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Scale Modeling Studies on Smoke Control using Smoke Screens in a Titled Tunnel Fire

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Abstract

Many tunnels, which are inclined to the horizontal, are built in Mainland China, Hong Kong and Taiwan. Smoke control systems are installed to minimize damage in tunnels in case of fire. However, the designs of smoke control systems were based on presumed smoke movement pattern without any experimental justification. Although smoke screens are always used for blocking smoke spread beneath the ceiling, the smoke movement in tilted tunnels with smoke screens is not fully understood. On the other hand, Computational Fluid Dynamics is widely applied to study smoke movement in big enclosures. Officers now have much better understanding on fire models. There are always challenges in the studies of smoke movement in fire hazard assessment, when only Computational Fluid Dynamics is adopted. Scale models are required to justify the numerical predictions.

In this paper, smoke movement pattern in a tilted tunnel model with smoke screens was studied. Data compiled from two sets of scale modeling experiments in tunnels, which are of same cross-sectional areas but in different shapes, were used. It was observed that smoke screens are not effective in blocking upward smoke movement in tunnels which are tilted to the horizontal by larger angles. This finding is very different from the smoke movement patterns assessed in many smoke management designs in tilted tunnels.

Keywords: Smoke control, longitudinal ventilation, tunnel, scale model

1. Introduction

As reported [1,2], many long railway and vehicular tunnels have been constructed for mass transport in Mainland China, Hong Kong and Taiwan over the past two decades. Some tunnels in hilly areas were constructed at an angle inclined [3,4] to the horizontal. Smoke control systems [5,6] are specified in newly constructed tunnels in many countries. Smoke screens [7] are commonly installed at the ceiling for blocking the movement of smoke front. However, even smoke movement is not fully understood in the tilted tunnels, and it is not known how smoke would spread through the screens. It should be noted that for tunnels inclined to the horizontal by angle θ, buoyancy would be accelerated by $g\sin\theta$ in the smoke movement along the longitudinal axis [3,8,9]. Such acceleration should be taken into consideration when installing smoke screens along the longitudinal tunnel axis. Presumed smoke movement pattern [4] for some tunnels or long corridors design should be justified.

There had been studies in the smoke movement in the literature [10], including those on the trench effects [11] after the King's Cross fires in UK. These fire hazards are quite different for tunnels in the Far East. In rapidly developing cities, trains are always crowded with high passenger loading [12]. Passengers are used to carrying heavy luggage and goods while traveling in some stations, such as Sheung Shui Station and Lo Wu Station of the East Rail Line in Hong Kong [13]. No data on heat release rate while burning a train fully packed with luggage is available. A low value of 17 MW was reported [14] for an empty train car on the Ma On Shan rail. It is not clear whether such value was derived from oxygen consumption calorimetry of burning the whole train car, or it was just estimated from heat release rate data measured by a cone calorimeter. The value is much lower than the heat release rate of burning combustibles of heavy goods vehicles (HGV), which can go up to 200 MW [15]. This value should be reviewed in the subway system [16]. Furthermore, the level of social awareness on fire safety is not as high in many developing countries. In the Far East, people seldom queue up orderly as in America, Europe and Japan. Therefore, codes and regulations [e.g. 7,17,18] in advanced countries cannot be applied directly in the Far East. In-depth study [12,16] is required to justify whether the selected fire hazards and associated assumptions adopted from overseas can be applied to the local environment.

Smoke movement in a tilted tunnel with smoke screens has been studied [3,8,9,19-22] using scale models. Scale models are very suitable for studying smoke movement [23], and it is also good for looking into post-flashover room fire with appropriate scaling factors, as suggested by Quintiere and associates [24], and updated recently [25]. Key results on smoke movement observed from two sets of scale models in a tilted tunnel will be reported in this paper.

