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Full Length Research Paper

Full-scale experiment research for performance analysis of a mechanical smoke exhaust system

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This full-scale experiment studies the efficiency of a mechanical smoke exhaust system by using hot smoke testing. The mechanical smoke exhaust system consisted of an air-conditioning system in a ceiling and its linear return diffusers were used as a smoke vent. To measure the efficiency of the system, the study included measurements of the smoke descending rate, the diffusion of heat into the room, and the visibility. Simultaneously, the diffusions of the smoke scenes were recorded and visually inspected. In accordance with Taiwan's regulatory body, the smoke exhaust flow rate was set at 1.0 CMM/m^2 as a reference. It was found that if the location of the smoke vent was established improperly, smoke turbulence was formed. The feasibility was assessed when the smoke exhaust flow rate was adjusted to 0.8 and 0.5 CMM/m^2. Finally, the effect of the total area ratio of the diffuser opening on the efficiency of the new system was studied by adjusting the area ratio to 2.5, 5, 10 and 15%. The experimental results proved that the global ceiling, used as a smoke vent, could exhaust smoke most effectively.

Key words: Visibility, smoke exhaust system, full-scale experiment, smoke descending rate.

INTRODUCTION

To allow persons in a fire to safely escape, the visibility of the fire scene must be good. Therefore, a smoke exhaust system must be installed in the building to; vent out the smoke, reduce the diffusion of smoke and to increase the visibility whilst a fire is occurring. The smoke exhaust system should be able to effectively prevent the smoke in a fire, thereby increasing the scene visibility.

There is much research on scene visibility during a fire (Jin, 2002; Collins et al., 1992; Wong and Lo, 2007). Collins carried out a functional analysis of exit signs. Wong pointed out that four factors affect the vision of observers. Widmann found that the equivalence ratio had a strong effect on the optical properties of post-flame soot agglomerates (Widmann et al., 2003). While previous studies and some building codes have suggested a visibility of 30 ft (10 m), NFPA 130 suggests a visibility of 100 ft (30 m) (National Fire Protection Association, 2000).

In Taiwan, "The Standard for Installation of Fire Safety Equipments Based on Use and Occupancy" was used as a reference for the visibility standard (National Fire Agency, 2008).

In 1993, Tamura and MacDonald (1993) built a 10-story experimental fire tower to evaluate the performance of the mechanical smoke exhaust system. They discovered that if one or two stair doors were open, including the one on the fire floor, smoke contamination of the stair shaft would occur. Many researchers (Reneke et al., 2001; Siu et al., 2002; Ma and Quintiere, 2003) adopted the large eddy simulation (LES) model to analyze the diffusion of smoke and reexamine the flow mechanics of smoke experimentally (Jianguo et al., 2005; Sherman et al., 2006). For those simulation studies, smoke was generated from the fire and spread to an observer. They discovered that the growth of indoor smoke was strongly affected by the ventilation system. Lin et al. (2007) combined the experimental data with a similar analysis in telephone central offices (TCO) and semiconductor clean rooms to find a characteristic length scale. Non-dimensional relations were deduced for the extent of

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the smoke containment and the onset of plume oscillations (Zhang et al., 2007).

Other studies explored the smoke diffusion effect in a fire. Fang and Yuan's experiments and Computational fluid dynamics (CFD) simulations were conducted in a small-scale enclosure and a large space to investigate early fire movements in a temperature-stratified ambient environment (Fang et al., 2007). Chow's experimental results showed that the smoke exhaust were more efficient when air-supply openings were placed at a distance away from the smoke exhaust openings. The experimental results also showed that the smoke control performance, even with a larger smoke exhaust rate, was poor if the air-supply opening was near the smoke exhaust opening (Yi et al., 2006).

According to local regulations in Taiwan, the design of a smoke exhaust system may vary with; the area of the smoke compartment, the position of the smoke exhaust outlet and the smoke exhaust flow rate. Thus, the ventilation system must be a prescription-based design. The smoke exhaust flow rate is required to be greater than 1.0 CMM/m^2 by the fire department. However, this value was set by presuming that the air flow rate had a proportional relationship with the floor area, without considering the structure of the building.

Efficiency measurements of the smoke exhaust system

Due to the need for global energy conservation, the available space of buildings, especially for high-rise buildings, has been greatly reduced. This constraint has reduced not only the construction costs, but also the air-conditioning requirements. In Taiwan, these buildings are required to include dedicated smoke exhaust ducts which are only active whilst a fire is occurring.

Inspired by these ideas, it was considered that if the smoke exhaust flow rate could be reduced, the cross-sectional area of the duct could also be minimized. Referring to the design concept of NFPA 90A (National Fire Agency, 2005), if the return air duct in air-conditioning systems and a smoke exhaust duct were combined, the spatial altitude above the ceiling could be reduced, effectively reducing the height of the building. However, it is important to evaluate the performance efficiency of this combined system under the same smoke exhaust flow rate as the system with separate return air and smoke exhaust ducts.

In this research, full-scale experiments inside an office space were studied by comparing the smoke exhaust efficiency of the proposed smoke exhaust system and the conventional system. The new smoke exhaust system used linear return diffusers as smoke vents, which were installed evenly in the ceiling and the space above the ceiling was used for smoke plenum. The experimental procedure included measurements of smoke diffusing phenomenon in the office, temperature variation, smoke descent rate and visibility in order to have; (1) An evaluation of the validity of the new smoke exhaust system, followed by (2) an investigation of the effect of a reduced smoke exhaust flow rate on the efficiency of the new system and finally (3) a study of the effect of the linear return diffuser on the open area.

EXPERIMENTAL APPARATUS AND LABORATORY MEASUREMENT

Experiment space

The experimental space was an office room with a length of 10.4 m, width of 9.6 m and a height of 3.6 m. Its floor area was 99 m^2. Similar to a typical office, light steel joist ceilings were installed at a height of 2.7 m.

According to fire regulations and legal stipulations of Taiwan, a designed smoke exhaust system must have the capacity to discharge smoke with a flow rate of at least 1.0 CMM/m^2. A 10% margin of error must be incorporated into the design and the total the smoke exhaust speed must be 1.82 CMS. Furthermore, the smoke vent of the system must be located in the centre of the ceiling, as shown in Figure 1A.

On the other hand, referring to NFPA 90A, section 1 to 3.1(e) in the 1st chapter, the air-conditioning system of the building can operate as a smoke exhaust system during an emergency. The NFPA 90A described that this type of air-conditioning system needed a level of integrity dependent upon; the building structure, the floor, the partition frame, the roof and the walls. The ceiling of the building must be fire-proof and have the ability to be used as a smoke barrier. This new smoke exhaust system used a square slit port as a smoke vent during a fire scenario and the space above the ceiling as a smoke plenum. The new smoke exhaust system is shown in Figure 1B.

In comparing the altitudes above both ceilings, the height value, H2, in the new system is smaller than the H1 value in the traditional system.

