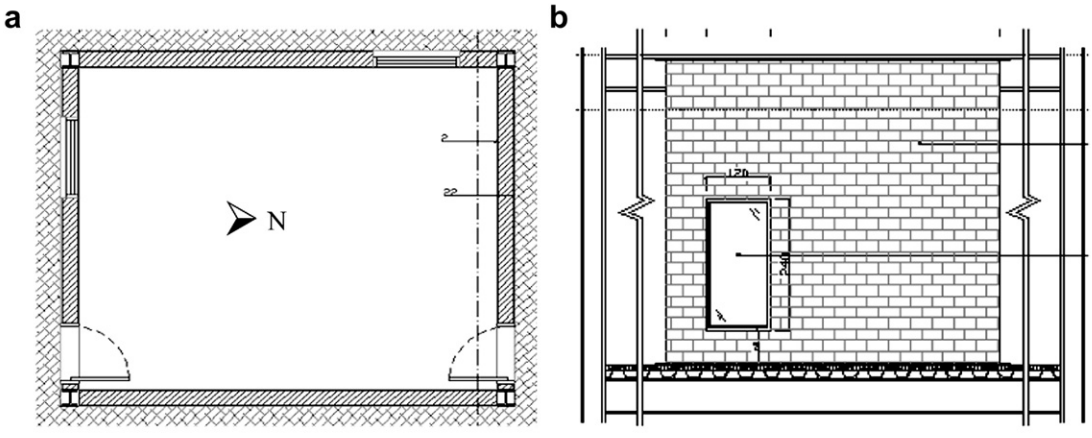
Fig. 2. Waste gas treatment system.

2.2. Investigated model office

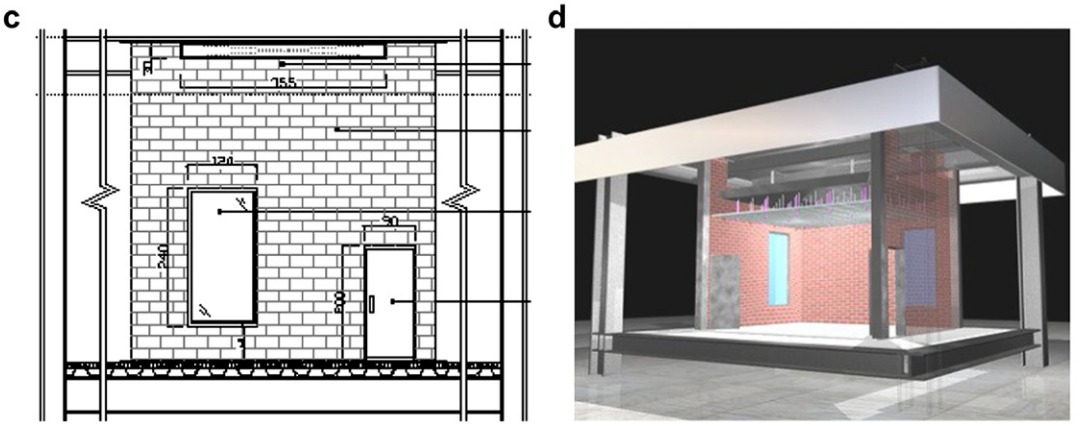
The investigated model office, as shown in Fig. 3, is located below the smoke collection hood (❶ in Fig. 1) of the 10 MW fire test facility. The interior plan dimension is 5.7 m × 4.7 m and the net ceiling height is 2.4 m. The walls are brick-laid in 0.26 m thickness with $U = 2.59\ W/m^2\ K$ (two aligned 0.12 m bricks ($\rho = 1650\ kg/m^3$, $k = 0.8\ W/m\ K$, $Cp = 0.84\ kJ/kg\ K$) and outside 0.001 m mortar layers ($\rho = 2000\ kg/m^3$, $k = 1.5\ W/m\ K$, $Cp = 0.8\ kJ/kg\ K$, $\varepsilon = 0.5$; where ε is emissivity)). The floor is made of a 3 mm steel deck ($\rho = 7860\ kg/m^3$, $k = 45\ W/m\ K$, $Cp = 0.48\ kJ/kg\ K$) and a 0.2 m concrete ($\rho = 2400\ kg/m^3$, $k = 1.5\ W/m\ K$, $Cp = 0.8\ kJ/kg\ K$, $\varepsilon = 0.5$). Both northeast and southeast wings have a 2.1 m × 0.9 m single door to be opened. The ceiling is made of a light rigid frame and gypsum board ($\rho = 910\ kg/m^3$, $k = 0.17\ W/m\ K$, $Cp = 1.19\ kJ/kg\ K$, $\varepsilon = 0.88$). To better directly observe behavior of the fire via sprinkler actuation and water droplets, two 2.4 m × 1.2 m fireproof windows are placed at the north wing of the western wall and the east wing of the southern wall. The distance between the window and ground is 0.6 m. See elevation of west and south in Fig. 3(b) and (c); the overall 3D view is in Fig. 3(d).

