SCALE MODEL STUDIES ON SMOKE MOVEMENT IN INCLINED TUNNEL WITH LONGITUDINAL VENTILATION AND SMOKE BARRIERS

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ABSTRACT

Smoke movement, which is induced by fire inside a tilted tunnel with smoke barrier and longitudinal ventilation system, was studied by scale models. The inclined angle was adjusted up to 20^o. Air speed, air and smoke temperature increase and the thickness of smoke layer were also studied. With the operation of ventilation fan, the critical velocity of ventilation was found.

1. INTRODUCTION

In the past 15 years, many tunnels have been built for trains or vehicles during the course of urbanization in the Far East [1]. Taking Shanghai as an example, there was no underground subway system before 1995. The total length of subway system increased [2,3] to over 227 km with 161 stations in 2005. However, several fires occurred in tunnels and caused significant property damage and heavy casualties. Fire safety in tunnel is now a huge concern due to the significant danger of fire in confined space. Fire temperature can go up to 100^oC and smoke movement is especially dangerous to people in the tunnel during fire [4].

A good tunnel ventilation system [5,6] can provide a better evacuation route. In smoke management inside tunnel, the required safe egress time (RSET) for people should be short. If the tunnel is protected by smoke management system, the available safe egress time (ASET) can be extended significantly if properly studied [7,8]. The total casualties can be reduced.

It is impossible to carry out full-scale burning tests for all tunnel projects to look into the smoke spread. Computational fire models are not yet well developed, even those for studying smoke movement and smoke management in tunnels. Scale models [9] are then applied to justify the smoke control design and fire models. In this paper, a scaled tunnel model with smoke barrier and ventilation system has been made. A scaled tunnel fire can study smoke movement inside an inclined tunnel [8,10]. In such a setting, smoke movement can be observed in the tunnel with different inclined angles. Smoke control can also be studied in tunnel installed with ventilation system. Critical velocity of ventilation inside the tunnel can also be measured.

A 1:50 scale model was constructed to study tunnel fire and the smoke movement. Smoke barrier, ventilation fan, illumination with light emitting diodes (LED), and thermocouples were set up. Smoke pellet was used to produce the white smoke. Propanol was used to burn up the smoke pellet. A total of 12 thermocouples would measure the temperature rise upon starting a fire.

2. EXPERIMENTAL DESIGN

The scale tunnel model was constructed with smoke barriers. Different angles can be adjusted to test the performance of barrier in the tunnel. The experiment can be divided into 2 stages. In stage 1 of experiment, the differences of the smoke movement in tunnels with or without the smoke barrier can be examined. In stage 2, different longitudinal ventilation speeds were used. The effect of smoke movement on the critical velocity was explored.

12 thermocouples were installed inside the tunnel, which would check the temperature changes during the test. A 2cm x 2cm metallic cylinder containing the smoke pellet was used to simulate the fire sources inside the tunnel. Propanol was used to burn up the smoke pellet. After the smoke pellet was lit, large amount of white smokes was produced. The smoke movement was recorded by different means, such as video recording, photo recording and temperature recording.

In stage 1, 6 tests were done in a laboratory. These tests could be classified into two types, namely “no barrier” and “with barrier”. For each type of testing, different angles were set, including “0^o inclined”, “10^o inclined” and “20^o inclined”. These 6 sets of tests are conducted to find the temperature differences and the smoke movement under different tunnel conditions.

In stage 2, tests with different ventilation velocities were done at one inclined angle. There were 3 inclined angles, including “0^o inclined”, “10^o inclined” and “20^o inclined”. For each set of inclined angle, the smoke movement, the temperature and the critical ventilation velocity were found.

Different assumptions were made in the tests. Since the tests were done in a laboratory, there was no air movement inside the laboratory after turning off all ventilation fans. Thus, the wind effect and other factors affecting smoke movement were ignored. On the other hand, smoke pellet was burnt by propanol immediately, but this is impossible in the real case. The smoke pellet was assumed to be burnt by propanol in 5 s. This condition is included in the calculation part.