EXPERIMENTAL SET-UP

The hot smoke test was employed to compare the efficiency of these two smoke exhaust systems. The experimental set up included a burning source and a system to record the smoke diffusion. The results of the full-scale hot smoke test and the smoke scenarios were recorded as empirical data and visual images. The empirical data sets were the temperatures underneath the ceiling, the temperatures in the smoke layer and the scene visibility. The visual images were the pictures and videos taken during the smoke tests. The smoke test equipment setup is described as below:

Burning source

A smoke generator (ViCount Compact 5000, Concept Corporation) was used to generate smoke diffusing phenomena using heat of up to 370°C; the maximum heating temperature of the ViCount Compact machine. To enhance the smoke buoyancy, a fire tray was used to raise the smoke. Referring to the Australian National Standards "AS 4391-1999, Smoke management systems-Hot smoke test" (Australian Standard, 1999), the size of the burning source was 420 × 297 × 65 (mm) and the fire tray had a combustion area of 0.125 m^2. As suggested in AS 4391, the fuel was methanol (CH_3OH). The temperature of the top smoke from the fire tray was 71°C and the smoke floating was consistent with this temperature, as shown in Figure 4A.

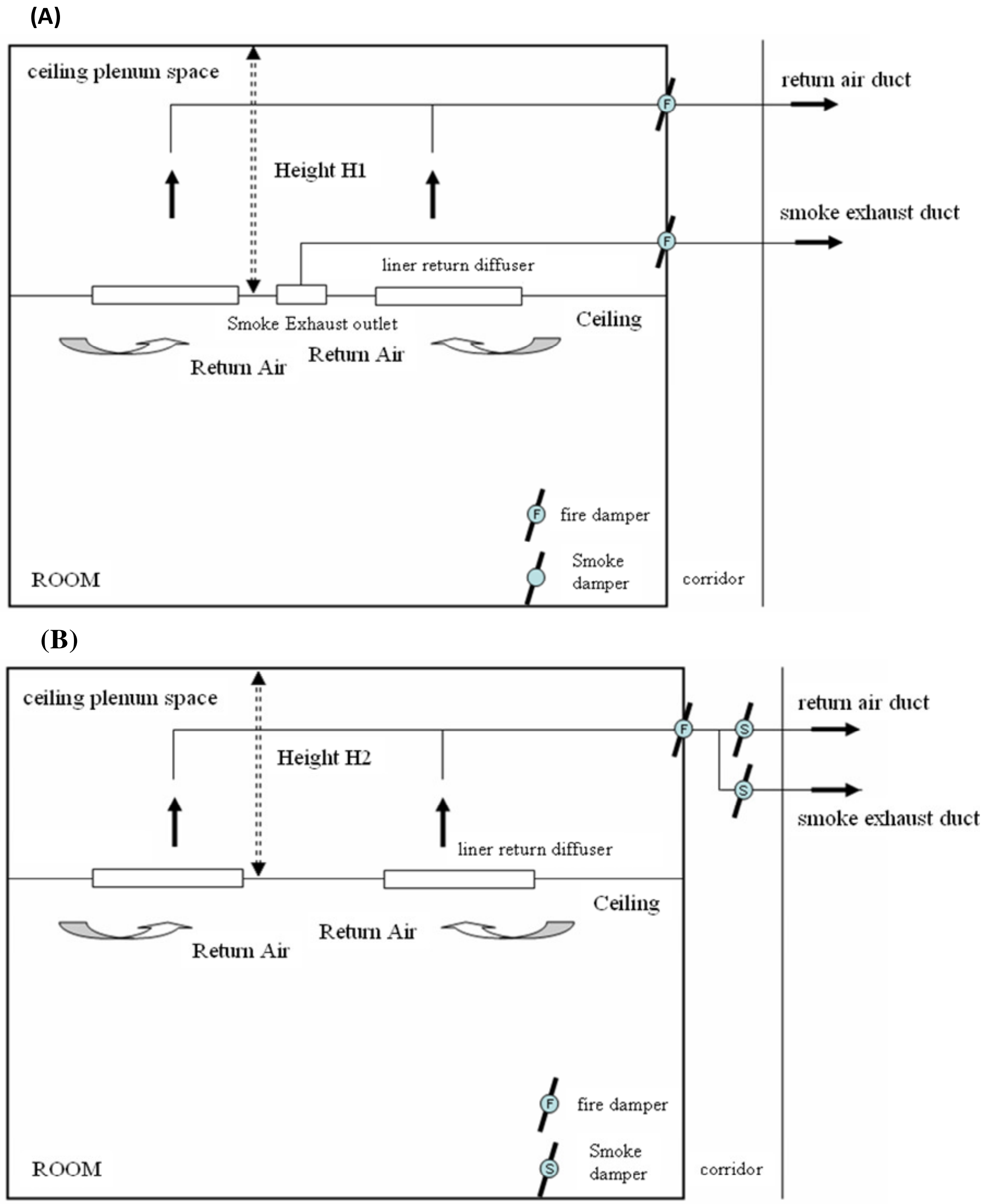

Figure 1. A schematic diagram of the; (A) traditional smoke exhaust set up; (B) combined new smoke exhaust set up.

Alpert (1971) found that the ratio between the radius of the fire plume and the room height was less than 0.15 in the early stages of the fire. Since the height of the room was 2.7 m, the maximum radius of the fire plume in the test was about 0.4 m. The radius of the fire plume was found to be significantly less than 0.4 m from Figures 4A and B. The combustion of methanol was recorded using a load cell and a recorder. The results are shown in Figure 2. From reference (Charles and Baukal, 2001), the standard combustion enthalpy of methanol is 5,420 cal/g. By calculation, the combustion rate and the combustion enthalpy of methanol were 1.9 g/s and 43.3 kW respectively. This measurement was repeated for every experiment, all of which resulted in identical combustion rates and enthalpies. It was found that the pattern of the fire plume was the same with Alpert's conclusion when the fire load was 43.3 kW.

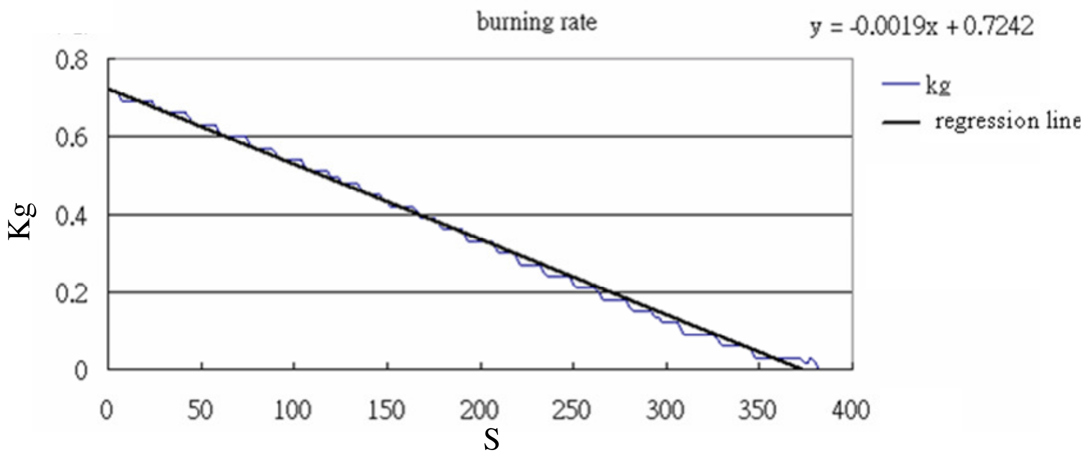

Figure 2. The combustion rate of methanol.