2.3. Sprinkler system

Four sprinkler heads, spaced uniformly in the model room and compliant with the Taiwanese regulation "Standards for Installation of Fire Safety Equipments Based on Use and Occupancy", were installed 0.15 m below the ceiling for each experiment, as shown in Fig. 4 (S_1–S_4). A pressure gauge and a pipe valve was installed sequentially upstream of each sprinkler head. The pressure gauge, placed between the valve and the sprinkler head, was used to observe sprinkler activation. The valve was closed when the pipe has contained water, in order to make the activated sprinkler head discharge a small amount of water. The sprinkler's K-factor is 80 $LPM/(bar)^{1/2}$, its temperature rating is 68 °C, its response time index (RTI) is 132 $(m\ s)^{1/2}$, and its C-factor is 0.6 $(m/s)^{1/2}$. All the



Plan view West Elevation



South Elevation 3DView(from the northeast)

Fig. 3. Schematic diagram of the investigated model office (not to scale).

abovementioned sprinkler head's properties are based on the manufacturer's estimation.

2.4. Experimental planning

The fire source used in the experiment is a 100 KW rectangular LPG burner with dimensions 18 cm × 18 cm. Various fire source locations, including the room's corners, walls, center etc. are selected for an office fire scenario, as shown in Fig. 4. To understand the effect of the walls on the spread of the thermal plume, the centers of the walls serve as fire source locations, numbered W_1–W_3. To understand the corner effect, the northwest corner serves as a fire source location, and is numbered C_1. The fire source location at the room center is numbered M_1. Other locations, numbered X_1–X_3, Y_1–Y_2, and Z_1–Z_2, are selected on symmetrical lines and diagonal lines. Because of symmetry, the experiment focuses on the right side (north wing).

2.5. Measurement and analysis

As shown in Fig. 5, ten K-type thermocouples are in one set tied vertically onto a thin iron chain referred to as a thermocouple tree. A total of 13 thermocouple trees are used in the experiment. Eight are placed at the corners (TCC series) and near walls (TCW series) of the room. The other 5 are placed near four sprinklers (T series) and the room center (TCM_1). The thermocouple tree in the northwest is numbered subscript 1; the others are numbered subscript 2–4 clockwise. The length of each thermocouple tree is 300 cm and divided into 10 points numbered No.0–No.9 from the ceiling to the floor. All of the points were 50 cm apart, except that the interval from No.0 to No.4 is 10 cm. The experiment was videotaped with a camera through a fireproof window of the model room in order to record the process. The fire scene in the room was also photographed. A data logger transferred voltages from the thermocouples, the differential pressure gauge, and the flow meter to computers. The YOKOGAWA DA 100 and DS 600 data acquisition system is used to make all temperature measurements. See Table 1 for the quantity, location, and height of thermocouples, differential pressure gauge, sprinklers, and gas analyzers.

3. Results and discussion

The experiment was conducted from September 27, 2006 to October 3, 2006, and Table 2 illustrates the overall results. Average ambient temperature and relative humidity during the experiments were 26.2 °C and 79% respectively. Figs. 9–11 show isotherm contours on horizontal planes in X-series tests. Figures (a_1) to (a_3) in Figs. 9–11 show the isotherms located 10 cm below the ceiling at intervals of 30 s from the start of the experiment. Figure (a_4) in Figs. 9–11 shows the isotherms 10 cm below the ceiling at the time when the first sprinkler is activated. Figures (b_1) to (b_4) in Figs. 9–11 show the isotherms located 20, 30, 40, and 50 cm below the ceiling when the first sprinkler is activated.