2. First Set of Scale Model Experiment

The first set of experiments on smoke movement in a tilted tunnel was labeled [19] as scale model SM1 in this paper. Some observations were reported by Chow et al. [3]. SM1 is a 1/25 scale model of a real tunnel of length 50 m, width 25 m and height 5.55 m with cross-sectional area 139 m^2. The scale model is 2 m long with cross-sectional area 665 cm^2, and it is made of transparent acrylic plastics as shown in Fig. 1. The inclination angle can be adjusted up to 30^o.

A small fire of heat release rate 1.8 MW was used to study the smoke movement pattern. However, it does not imply that the design fire for tunnel is so low. Such a value was only adopted to study smoke movement. The necessity of suppression system in tunnels with vehicles carrying high amount of combustibles is another issue, and it has to be studied separately. The fire was scaled down [19,23] to 0.097 kW by burning propanol. Pellets were put in the pool fire to generate smoke for photo-taking. Effect of smoke screens on blocking smoke was then studied.

Smoke movement patterns at different inclination angles in SM1 were recorded. Typical results for the tunnel inclined to the horizontal by 0^o and 20^o without a smoke screen as reported by Chow et al. [3] are shown in Fig. 2. The pictures indicate how smoke moved up the tunnel in the absence of a smoke screen.

As observed, for the tunnel which are not inclined to the horizontal, smoke moved up to the ceiling as plume due to buoyancy. A ceiling jet as in Fig. 2a was then resulted.

For the tunnel inclined to the horizontal by an angle of 20^o, smoke did not move down to the lower end of the tunnel. Smoke moved faster along the upper end of the tunnel due to the acceleration vector $g\sin\theta$. Smoke even started to descend as shown in Fig. 2b. Based on this observation, another scale tunnel model SM2 was constructed for further studies.

3. Smoke Screens in Horizontal Tunnels

Effect of smoke screen on smoke control in tilted tunnels in SM1 will be studied in more detail later [21]. The same 0.097 kW propanol fire corresponding to a 1.8 MW real fire was used in the model. Typical smoke pattern in the tunnel model with a smoke screen of depth 12 cm was taken out.

For the model of horizontal tunnel, a smoke reservoir was found in the ‘fire’ zone, as shown in Fig. 3. It is observed that the smoke screen can prevent horizontal smoke spread in the ‘protected’ zone as in Fig. 3d.

4. Smoke Screens in Tilted Tunnels

Smoke movements in the tunnel model SM1, which are tilted at 10^o and 20^o, are shown in Figs. 4 and 5 respectively. Without the smoke screen in the tunnel model that is tilted by 10^o, smoke moved up and then descended to the floor level as shown in Fig. 2b. However, with a smoke screen in a tunnel tilted by 10^o to the horizontal as in Fig. 4, the spreading of smoke was stopped by the screen. The lower part of the fire zone was free of smoke. A smoke reservoir was formed in areas between the screens. However, smoke passed through the smoke screen and spread to the 'protected' zone because of the acceleration vector $g\sin\theta$.

As Fig. 4d shows, smoke spread to higher level in tunnels which are tilted by 10^o to the horizontal. The 'protected' zone would then be full of smoke. Smoke would even spread to the lower level.

In Fig. 5, the results are highly similar to Fig. 4d in the initial stages in a tunnel which are inclined to the horizontal by 20^o. However, in later stages, smoke would spread along the tunnel to the ground level after moving down the smoke screen.

5. Second Set of Scale Model Experiments

Another set of experiments was carried out [22] in the second scale model labeled as SM2. The tunnel is rectangular in shape with area 675 cm^2, which is similar to SM1 as shown in Fig. 6. The technique of scale modeling studies, which are used in SM1, was used.

Smoke movement patterns observed in SM2 are shown in Fig. 7. Results in possible smoke movement [26] deduced from the observations in SM2 are shown in Fig. 8.

6. Discussion

Different stages of smoke movement in a horizontal tunnel can be observed from the scale model SM1 in Fig. 3:

- Being blocked by the screen at the fire zone.
- Moving down along the screen.
- Passing through the screen to the protected zone.
- Spreading to the protected zone above.