Measurement equipment of smoke diffusion

The smoke visibility was measured by shining a laser through the smoke and detecting the attenuated light intensity with a luminance meter. The luminance meter was fixed 1 m from the light source. The light could be attenuated via absorption, reflection and refraction in the smoke. When the luminance meter received weaker light, it indicated the scene visibility was poorer.

There were many factors which could affect the visibility of the fire scene. This included the diameter of smoke particles, the absorption coefficient of the smoke, the light wavelength of the laser and the properties of the attenuating objects (light-emitting source or light reflecting source). Many (Gwynne et al., 2001) have studied the optical density of smoke during combustion by calculating the extinction coefficient (K). The extinction coefficient of smoke is relevant to scene visibility, and plays an important role for a fire victim to egress. According to the Beer-Lamber Law, when a flux with a wavelength (λ) passes through the smoke layer, the intensity of the light is attenuated according to the following relation (National Fire Agency, 2005):

$$I_{\lambda} = I_{\lambda 0} \exp(-KL)$$

Herein $I_{\lambda 0}$: Intensity of incident light (cd); I_{λ} : Intensity of attenuated light (cd); L : Thickness of smoke layer (m); K : Extinction coefficient (m-1);

In a fire scene, light-emitting objects provide more visibility than light-reflecting objects by 2 to 4 times (Mulholland, 2002). The scene visibility and the extinction coefficient can be related as follows (Klote et al., 2002):

$K \times S = 8$, for light-emitting objects,

$K \times S = 3$, for light-reflecting objects,

where K = Extinction coefficient (m-1); S = Scene visibility (m).

There were 4 pieces of equipment used to measure smoke diffusion in order to quantify the efficiency of the smoke exhaust systems.

Temperature measurement system

The temperature of the indoor office space was measured using thermocouples to investigate the distribution of air flow. There were 9 thermocouple trees, measuring the temperature at heights of 2.7, 2.2 and 1.8 m from Point A to Point I at a certain location, as shown in Figure 3. Considering the human visual height is at about 1.8 m, the minimum measuring height for temperature and smoke concentration was 1.8 m. Thus, there were 27 data points for each smoke test. The thermocouple tree was constructed by using 3 thermometers (K-type) and a recorder (YOGOKAWA MV200).

Smoke sensor system

A series of smoke sensors were installed at heights of 2.7, 2.2 and 1.8 m on Point D, as illustrated in Figure 3. These sensors conformed to Taiwan National Standards CNS 8874 code, and could detect a 15% volume concentration of smoke. This equipment was self-developed for this research and could record the time of the smoke descent from top to bottom.

Visibility measurement equipment

Applying light scattering theory to smoke, a light transmitter and a light-receiver were installed at different heights for precise measurements. The light-transmitter was an industrial light laser pointer with power consumption of 5mW and a wavelength of 650nm. The light-receiver was a digital luxmeter (TES-1336A). It has a light sensor with a wavelength sensitivity range of 380 to 780 nm. The transmitter and receiver were placed at Point A and Point D respectively; a distance of 1 meter from each other as shown in Figure 3.

Photograph system

Referring to FigureCH1 to CH4 indicate the positions of closed-circuit television (CCTV) cameras for video recording of the smoke distribution. CH4 was used to record the smoke conditions inside the plenum above the ceiling. CH1 and CH2 were used to record the smoke descent inside the room. CH3 was used to focus the LED light in the smoke layer sensor system so that the attenuation

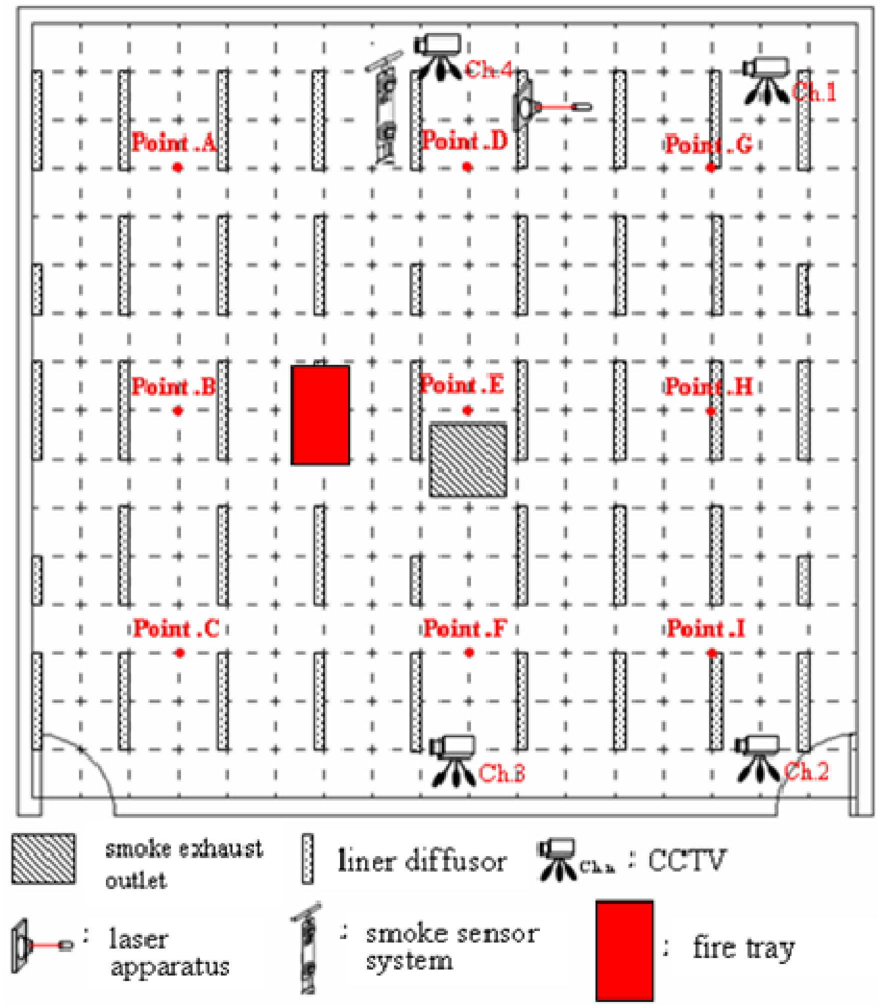

Figure 3. An illustration of the position of each instrument.

of light could be observed visually during smoke descent.