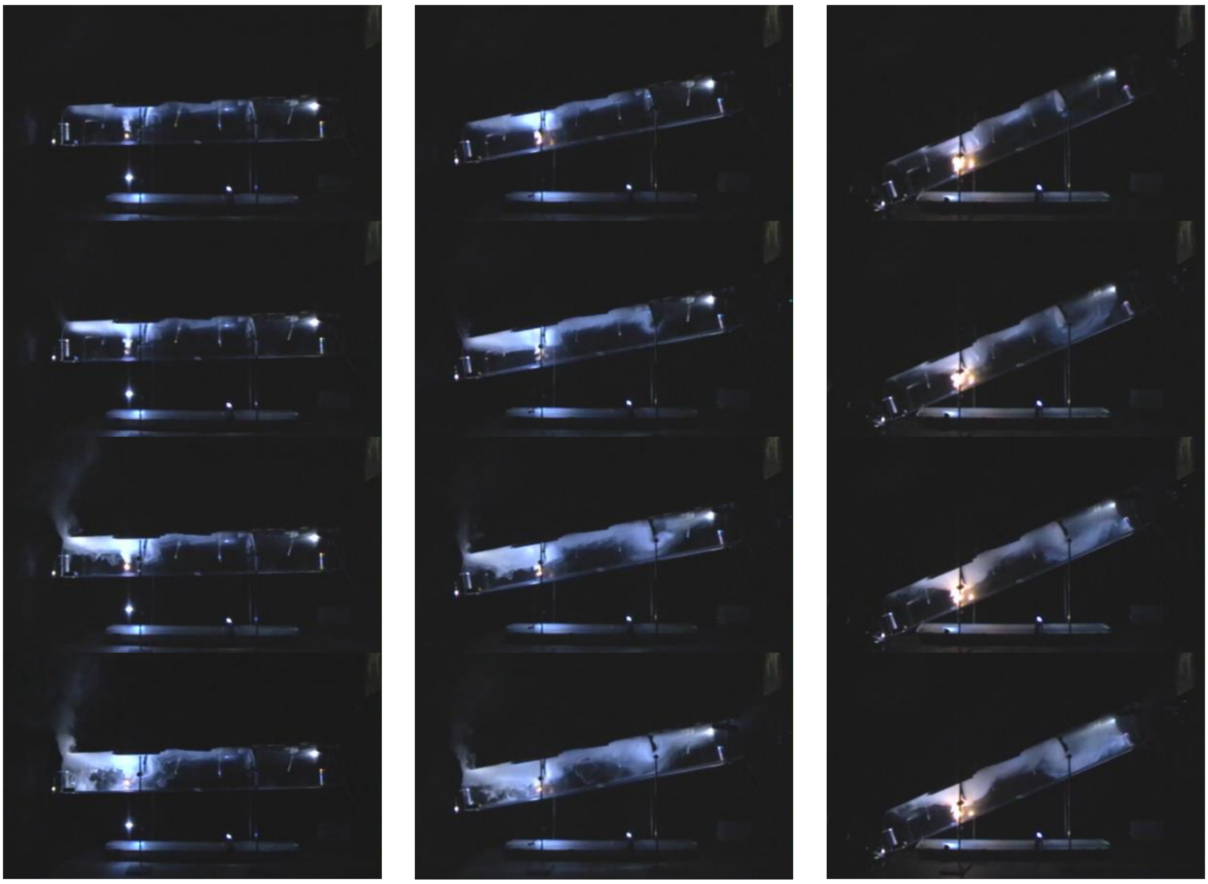
3. EXPERIMENTAL RESULT

In stage 1, 6 sets of tests were done in laboratory. These tests can be classified into two types, “no barrier” and “with barrier”. For each set of test, different inclined angles were set, “0^o inclined”, “10^o inclined” and “20^o inclined”. These 6 sets of tests can be used to find the smoke movement under different tunnel conditions.

In stage 2, many sets of tests were done in laboratory. These tests can be classified into different inclined angles, 0^o, 10^o and 20^o. At each angle, different velocities of ventilation were found. These different tests can be used to find the critical velocity of ventilation for different inclined angles of the tunnel.