3.1. Fire source at the center

As shown in the temperature data in Table 2 and curve LPG-M_1-W in the top left of Fig. 6, sprinkler S_4 is the first to be actuated at

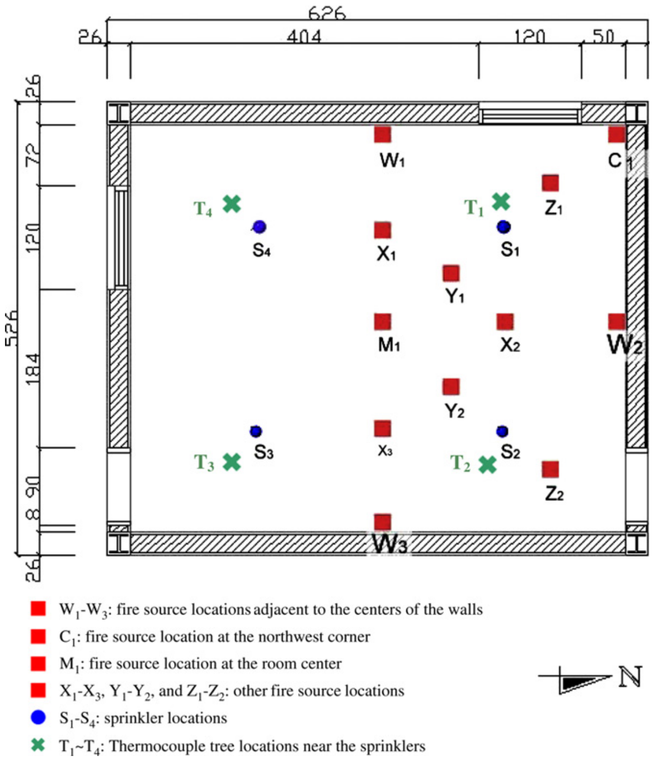


Fig. 4. Illustrative fire source locations.

the center fire case, at 142 s. It is shown that, due to the indoor flow pattern, cooler ambient air is introduced from the northern door, flows around sprinklers S_2 and S_3, and then flows out of the southern door. Sprinklers S_1 and S_4 show higher temperatures than S_2 and S_3 and thus can be activated more quickly.

3.2. Fire source close to the wall

Temperature curves of the wall fire cases are shown on the top right, bottom left, and bottom right in Fig. 6. Due to the effect of the wall, flames here are higher than those located farther from the wall. When the fire source is located at W_1, smoke quickly accumulates in the upper level, and a strong hot plume is able to actuate the nearest sprinklers, S_1 and S_4. Sprinklers S_2 and S_3 are actuated when the fire source is located at W_2 and W_3, respectively. The thermal plume from fire location W_2 flows upwards to the ceiling and turns towards the southern door, passing near and actuating sprinkler S_2. Cases LPG-W_1-W and LPG-W_3-W illustrate the same situation. Therefore, both the distance and the flow pattern need to be considered in the actuation of a sprinkler for such a condition. The average actuation time of the sprinklers is approximately 99 s, which is 43 s quicker than if the fire source is located at the room center M_1.

3.3. Fire source at corner

The top left figure in Fig. 7 shows the temperature curves of the corner fire. The hot plume coming from the fire in the corner is quite concentrated and rises quickly. After reaching the ceiling, the hot gas spreads and dissipates toward the southern door. At 75 s, sprinkler S_1 is activated.

3.4. Fire sources at other locations

Experiment series X, Y, and Z were conducted to investigate sprinkler actuation with different fire locations. Locations X_1, X_2, and X_3 are located farther from the sprinklers. Y_1, Y_2, Z_1, and Z_2 are located closer to the sprinklers. As shown in Figs. 7 and 8 and Table