Experiment pan

The traditional smoke exhaust system was first established accordingly to the legal regulations. This was then followed by the installation of the new smoke exhaust system. Subsequently, parametric analyses of these two systems were carried out, including the smoke exhaust flow rate and the total area of the linear return diffuser. The following analyses were discussed.

i. The efficiency measurements of the smoke exhaust systems and a comparison of the efficiency of the traditional and new smoke exhaust systems.
ii. Investigating the efficiency of the new smoke exhaust system by changing the smoke air flow.
iii. Investigating the efficiency of the new smoke exhaust system by changing the cross-sectional area of the linear duct.

The list of hot smoke tests is given in Table 1. Each test was represented by 4 characters, representing the system and the condition. Taking TY10 as an example:

The 1st character – T, indicates the traditional system and N indicates the new system,
The 2nd character - Y indicates yes for air make-up,
The 1st digit - 1 indicates a smoke exhaust flow rate of 1.0 CMM/m^2, 2 for 0.8 CMM/m^2 and 3 for 0.5 CMM/m^2,
The 2nd digit - 0 indicates an open area percentage of zero for the traditional system (0);
In the new system, symbol 1 indicates 2.5%, 2 indicates 5%, 3 indicates 10% and 4 indicates 15%.

RESULTS AND ANALYSIS

In this research, the office room was chosen because its evacuation time during an emergency must be short. As stated in the “Fire Prevention and Safety Establishment Standard for Various Interior” document (Chen, 2007), the office is classified as a class B interior. The internal evacuation time required is 84 s.

Since escape action may be delayed for people inside, the maximum time for full smoke spread was 180 s. In order to collect more information, the recordings of all tests in this research were ceased after 160 s. These time

Table 1. A list of hot smoke tests in the full-scale experiment.

Traditional smoke exhaust system		New smoke exhaust system				
		Diffuser open area in ceiling / Flow rate (CMM/m^2)	2.5%	5%	10%	15%
1.0 CMM/m^2	TY10	1.0	NY11	NY12	NY13	NY14
		0.8	NY21	NY22	NY23	NY24
		0.5	NY31	NY32	NY33	NY34

based recordings were analyzed to determine the advantages and disadvantages of the new smoke exhaust system using the traditional smoke exhaust system as a reference.

The effect of smoke exhaust flow rate

Visual observation of the smoke layer

Smoke from the fire scenario could hinder visibility for a victim, hence creating a panic situation. To measure visibility, the indoor smoke scenes were first measured visually. Fig. 4(A) and (B) are pictures of the experimental results under various conditions using the CCTV system. After 180 s, the entire room of the traditional smoke exhaust system (TY10) was filled with smoke. The room of the new smoke exhaust system (NY11, NY21 and NY31) provided an improved smoke extraction performance.

In investigating the effect of the smoke exhaust flow rate on the efficiency of the new system, it was observed that a higher flow rate provided better visibility. Namely, NY11 (a flow rate of 1.0 CMM/m^2) provided the best visibility. NY21 (a flow rate of 0.8 CMM/m^2) still provided a visible path to the exit. For NY31 (a flow rate of 0.5 CMM/m^2), although its visibility was the least impressive compared with the former two cases, the smoke layer was mainly suspended underneath the ceiling. Overall, the new system provided good visibility up to 1.8 m, allowing safe evacuation to be carried out.

In this research, a perpendicular smoke layer sensor system was constructed by using a series of Taiwanese-made smoke sensors. This system could detect smoke concentrations of up to 15% volume at different heights. A self-developed timer was attached to record the exact sensing time.

From Figure 5, after the smoke generator was started, smoke reached 2.7 m in about 15 to 20 s in both systems. In the traditional system, TY10, the smoke descended to 2.2 m after 35 s. In comparison to the new systems; NY11, NY21 and NY31, the smoke descended to the same level after 90, 54 and 57 s respectively. The smoke descents in the new system were slower than the traditional system. In the traditional system, TY10, smoke descended to 1.8 m after 89 s. In the new system, the smoke reached 1.8 m after 97, 111 and 119s for the NY11 system with a flow rate of 1.0 CMM/m^2, the NY21 system with a flow rate of 0.8 CMM/m^2 and the NY31 system with a flow rate of 0.5 CMM/m^2 respectively. These results indicated that the new smoke exhaust system slowed down the descent of smoke. Since the smoke exhaust grill of new system type was evenly spread, exhaust air was reduced by efficiently exhausting smoke.

Temperature alterations

The temperatures of the offices were measured using a thermocouple tree. The recording frequency was 2 s. The indoor temperature distribution and alterations in each condition were investigated by conforming to the N% principle in NFPA.

By observing the temperature alteration under each condition, Figure 6A illustrates that the indoor temperature was altered at 2.7 m. After 90 s, the rise in temperature in all conditions was restrained. It is believed that this phenomenon was related to the smoke blower. At 240s, the temperatures in the new system with a flow rate of 1.0 CMM/m^2 (NY11) and a flow rate of 0.8 CMM/m^2 (NY21) were 43.7 and 45.4°C respectively. In comparison to the traditional system, the temperature of TY10 at the same time was 50°C. Thus, NY11 and NY21 showed lower temperatures. On the other hand, the indoor temperature of NY31 with a flow rate of 0.5 CMM/m^2 was 50.8°C, which was close to the temperature of the traditional system.

Figure 6B shows the temperature distribution at 1.8 m. It was observed that NY11 and NY21 provided a lower indoor temperature than TY10 after 100 s. However, NY31 had a higher indoor temperature than the traditional system. The results display that an excessive reduced exhaust air extraction volume reduced the effect of smoke exhausting.

Visibility measurement

A light was transmitted from a laser through the smoke layer and a detector was used to measure the intensity of the light. From the intensity, the scene visibility was measured and its value was used to determine exit safety.

Table 2. The visibilities (m) of smoke scenes in the traditional and the new smoke exhaust systems during the smoke tests.

Height (m)	Seconds	0	30	60	90	120	150	180
2.7	TY10	∞	14	2	3	2	2	2
	NY11	∞	15	4	5	3	3	2
	NY21	∞	7	3	2	2	2	2
	NY31	∞	15	3	2	3	3	2
2.2	TY10	∞	191	9	3	3	2	3
	NY11	∞	788	102	13	9	9	10
	NY21	∞	256	22	4	7	5	2
	NY31	∞	1556	13	4	3	2	2
1.8	TY10	∞	∞	47	14	8	6	12
	NY11	∞	∞	876	89	46	41	20
	NY21	∞	∞	876	29	49	30	16
	NY31	∞	1748	580	20	10	8	6
1.2	TY10	∞	∞	102	39	42	17	49
	NY11	∞	∞	840	334	149	184	165
	NY21	∞	∞	836	136	276	183	63
	NY31	∞	∞	∞	79	79	58	75

To calculate visibility, Equation (1) was used by adopting the data from light intensity and the visibilities of all conditions are tabulated in Table 2. The Table consists of visibility values at different heights and times for each condition (TY10, NY11, NY21 and NY31).