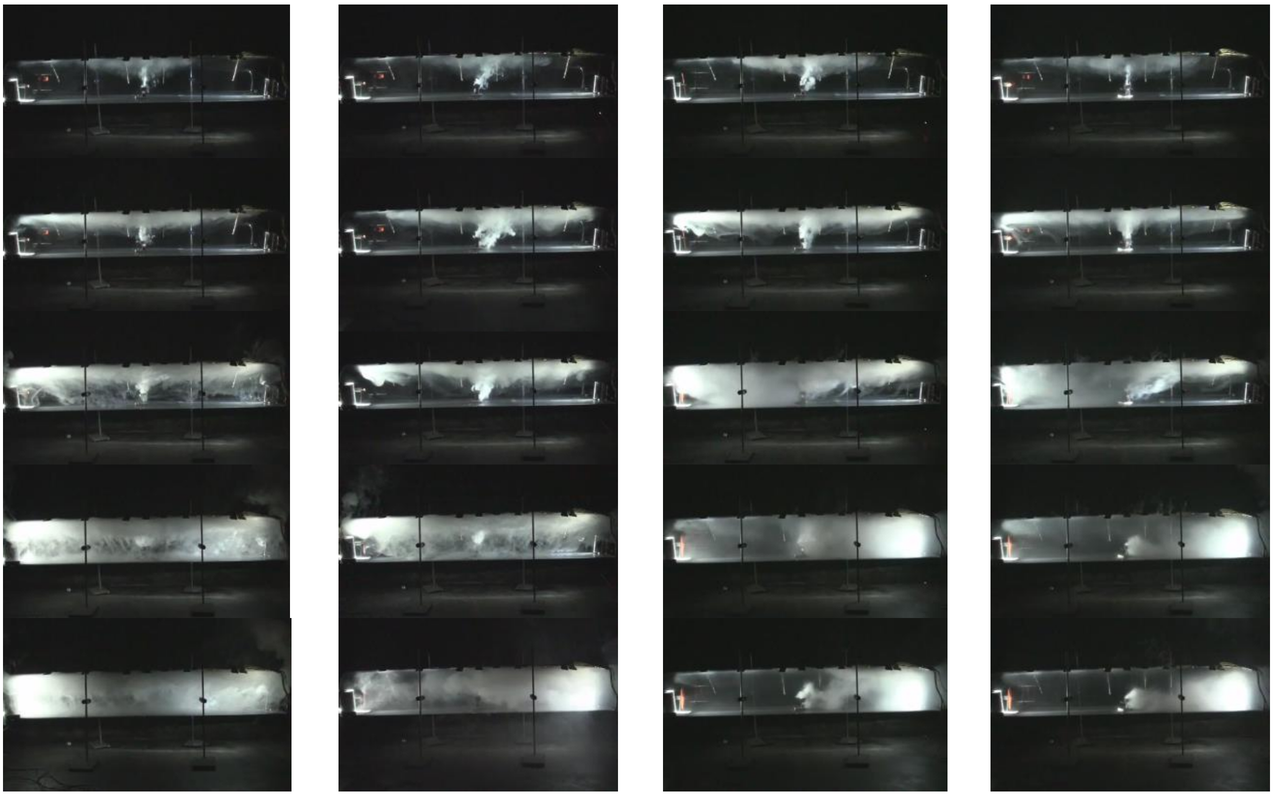
In the experiment, LED lamps were used to facilitate video recording, hence, it enables better observation of the smoke movement pattern. Results of the smoke movement are shown in Figs. 1 to 4.

Fig. 1 shows the smoke movement inside the tunnel with smoke barrier, while Figs. 2 to 4 show the smoke movement inside tunnel with different velocities of ventilation.