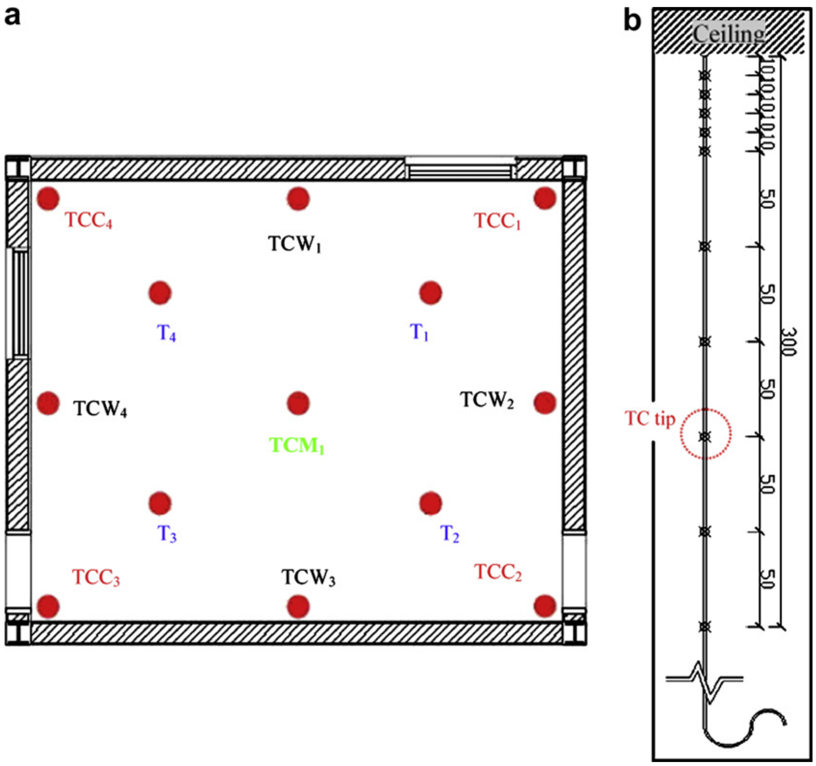


Fig. 5. (a) Thermocouple tree locations and (b) thermocouple tree.

Table 1
Measurement apparatus used in this study.

Equipment	Quantity	Position and marks	Height from the ground	Explanations
Thermocouple trees	13	TCC$_1$, TCC$_2$, TCC$_3$, TCC$_4$, TCW$_1$, TCW$_2$, TCW$_3$, TCW$_4$, T$_1$, T$_2$, T$_3$, T$_4$, TCM$_1$ (As shown in Fig. 6(a))	As shown in Fig. 6(b)	
Thermocouples	8	TGO$_1$, TGO$_2$, TGI$_1$, TGI$_2$ TWO$_1$, TWO$_2$, TWI$_1$, TWI$_2$ (As shown in Fig. 3(a))	TGO$_1$, TGI$_1$:240 cm TGO$_2$, TGI$_2$:160 cm TWO$_1$, TWI$_1$:240 cm TWO$_2$, TWI$_2$:160 cm	Inside/outside watching window and internal/external wall
Differential pressure gauge	2	BDP$_1$, BDP$_2$ (As shown in Fig. 3(a))	BDP$_1$:50 cm BDP$_2$:150 cm	BDP$_1$: northeast BDP$_2$: southeast
Sprinklers	4	S$_1$, S$_2$, S$_3$, S$_4$ (As shown in Fig. 3(a))	225 cm	
Gas analyzer	2 sets	G$_1$, G$_2$ (As shown in Fig. 3(a))	180 cm	G$_1$: northwest G$_2$: southeast

Table 2
Experiment results.

Number	Location of burner	Activated sprinkler	Sprinkler actuation time (sec)	Gas temperature (°C)
LPG-M$_1$-W	M$_1$	S$_4$	142	103
LPG-W$_1$-W	W$_1$	S$_4$	97	103
LPG-W$_2$-W	W$_2$	S$_2$	91	99
LPG-W$_3$-W	W$_3$	S$_3$	109	104
LPG-C$_1$-W	C$_1$	S$_1$	75	107
LPG-X$_1$-W	X$_1$	S$_4$	141	103
LPG-X$_2$-W	X$_2$	S$_1$	123	105
LPG-X$_3$-W	X$_3$	S$_4$	130	100
LPG-Y$_1$-W	Y$_1$	S$_1$	61	83
LPG-Y$_2$-W	Y$_2$	S$_2$	96	103
LPG-Z$_1$-W	Z$_1$	S$_1$	73	99
LPG-Z$_2$-W	Z$_2$	S$_2$	92	84

2, because they are closer to the sprinklers than the X series, the Y and Z series actuate more quickly than the X series.

Y$_1$ and Z$_1$ are located near the northwest corner and experience a more concentrated thermal plume. Y$_2$ and Z$_2$ are located at the north door and experience an air cooling effect. Thus, for fire source locations Y$_1$ and Z$_1$, the sprinkler actuation time is shorter than that of Y$_2$ and Z$_2$.

From Figs. 9–11, one can see that the upper-layer smoke is affected by walls and tends to have a high temperature when the fire source is at X$_1$ and X$_2$. When the fire source is at X$_3$, the isotherms are disturbed because of the effect of outdoor airflow from the two doors. The isotherms in LPG-Y$_1$-W and LPG-Z$_1$-W (not shown in this study) show the effect of concentrated heat in a corner. The temperature field spreads outward from the highest temperature in the corner. The isotherms of LPG-Y$_2$-W and LPG-Z$_2$-W (not shown) indicate that when the fire source is located at Y$_2$ or Z$_2$, airflow from the northern door reduces the temperature around sprinklers S$_2$ and S$_3$. Again, the isotherms here are disturbed.