Observations at a height of 2.2 m show that the visibility in the traditional system after 60 s was 9 m. After 90 s, the value dropped to 3 m, whereas the new system provided visibilities of 102, 22 and 13 m for the NY11, NY21 and NY31 systems respectively after 60 s. These values decreased to 13, 4 and 4 m respectively after 90 s. These results demonstrate that all three conditions in the new system provided better visibility than the traditional system.

Observations at a height of 1.8 m show that the visibility in the traditional system after 60 s was 47 m and the value dropped to 14 m after 90 s. The new system provided visibilities of 876, 876 and 580 m for the NY11, NY21 and NY31 systems respectively after 60 s. These values were decreasing to 89, 29 and 20 m respectively after 90 s. This data further confirmed that the new system could promote better indoor visibility.

According to the NFPA 130 regulation standard, the visibility at 1.8 m has to be larger than 10 m for one to safely egress the scene of the fire. The time required for one to evacuate from this experimental space was 84 s. The new smoke exhaust system could maintain the visibility of the experimental space above 20 m and was proven to be able to assist the escape of fire victim effectively and smoothly.

The effect of the total area ratio of the diffuser opening

Visual observation on the smoke layer

From the foregoing, the efficiency of the new smoke exhaust system with a flow rate of 0.5 CMM/m^2 was similar to the traditional smoke exhaust system with a flow rate of 1.0 CMM/m^2. By adopting this flow rate, we study the effect of the diffuser area on the efficiency of the new system. The flow pattern in the room changed with different diffuser open areas. Therefore, the efficiency of the smoke exhausting system will be affected. The experiments were carried out by manipulating the ratios of the diffuser open area over the total area of the ceiling, which were 2.5, 5, 10 and 15%.

The smoke scenes were recorded using the CCTV system. From Figures 7A and B, it was found that after 180 s, smoke accumulated beneath the ceiling under the new NY31 system conditions (flow rate of 0.5 CMM/m^2 and diffuser open area of 2.5%). It was observed that this smoke accumulation decreased when the open area ratio was higher. In regards to the NY34 system (flow rate of0.5 CMM/m^2 and a diffuser aperture ratio of 15%), it was clearly seen that the smoke diffused through the ceiling to the plenum above. By comparison, the smoke accumulation

Table 3. The temperature alterations with different ratios of diffuser open area in the new smoke exhaust system with a flow rate of 1.0 CMM/m^2 (unit: ℃).

Height (m)	Seconds	0	30	60	90	120	150	180	210	240
2.7	NY11	28.9	35.9	41.0	45.0	43.2	45.4	44.1	45.0	43.7
	NY12	28.9	35.9	40.2	43.2	45.0	46.4	44.9	43.6	42.4
	NY13	27.2	33.5	36.6	40.2	39.9	40.3	39.3	39.6	42.1
	NY14	28.1	32.2	34.7	38.1	38.7	37.9	39.0	40.8	39.6
2.2	NY11	28.5	29.4	33.8	36.8	34.6	33.8	33.8	34.6	35.2
	NY12	28.5	29.3	32.9	35.6	33.6	33.9	34.0	34.6	34.7
	NY13	26.8	27.5	29.2	31.2	31.4	31.2	31.5	31.0	30.3
	NY14	27.6	28.1	30.4	31.5	30.1	29.6	30.3	30.4	30.9
1.8	NY11	28.4	28.7	30.1	30.9	30.9	31.2	30.9	30.9	31.0
	NY12	28.4	28.6	29.7	30.4	30.3	30.7	30.5	30.9	31.4
	NY13	26.7	26.8	27.2	28.0	28.3	27.3	27.1	27.1	27.2
	NY14	27.4	27.9	28.1	28.9	28.8	28.3	28.3	28.3	28.3

Table 4. The temperature alterations with different ratios of diffuser open area in the new smoke exhaust system with a flow rate of 0.8 CMM/m^2.

Height (m)	Seconds	0	30	60	90	120	150	180	210	240
2.7	NY21	28.8	37.3	42.9	45.9	44.3	46.4	46.3	46.1	45.4
	NY22	29.0	37.0	40.8	43.0	43.0	43.4	44.1	45.7	46.5
	NY23	27.5	34.8	36.8	39.6	42.8	42.7	41.7	40.5	41.6
	NY24	28.0	33.0	36.3	41.2	40.7	40.8	40.2	41.9	40.2
2.2	NY21	28.3	29.6	35.9	39.6	38.6	36.5	35.6	36.2	36.7
	NY22	28.4	29.0	33.3	36.5	35.1	35.7	34.8	35.5	36.3
	NY23	26.8	27.3	30.6	31.8	31.6	33.5	32.8	33.2	32.9
	NY24	27.5	28.7	30.0	32.3	31.6	31.7	31.5	32.2	32.6
1.8	NY21	28.4	28.6	30.4	31.3	31.0	32.3	31.3	31.4	31.2
	NY22	28.5	28.6	29.4	30.6	30.5	30.7	31.7	30.9	31.1
	NY23	26.8	27.1	27.3	28.6	28.0	27.4	28.0	27.9	27.8
	NY24	27.5	28.0	28.2	29.0	28.7	28.9	28.9	29.9	29.3

underneath the ceiling for these larger open areas was insignificant.

These phenomena show that when the diffuser open area increased from 2.5 to 15%, a larger amount of lighter smoke diffused through the ceiling. Hence, it was proven that an increase in the diffuser open area could help smoke float to the plenum above the ceiling. During a fire, a larger opening could effectively slow down the smoke descent and allow a greater evacuation time.

Temperature alterations

Tables 3, 4 and 5 contain the temperature variations under different diffuser open areas for flow rates of 1.0, 0.8 and 0.5 CMM/m^2 respectively in the new system.

In Table 3, the flow rate was fixed at 1.0 CMM/m2. Focusing on a height of 1.8m, the temperature of NY11 in the new system was 30.9℃ after 90 s. On the other hand, the temperatures of the experimental space of NY12, NY13 and NY14 in the new system were 30.4, 28.0 and 28.9℃ respectively. These results showed that a larger diffuser open area also provided relatively lower temperatures.

Table 4 demonstrates the temperature variations of the office in the new system with a flow rate of 0.8 CMM/m^2. Focusing on a height of 1.8 m, the spatial temperature of NY21 in the new system was 31.3℃ after 90 s. On the

Table 5. The temperature alterations with different ratios of diffuser open area in the new smoke exhaust system with flow rate of 0.5 CMM/m^2 (unit: ℃).