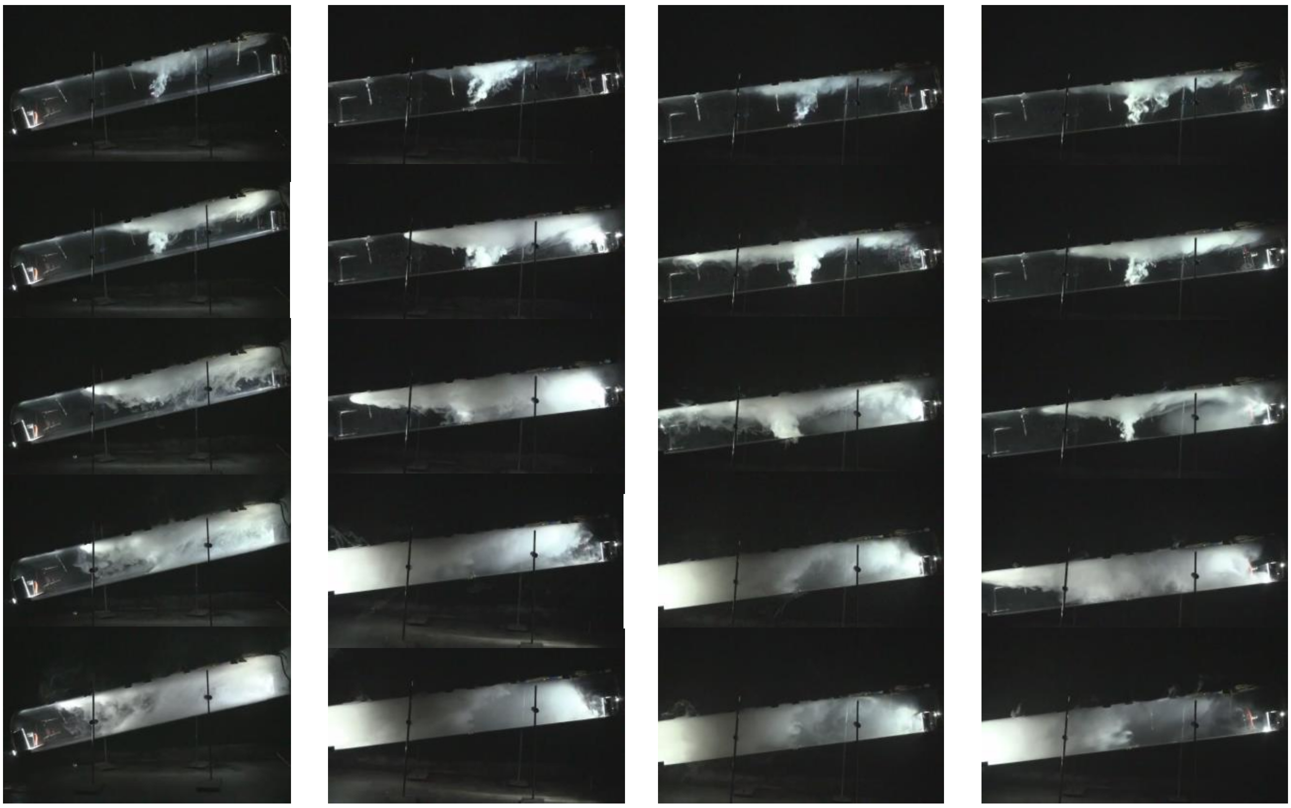
(a) Horizontal arrangement (b) 10^o inclined (c) 20^o inclined