As reported in the literature [4], the smoke movement pattern is shown in Fig. 9a. This is very different from the findings of the study with scale model SM1 as in Figs. 3 and 5. The proposed smoke pattern as shown in Fig. 9a is a key part in designing the smoke control system. Such phenomenon must be demonstrated by experiments because any deviation from such pattern would give improper design data.

With a smoke screen, different kinds of smoke spread in different stages will arise. The results are shown clearly in Figs. 4 and 5 for SM1 and Fig. 7 for SM2.

Four stages of smoke movement are identified in a tilted tunnel:

- Stage 1: Being blocked by the screen at the fire zone.
- Stage 2: Moving down along the screen.
- Stage 3: Passing through the screen to the protected zone.

- Stage 4: Spreading to the protected zone above, from higher side as in Fig. 4a, and lower side as in Fig. 5d.

Such stages might lead to density jump after striking the smoke screen. Smoke that moved up to the higher end would be directed down along the screen. Therefore, any smoke control design should be justified by experimental studies. At the very least, a scale model should be used as discussed above. Otherwise, the fire safety systems might not work as expected in case of fire.

7. Conclusion

From the observed smoke movement patterns in two sets of scale model SM1 and SM2, a smoke screen cannot block smoke in the fire zone for tunnels which are tilted to the horizontal. Smoke would spread through the screen to the protected zone. At least four stages of smoke spread through the screen are observed. At angles over 20^{o}, larger amount of smoke was observed to flow in the tunnel. Smoke would even move along the ground level as shown in Fig. 5d. Such results are very different from those assumed in some projects [4], as in Fig. 9a. Smoke can move up to the ceiling after spreading through the screen, as in Fig. 9b for tunnels with smaller tilted angles. But for larger tilted angles, smoke would spread to the lower level as in Fig. 9c.

Design of smoke screen depends on heat release rate of the fire, tunnel air speed induced by the fire, and the type of fuel. In tunnels which are tilted to the horizontal by larger angles, installing smoke screens in tunnels even directs smoke to lower levels. This should be studied in greater detail with full-scale burning experiments. As raised recently [16,27], adequate fire safety provisions must not merely be designed to guarantee the safety of occupants. The firefighting strategy, rescue strategy, safety and health of firemen must not be affected. Smoke descending to low levels in tilted tunnels would pose a great threat to firefighting. Scale modeling technique [23-25] can be applied, at least to justify CFD predictions [28], in order not to repeat making assumptions [4,26] without experimental evidence.

8. Additional Comments

The paper was published as a journal paper [29]. With the practice of publisher, preprint is allowed to upload at a website. There are further studies on this topic [30-43].

Acknowledgment

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JAFS_SmokeScreenSM3C1c

Record:
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A466UL22-1b (opened 3 Aug 2023)
A466UL22-1c (opened 5 Aug 2023)