3.5. *Comparison of actuation times*

Data from experiments (M$_1$, X$_1$, and W$_1$), (M$_1$, X$_2$, and W$_2$), and (M$_1$, X$_3$, and W$_3$) are compared to verify the wall effect. In the experiment where the fire source is located in the room center (M$_1$), the actuation time of the sprinklers is 1.43 times that for fire sources near the walls (the average actuation time of W series). The actuation time of the sprinklers of experiment X series is about 1.33 times that for fire sources near the walls (W series average). The average actuation time of the sprinklers of experiment M and X series is about 1.35 times that for fire sources near the walls (W series average). These results agree with the phenomenon that the gas temperature in the upperlayer of a fire source on the wall is 1.3 times that at the room center. That is, the higher gas temperature of the upperlayer directly affects the actuation time of sprinklers. Actuation times of the X series, which are closer to sprinklers, are even longer than those of the W series, which are farther from sprinklers. This demonstrates the impact of the wall effect.

Comparing the temperature curves and isotherm contours in the M$_1$, Y$_1$, Z$_1$, and C$_1$ diagonal line experiments, one can observe

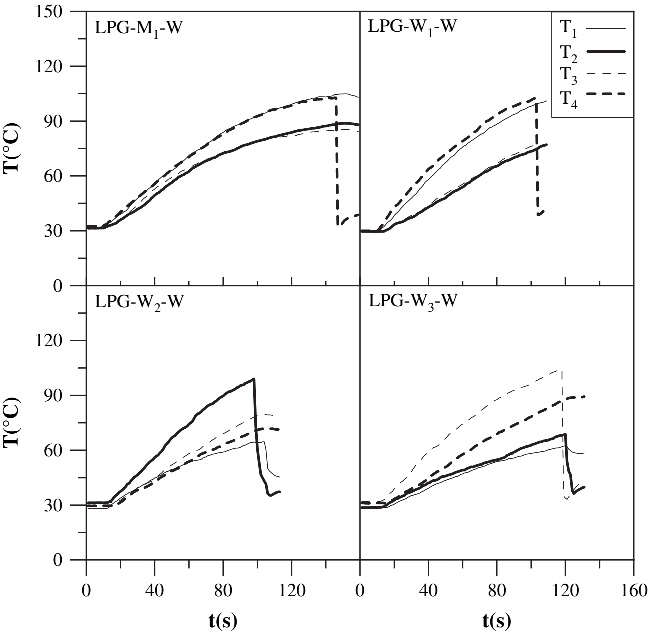


Fig. 6. Temperature around the sprinklers with fire sources at the room center and near the walls.

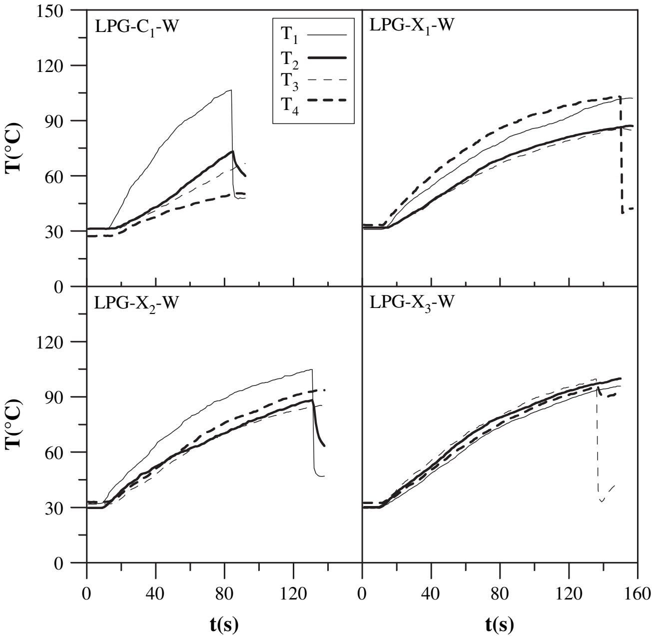


Fig. 7. Temperature curves around the sprinklers with fire sources at the corner and other locations.

that when the fire source is located near the corner, gas temperature near the fire source increases more quickly, which conforms to the corner effect. However, sprinkler actuation time is not particularly short. After investigating isotherm contours (not shown in this study), one explanation may be the distance between the fire source and the sprinklers, which can be referred to as one of the factors affecting actuation of the sprinklers. Thus, there are two factors affecting actuation time: (1) distance between the fire source and the sprinklers, and (2) the wall (or corner) effect. The reason that the actuation time of the Y series is quicker than that of the X series is the distance between the fire sources and sprinklers.