Height (m)	Seconds	0	30	60	90	120	150	180	210	240
2.7	NY31	29.2	37.5	40.8	45.5	46.9	48.9	48.6	48.5	50.8
	NY32	29.2	38.2	40.5	45.1	44.2	43.3	43.6	43.7	45.6
	NY33	27.4	33.5	36.6	41.9	43.4	42.2	44.0	44.7	43.6
	NY34	28.4	33.6	33.9	38.8	40.1	41.7	42.1	44.1	44.1
2.2	NY31	28.8	30.2	34.3	37.7	40.0	41.8	41.6	43.4	43.6
	NY32	28.7	29.7	33.2	36.9	37.5	37.3	37.1	38.6	39.1
	NY33	26.9	27.8	29.8	31.7	33.5	34.8	34.9	35.1	35.3
	NY34	27.8	28.2	30.8	33.1	33.3	33.4	34.5	35.1	35.2
1.8	TY10	28.2	28.4	29.6	30.5	32.2	31.6	32.1	32.5	32.5
	NY31	28.8	28.8	30.2	31.0	31.6	32.8	33.1	33.3	32.7
	NY32	28.7	28.9	29.5	29.8	31.0	32.5	32.8	33.5	33.1
	NY33	26.8	27.1	27.4	28.5	28.5	28.9	29.9	29.8	29.8

other hand, NY22, NY23 and NY24 possessed the spatial temperatures of 30.6, 28.6 and 29℃, respectively.

Table 5 demonstrates the experimental temperatures of the new system with a flow rate of 0.5 CMM/m^2. Similarly focusing on a height of 1.8 m, NY31 in the new system had a spatial temperature of 30.5℃ after 90 s. The spatial temperatures of NY32, NY33 and NY34 were 31, 29.8 and 28.5℃ respectively, showing a tendency for the temperature to decrease for larger diffuser open areas.

Visibility measurements

Tables 6, shows the visibilities of the new smoke exhaust system at different flow rates and different diffuser open area ratios. However, only the visibilities at height of 1.8 m will be discussed. Table 6 demonstrates the visibilities of smoke scenarios at a flow rate of 1.0 CMM/m^2. NY11 provided a spatial visibility of 89 m after 90 s. NY12, NY13 and NY14 provided spatial visibilities of 45, 884 and 1000 m respectively after 90 s. The results indicated that a higher diffuser open area promoted visibility. After 90 s, it was observed that the 10% diffuser open area gave the best visibility compared with other ratios of diffuser open area.

NY21 provided a spatial visibility of 29 m at 90 s. NY22, NY23 and NY24 had visibilities of 25, 1172 and 444 m respectively after 90 s. It also shows a tendency of the visibility to increase as the diffuser open area increased. However, after 90 s, the systems with a 10% diffuser open area still provided the best visibility.

NY31 provided a spatial visibility of 20m after 90s. NY32, NY33 and NY34 allowed visibilities of 21, 436 and 1000 m respectively after 90 s. These results imply that a higher diffuser open area leads to better visibility. Similarly, after 90 s, it was found that a 10% diffuser open area presented the best visibility among other conditions. This was found to be due to the air flow pattern being stable and undisturbed at 10% diffuser open area.

These results proved that the new smoke exhaust system could provide good visibility for flow rates of 1.0, 0.8 and 0.5 CMM/m^2. It was also discovered that a larger diffuser open area could provide better visibility. Hence, a larger diffuser open area could enhance the efficiency of the new smoke exhaust system. The system run with a 10% diffuser open area provided the highest efficiency to extract the smoke from the office.

DISCUSSION

The efficiency of smoke exhaust

The experimental results were derived to analyze the efficiency of the smoke exhaust systems digitally. The initial approach used the naked eye to observe the smoke distributions inside the experimental space. From Figure 4, the existing smoke exhaust system in a Taiwan office area as set out by the regulations of the Fire Department in Taiwan was proved not to be the most efficient. If the system was modified, its efficiency in exhausting smoke could be improved.

The smoke layer sensor system could replace the judgment of the naked eye by measuring the duration of the smoke descent. In Figure 5, the results showed that smoke descended to 1.8 m after 89, 97, 111 and 119 s for the TY10, NY21, NY31 and NY11 systems respectively. The results were consistent with Figure 4.

The results also indicated that the traditional smoke exhaust system could easily allow for the formation of smoke turbulence. The analytical reason for this was the system possessed only one or two groups of smoke vents.

Table 6. The visibilities (m) of smoke scenes with different ratios of diffuser open area in the new smoke exhaust system with different flow rate.

Height (m)	Seconds	0	30	60	120	180
2.7	NY11	∞	15	4	3	2
	NY21	∞	7	3	2	2
	NY31	∞	15	3	3	2
	NY12	∞	12	12	7	6
	NY22	∞	26	5	3	2
	NY32	∞	11	4	2	2
	NY13	∞	17	75	22	26
	NY23	∞	25	39	19	10
	NY33	∞	40	44	10	7
	NY14	∞	33	68	14	10
	NY24	∞	41	26	5	3
	NY34	∞	9	12	9	3
1.8	NY11	∞	∞	876	46	20
	NY21	∞	∞	876	49	16
	NY31	∞	clear	580	10	6
	NY12	∞	∞	876	31	27
	NY22	∞	∞	clear	21	16
	NY32	∞	∞	580	11	7
	NY13	∞	∞	∞	884	59
	NY23	∞	clear	∞	89	80
	NY33	∞	∞	∞	583	583
	NY14	∞	∞	∞	116	221
	NY24	∞	∞	∞	27	13
	NY34	∞	∞	∞	57	219

The value shows “clear” when visibility is more than 1000 m.

To remove the smoke as quickly as possible, the smoke exhaust flow rate had to be set very high.

Through observation, once the air blower was started, the system was initially able to remove the smoke. However, after 120 s, smoke turbulence formed from the indoor air flow. At the conclusion of the experiment the entire room was filled with smoke. Such an incident might prevent a victims exit.

Next, measurements of temperature changes were used to investigate the smoke distribution. It was discovered that the traditional and new system provided different temperature alterations, as shown in Figures 6A and B. From Figure 6B, it was observed that the temperatures at 1.8 m after 120 s in the new system NY11 and traditional system TY10 were 30.9 and 32.6℃ respectively. Therefore, it can be clearly distinguished that the new system provided a lower indoor temperature than the traditional system.

Regarding visibility, it was observed that there was a large difference between the new and the traditional system at a height of 1.8 m. After 60 s, the visibility of the traditional system was 47 m, the value dropped to 14 m after 90 s.

For NY11, NY21 and NY31 in the new system, their visibilities were respectively 876, 876 and 580 m after 60 s and these values dropped to 89, 29 and 20 m respectively after 90 s. This clearly demonstrated that the new smoke exhaust system possessed an improved smoke extraction ability.

The adjustment of the smoke exhaust flow rate

In this research, the new smoke exhaust system utilized the entire ceiling as smoke vents. It provided a larger surface area to extract the smoke from the space, resulting in an improved exhaustion efficiency. Therefore, the flow rate of smoke could be adjusted due to its superior performance.