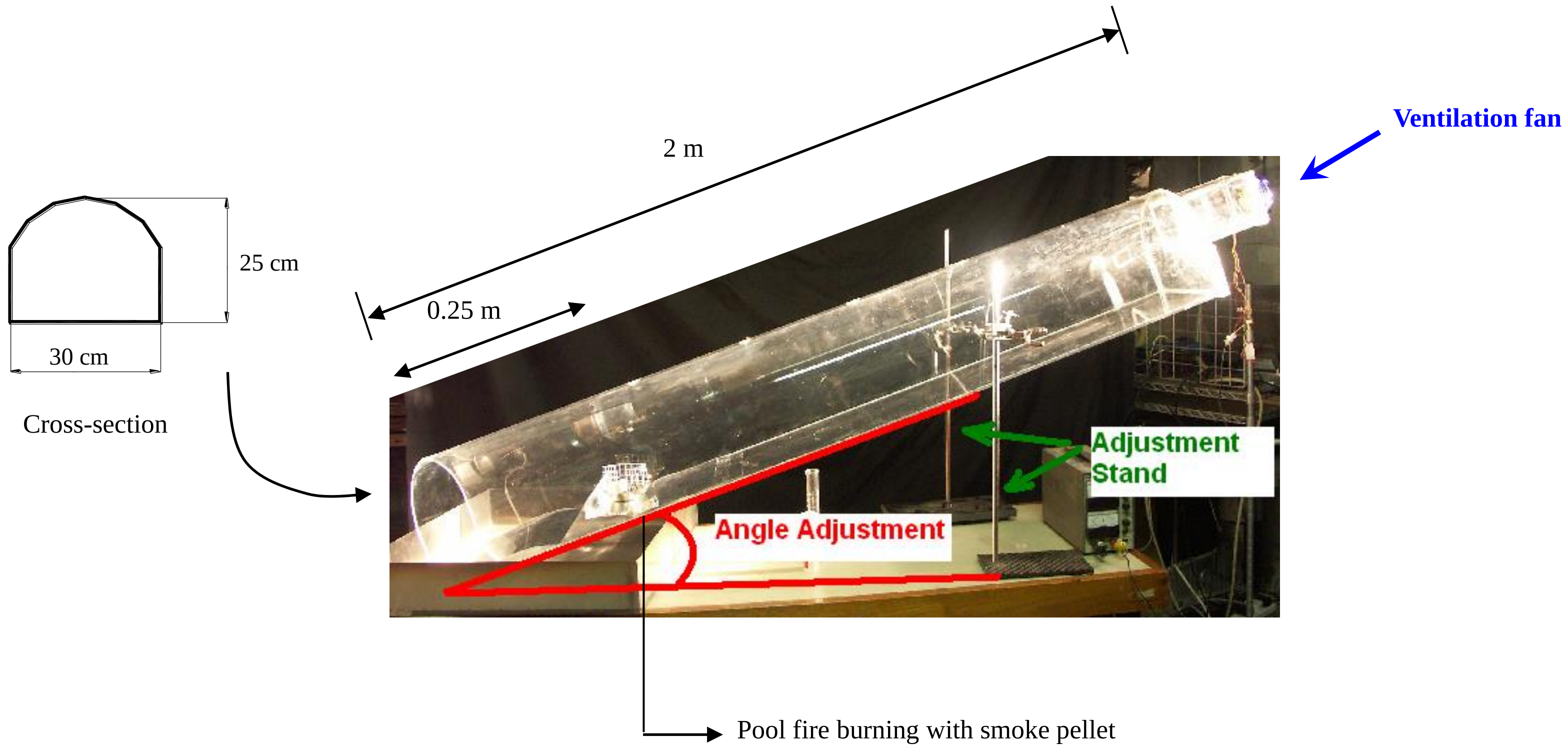
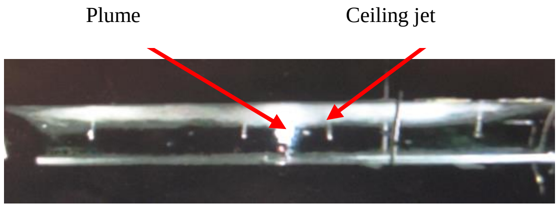
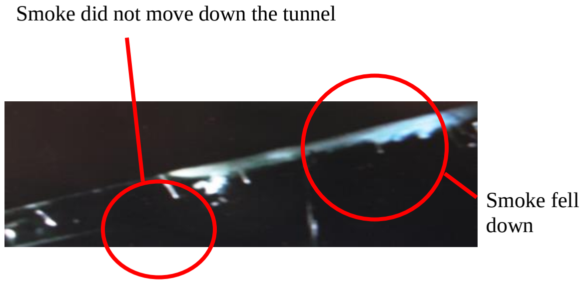


Fig. 1: The scale tunnel model SM1, Chow et al. (2010)