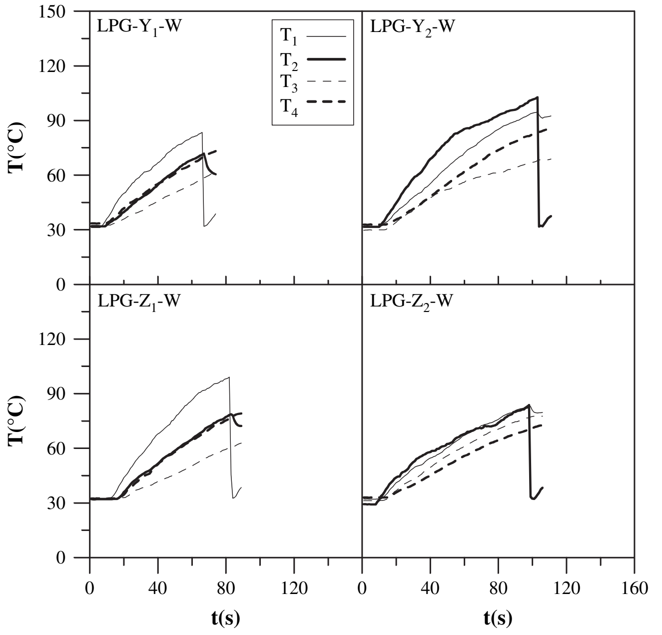


Fig. 8. Temperature curves around the sprinklers when fire sources are at locations X, Y, and Z.