Observing the change in visibility, the visibilities of the traditional system after 30s, 60s and 90 s were 1000m, 47 and 14 m respectively. The visibilities of the new system with the prescribed flow rate of 1.0 CMM/m^2 after 30, 60 and 90 s were 1000, 876 and 89 m respectively. When

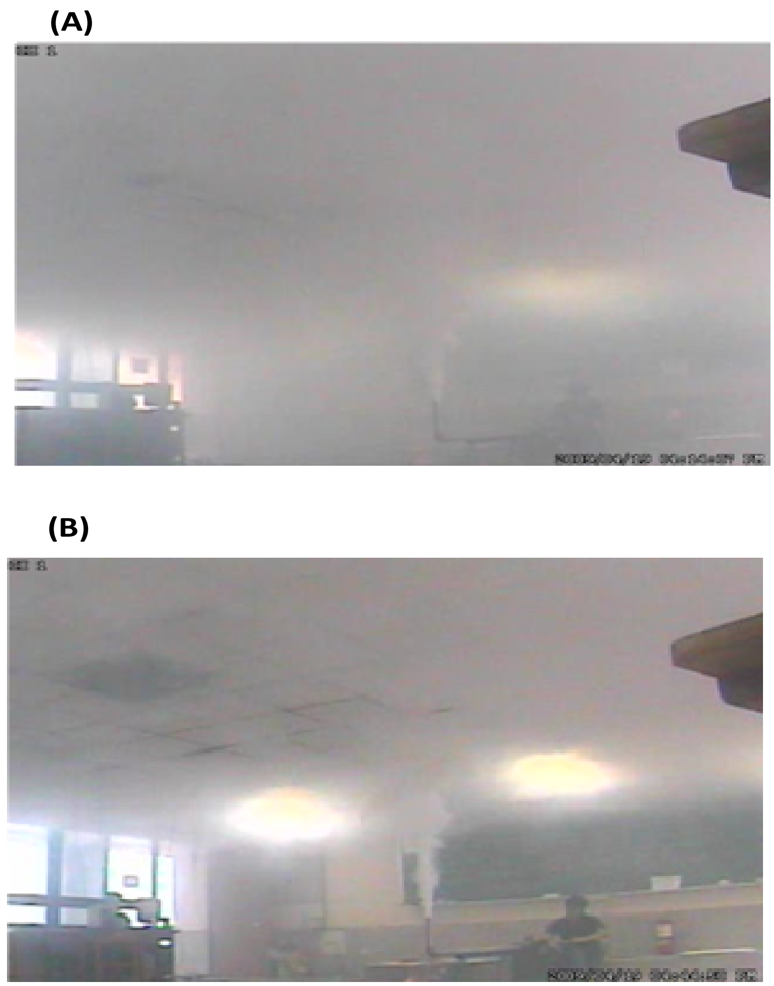

Figure 4. Smoke distribution of the; (A) traditional smoke exhaust system at 180 s; (B) new smoke exhaust system with a flow rate of 1.0 CMM/m^2 at 180 s.

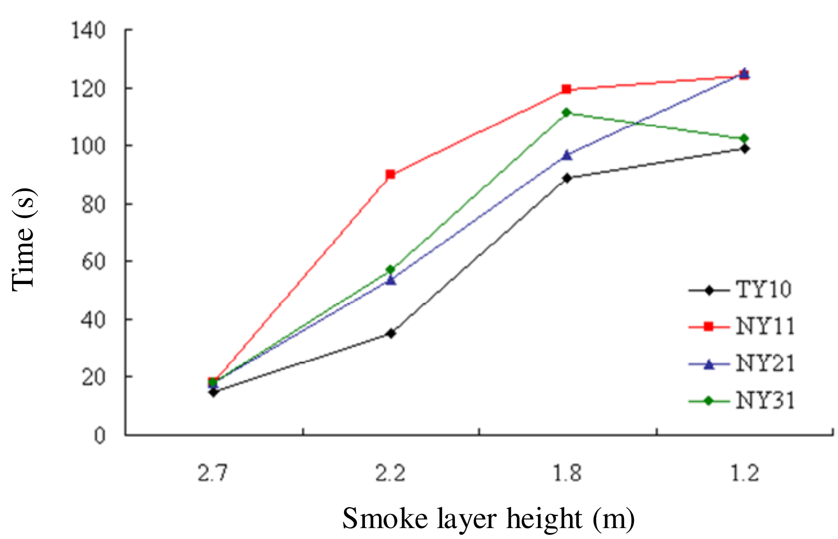

Figure 5. The smoke descent duration in the traditional and new smoke exhaust systems.