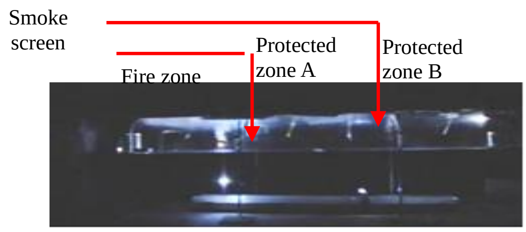
(a) No inclination



(b) Inclined at 20°

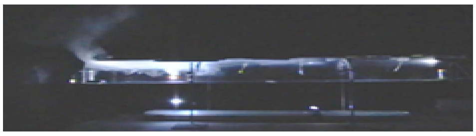
Fig. 2: Smoke pattern without a smoke screen in SM1

(from Chow et al. 2010)

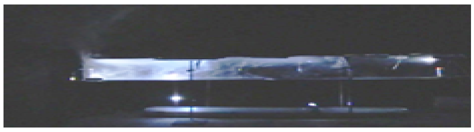


(a) Blocked by screen

(b) Smoke spread to the protected zone A



(c) Smoke moved down the screen



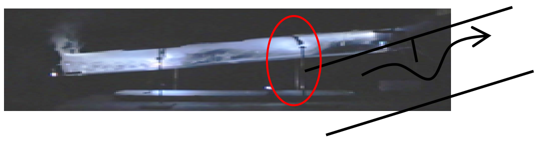
(d) No smoke in protected zone B

Fig. 3: Stages of smoke movements for horizontal arrangement of SM1 with smoke screen

(a) Stage 1: Blocked by the screen at the fire zone

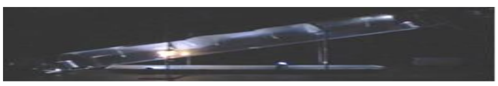
(b) Stage 2: Moving down along the screen