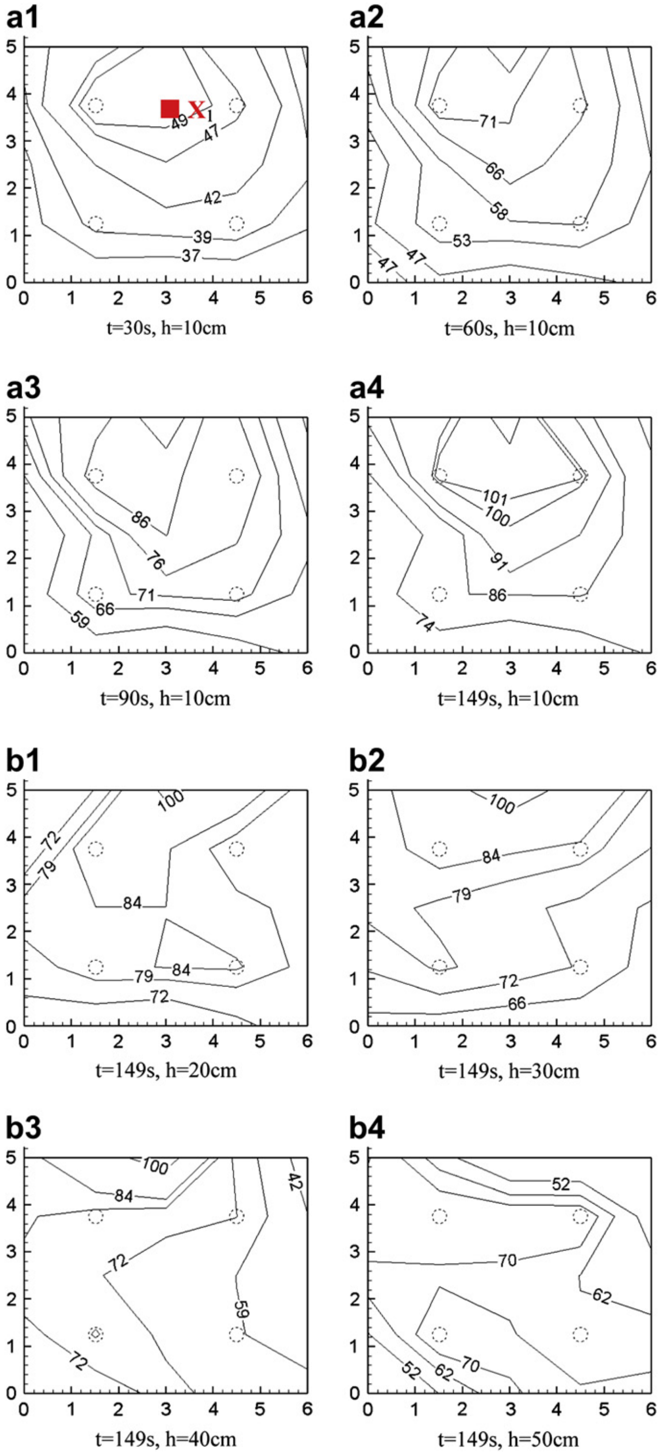
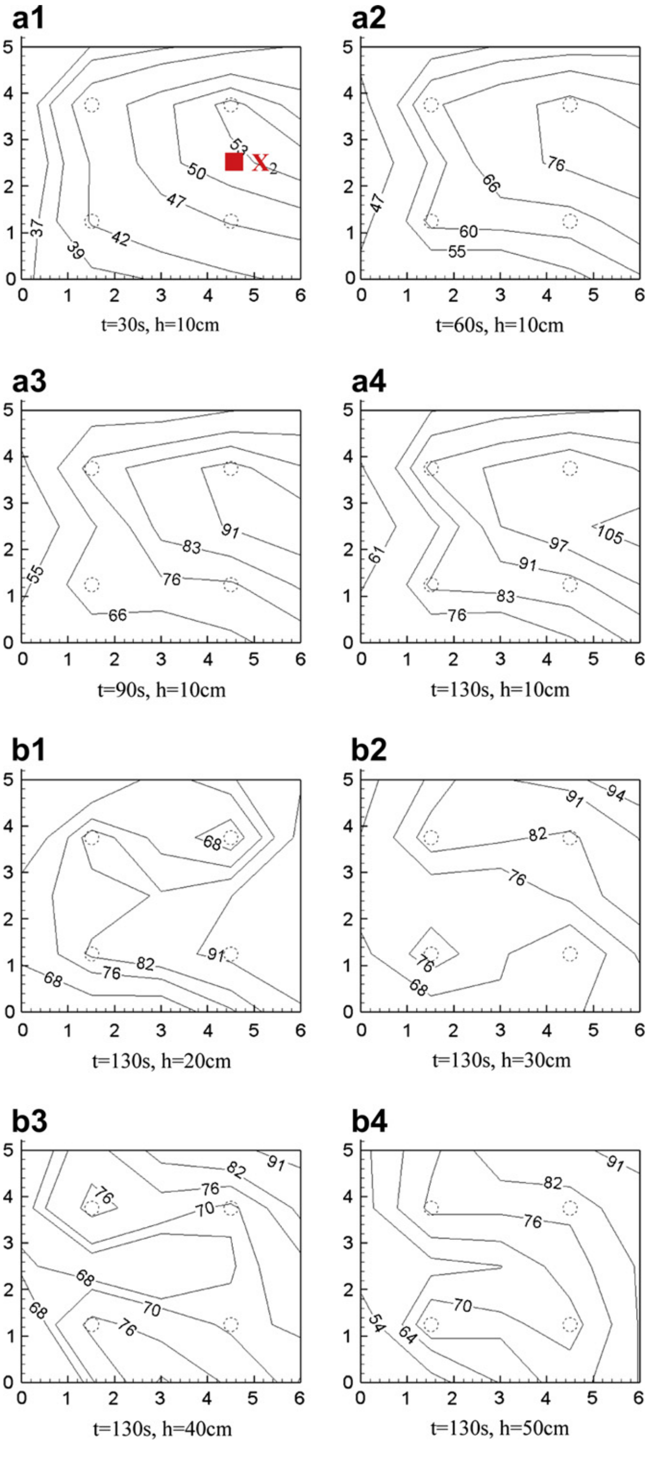


Fig. 9. LPG-X_1-W (fire at location X_1 in reference to Fig. 4) isotherms.