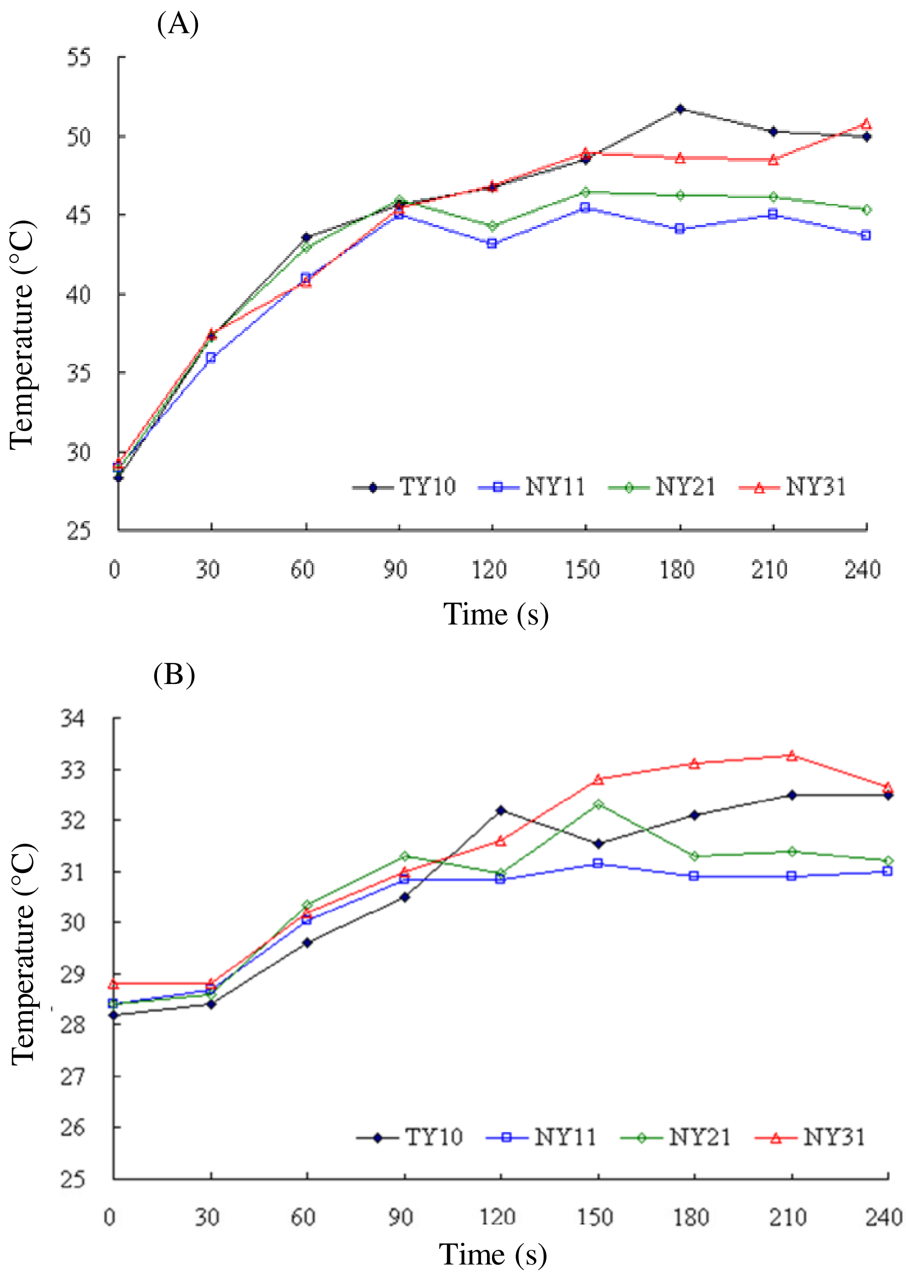

Figure 6. Temperature changes at heights of; (A) 2.7 m and (B) 1.8 m in both smoke exhaust systems.

the flow rate was reduced to 0.8 CMM/m^2, their visibilities after 30, 60 and 90 s became 1000m, 876 and 29 m respectively. Further reducing the flow rate to 0.5 CMM/m^2, the visibilities after 30, 60 and 90 s were 1748, 580 and 20 m respectively.

According to the N% theory of NFPA 92B (National Fire Protection Association, 2005), smoke distribution analysis can be extracted from the data of temperature changes. Adopting this methodology, our results used this data to justify the improvement seen in the new system.

Comparing the data after 120 s at a height of 1.8 m in Figure 6B, the temperatures of NY11 and NY21 in the new system were 30.9 and 31.0°C respectively, whereas the temperature of TY10 in the traditional system was 32.6°C. The NY11 and NY21 conditions provided a relatively lower indoor temperature compared to the traditional system. Conversely the temperature of the NY31 system was 32.2°C, which was very close to the temperature of the traditional system.

In looking at the smoke descent duration in Figure 5, the temperature alteration data in Figure 6 and the visibility analysis in Table 2, it can be concluded that the

(A)

(B)

Figure 7. Smoke distribution in the new smoke exhaust system with a flow rate of 0.5 CMM/m2 and a diffuser open area of; (A) 2.5% and (B) 15.0% at 180 s.

new system at a lower flow rate of 0.8 CMM/m^2 could still outperform the traditional system. At a further lower flow rate of 0.5 CMM/m^2, its improvement in exhausting smoke was not significant.

The effect of total area ratio of diffuser opening

In this study, it was found that the total area ratio of diffuser opening played an important role in the performance of the new smoke exhaust system. Therefore, the number of diffusers was extremely influential.

From the visual observations in Figure 7, a higher percentage of diffuser open area provided a more efficient smoke exhaust system. The data in Tables 3, 4 and 5 also indicated that the temperature reduced inversely as the diffuser open area increased.

Focusing on a height of 1.8 m with a flow rate of 1.0 CMM/m^2, the temperature of the new system with a diffuser open area of 2.5% was 30.9℃ after 90 s and its visibility was 89 m. When the diffuser open area was 15%, its temperature was 28.9℃ and its visibility was 1000m. At a reduced flow rate of 0.8 CMM/m^2, when the diffuser open area in the new system was 2.5%, the temperature after 90 s was 31.3℃ and the visibility was 29 m. When the diffuser open area was 15%, the temperature was 29℃ C and its visibility was 444 m. With a further reduced flow rate of 0.5 CMM/m^2, when the diffuser open area in the new system was 2.5%, the temperature after 90 s was 30.5℃ and the visibility was 20 m. When the aperture was 15%, the temperature was 28.5℃ and the visibility was 1000m.

From Tables 6, 7 and 8, it was derived that a 10% diffuser open area provided the best visibility with increasing time compared to the open area percentages of 2.5, 5 and 15%. The results also proved that the efficiency of the new smoke exhaust system was being enhanced as the diffuser open area increased regardless of the smoke exhaust flow rate.

CONCLUSIONS

The smoke exhaust system is extremely important to buildings as it can prevent smoke from thickening. According to Taiwan regulations, the smoke exhaust flow rate must be directly proportional to the floor area. This full scale experiment adopted hot smoke tests to simulate the distribution of smoke during a fire in order to measure the efficiency of the smoke exhaust system.

The research created a new smoke exhaust system by utilizing the linear return diffusers of the air conditioning system in the ceiling as a smoke vent. To keep the room temperature constant, the return diffusers were evenly distributed from a fluid dynamics perspective. The efficiency of this smoke exhaust system was quantified by recording the time taken for smoke decent to occur, the temperature distribution in the room and the visibility at various heights. Simultaneously, the smoke thickening was recorded and observed by a participant. The conclusions are summarized further.

The efficiency of smoke exhaust

The experimental results proved that the design of a smoke exhaust system can substantially improve its efficiency. The efficiency measurement of the smoke exhaust system can be quantified from various analyses. This research used visual observations on the recorded smoke scenes in different conditions initially.

Through various test measurements, it was found that the traditional smoke exhaust system readily created smoke turbulence and hence hindered a fire victims egress from the scene. The measurements of temperature alteration proved that the traditional smoke exhaust system did not remove heat effectively because of its higher indoor temperature. The visibility measurements indicated that the traditional smoke exhaust system performed poorer than the new system. The new smoke exhaust system controlled thickening smoke underneath the ceiling as the plenum above the ceiling was able to store the smoke. The new smoke exhaust system, not only retarded the smoke descent, it could also potentially prevent a panic situation during a smoke scenario.

The adjustment of the smoke exhaust flow rate

In searching for the possibility of reducing the smoke exhaust flow rate, the initial results implied that if a suitable smoke exhaust system was planned properly, a reduction in flow rate was feasible. The new smoke exhaust system was using a “global ceiling” as the smoke vent and its ability to exhaust smoke was seen to be superior. The visual recording, the measurements of temperature alterations and the visibility measurements further supported the hypothesis that the smoke exhaust flow rate could be reduced.

The effect of total area ratio on the diffuser opening

In studying the effect of the diffuser open area ratio on the ability to exhaust smoke, it was found that a larger open area improved this ability. However, the experimental results proved that a diffuser open area ratio of greater than 10% did not provide a significant improvement.

In conclusion, this research could provide a crucial reference for the safety of buildings and reduce the construction costs of high-rise buildings.

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