(c) Stage 3: Passing through the screen to the protected zone B

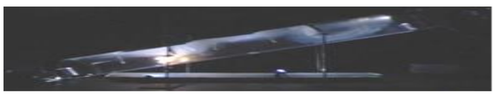


(d) Stage 4: Spread up to the protected zone B above

Fig. 4: Smoke movements in SM1 tilted at 10º to horizontal with smoke screen



(a) Stage 1: Blocked by the screen at the fire zone

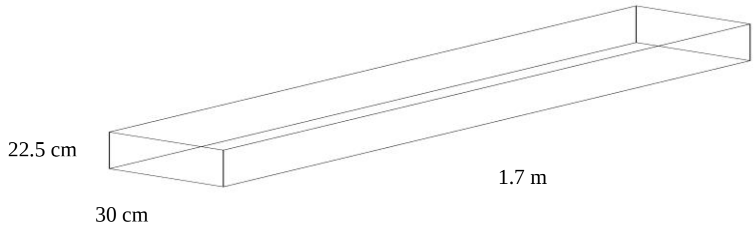


(b) Moving down along the screen

(c) Stage 3: Passing through the screen to the protected zone B

(d) Stage 4: Spread up to the protected zone B above

Fig. 5: Smoke movements in SM1 tilted at 20º to horizontal with smoke screen



(a) Schematic drawing

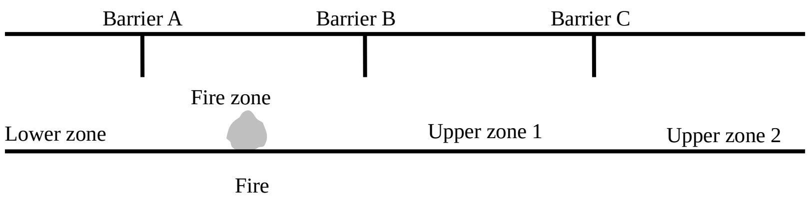
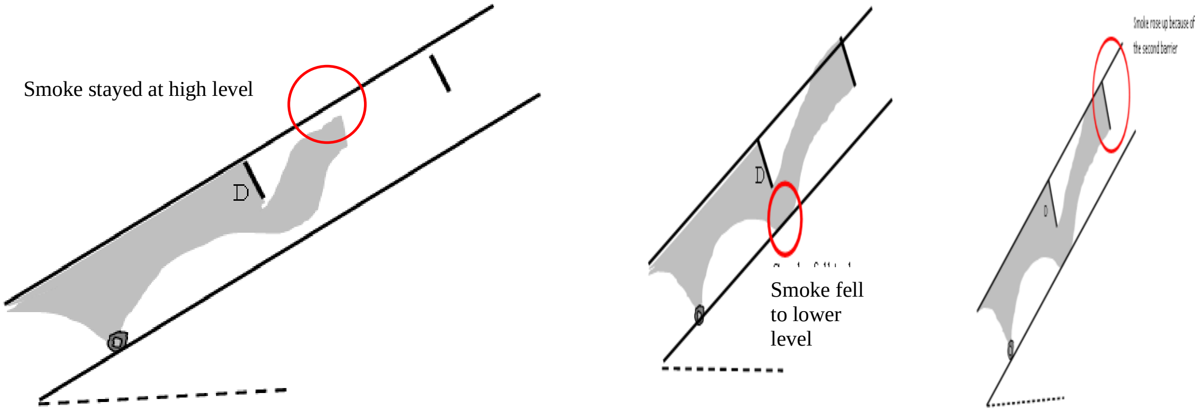


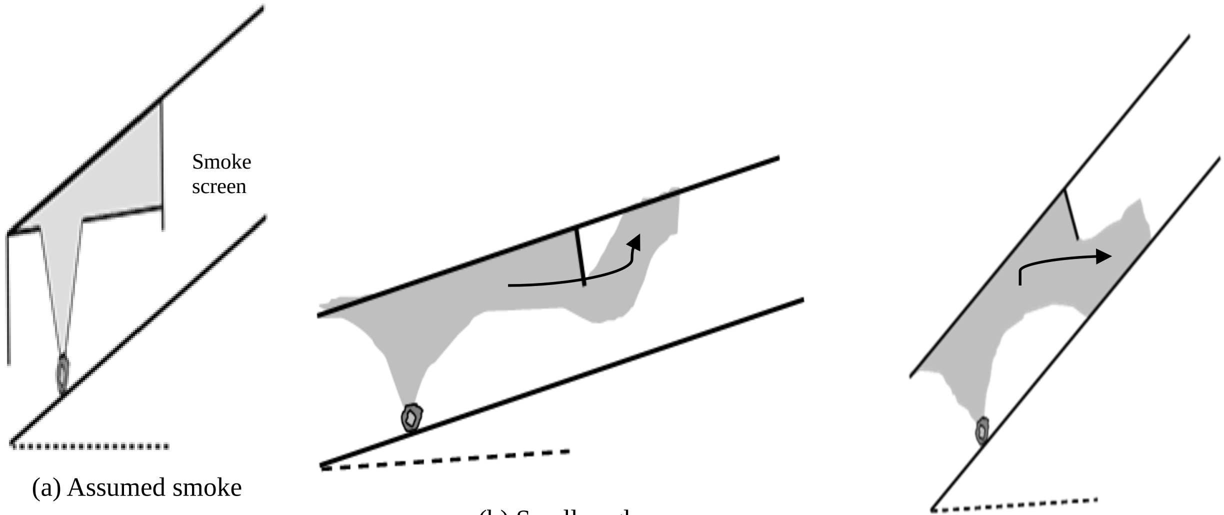
Fig. 6: The tunnel model SM2

Fig. 7: Smoke movement patterns observed in SM2



(a)Small D (b) Large D (c)

Fig. 8: Smoke movement



(a) Assumed smoke reservoir in a local project (Ip and Luo 2005)

(b) Small angle

(c) Large angle

Fig. 9: Smoke movement