Fig. 1: Smoke movements inside the tunnel with smoke barrier



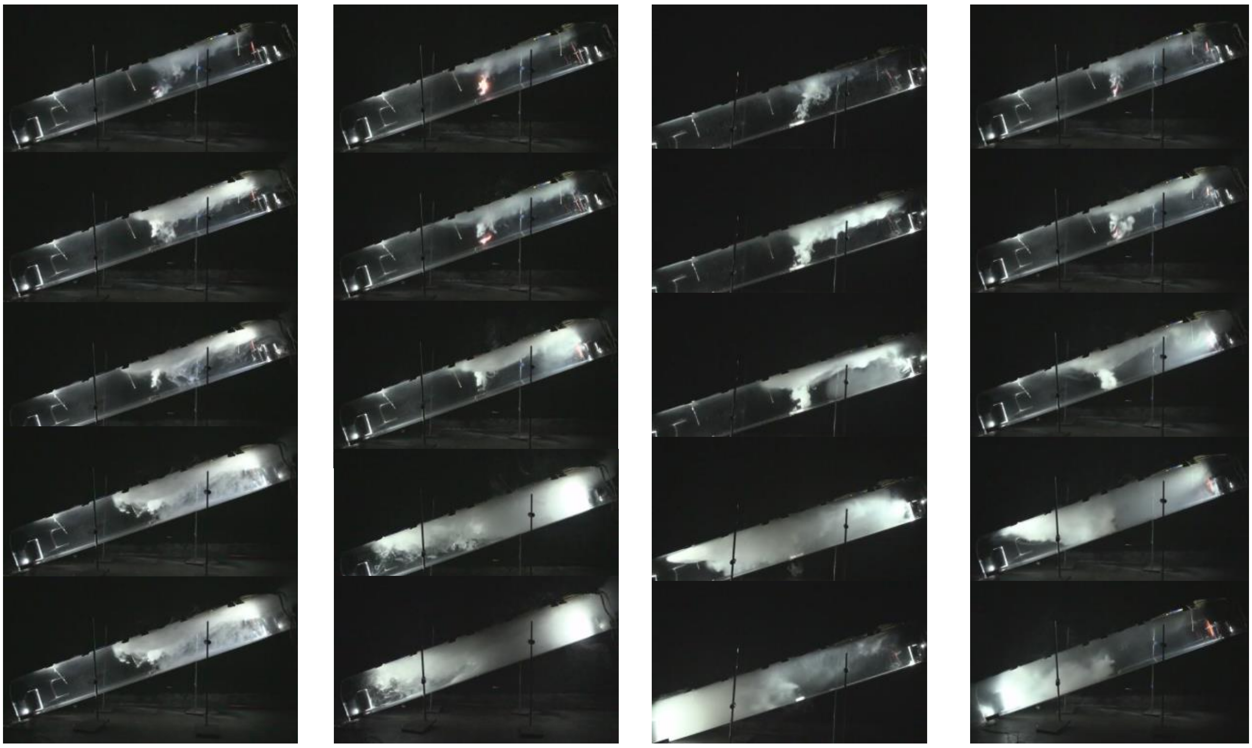
(a) No Longitudinal ventilation (b) Velocity = 0.5 ms^{-1} (c) Velocity = 1 ms^{-1} (d) Velocity = 1.5 ms^{-1}

Fig. 2: Smoke movements inside the horizontal tunnel



(a) No ventilation (b) Velocity = 0.5 ms^{-1} (c) Velocity = 0.55 ms^{-1} (d) Velocity = 0.7 ms^{-1}

Fig. 3: Smoke movements inside the tunnel inclined at 10^o



(a) No ventilation (b) Velocity = 0.5 ms^{-1} (c) Velocity = 0.7 ms^{-1} (d) Velocity = 1 ms^{-1}

Fig. 4: Smoke movements inside the tunnel inclined at 20^o

4. DISCUSSION

The pictures illustrate the smoke movement inside the tunnel. In stage 1 (Fig. 1), smoke was blocked by smoke barrier for a few seconds. From Fig. 1c, in a tunnel which is inclined at 20^o with barrier, smoke could not pass through the tunnel directly. Smoke was blocked by smoke barrier for about 2 s to 3 s, then went down and continued to move upward. Since this is a scaled model, the time for resisting smoke movement in actual scenario can be calculated.

In stage 2, a ventilation fan was installed in tunnel to control the smoke movement. In Fig. 2 to 4, smoke movement with different velocities of ventilation are shown. Smoke movement is affected by velocities of ventilation. If the velocity of ventilation is too slow, it cannot resist the upward force of smoke and smoke can come out directly. If the velocity of ventilation is too high, smoke will go downward immediately.

In Figs. 3 and 4, the critical velocity of ventilation fan is found. The critical velocity is resulted when the positive pressure produced by the fan is equal to the upward force produced by the smoke. In Fig. 4, the critical velocity of fan is 0.55 ms^{-1} when the inclined angle of tunnel is 10^o. This occurs because smoke movement is uncontrollable when fan velocity has been set at 0.5 ms^{-1} and 0.7 ms^{-1}. For the same reason, the critical velocity of fan is 0.7 ms^{-1} when inclined angle of tunnel is 20^o.