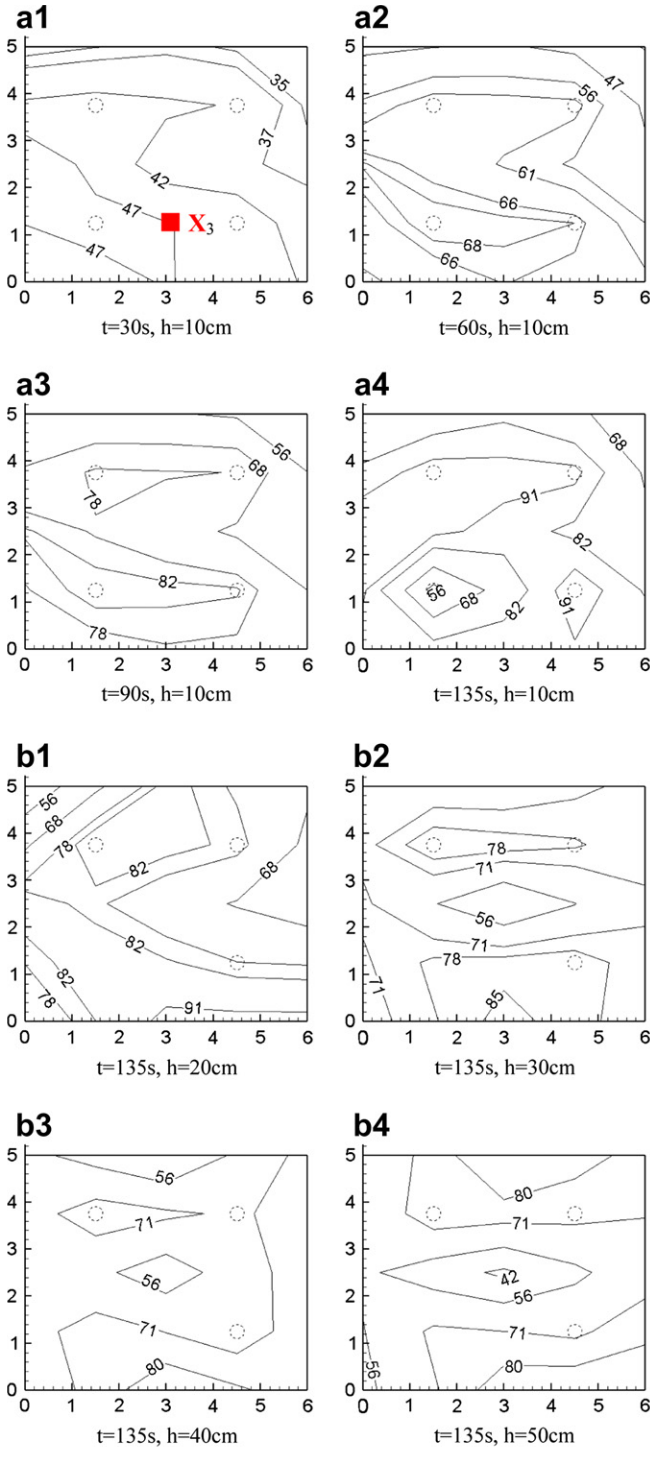
The reason that the W series actuates faster than the X series is because of the wall effect. Overall, M_1 is the position of slowest sprinkler response.

The gas temperature around the actuated sprinklers is between 99 °C and 105 °C. Generally, the sprinklers are actuated when the nearby air reaches 100 °C. Comparing Y_1 and Z_1 experiments, the T_1 temperature curve in experiment Y_1 is similar to that in experiment Z_1; the influence on the sprinkler actuations should be similar. Thus, the result of experiment Y_1 could be caused by a breakdown of the sprinkler head. Because of the location close to the northern door in



t=30s, h=10cm
t=60s, h=10cm
t=90s, h=10cm
t=130s, h=10cm
t=130s, h=20cm
t=130s, h=30cm
t=130s, h=40cm
t=130s, h=50cm

Fig. 10. LPG-X_2-W (fire at location X_2 in reference to Fig. 4) isotherms.



t=30s, h=10cm
t=60s, h=10cm
t=90s, h=10cm
t=135s, h=10cm
t=135s, h=20cm
t=135s, h=30cm
t=135s, h=40cm
t=135s, h=50cm

Fig. 11. LPG-X_3-W (fire at location X_3 in reference to Fig. 4) isotherms.

experiment Z_2, the gas temperature near the actuated sprinkler head S_2 is cooled by introduced ambient air and is still low.

4. Conclusion

This study explores the influence of different fire source locations on the actuation of sprinklers in an office fire. Twelve fire source locations were tested, including the room center, the wall center, corners, and other locations with different distances to the sprinklers. The findings show that the actuation time of the sprinklers is affected by the fire source locations and heat conduction properties of the glass bulb of sprinklers. When the fire source is closer to the sprinklers, corners, or walls, the actuation time of the sprinklers is shorter. Because of the wall effect, hot gas is more likely to be induced to flow upwards, and accumulation of upper level smoke is quicker. Average actuation time of all the tests is 102 s, around 40 s faster than if the fire source is located in the room center. For fire sources in corners, sprinklers are quickly activated at the experimental time 75 s, showing concentrated hot gas flow.

Acknowledgements

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