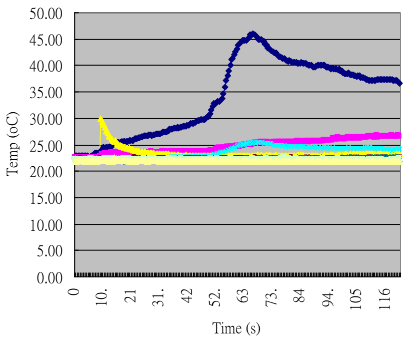
5. AIR TEMPERATURE

Air temperature changes were recorded during the tests as well. Fig. 5a to f show the temperature changes during different stages of the tests. Since it is impossible to burn up the smoke pellet immediately, an assumption was made. The time for burning up the smoke pellet by propanol was assumed to be 5 s. Air temperature differences measured are shown in Figs. 5a to f.

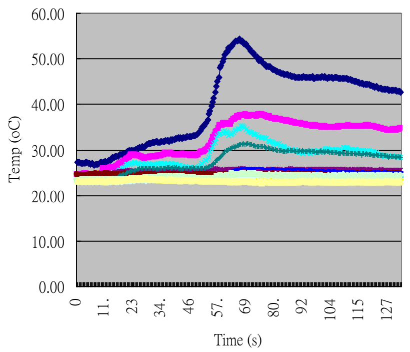
Figs. 5(aii) and (bii) show the temperature differences for the test in a tunnel with a "10^o inclined angle". Fig. 5 (aii) shows the temperature change inside tunnel when smoke barrier has been installed. Fig. 5 (bii) shows the temperature changes inside tunnel when 0.55 ms^{-1} velocity of ventilation has been set.

When the temperatures in a tunnel at an inclined degree of10^o inclined with barrier and that in a tunnel at an inclined degree of 10^o with 0.5 ms^{-1} velocity of ventilation are compared, thermocouples inside the tunnel with barrier (Fig. 5(aii)) show big difference. It means that smoke is blocked by the smoke barrier. Through the graphs, the time for smoke movement can also be found.

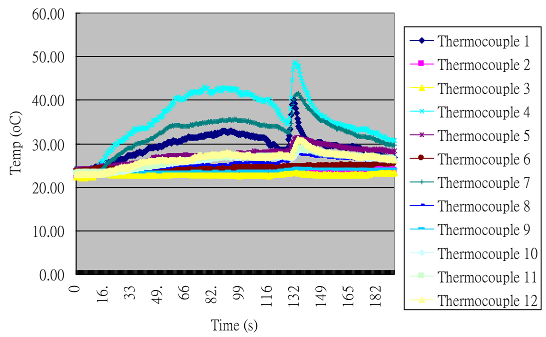
In Figs. 5a(i) to (iii), the time for temperature to reach 50°C is about 60 s in the tunnel with barrier. However, temperature does not rise too much when ventilation system has been installed in tunnel. After 20 s, the maximum temperature inside tunnel is about 40°C. From the graphs, the time of smoke movement inside tunnel in real case can be calculated.



(i) 0° inclined with smoke barrier

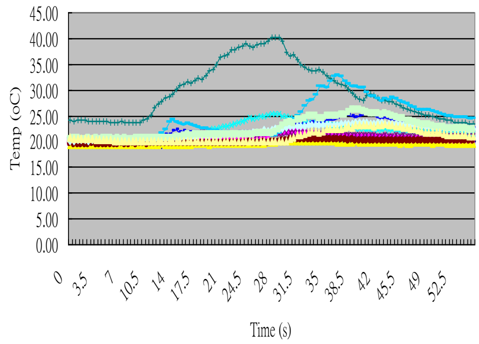


(ii) 10° inclined with smoke barrier

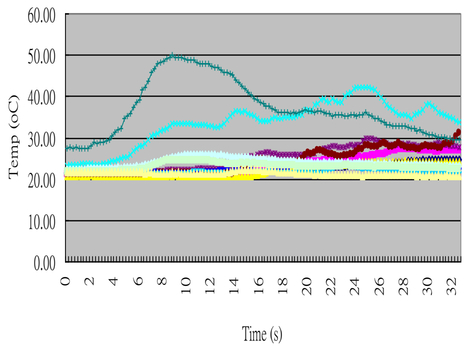


(iii) 20° inclined with smoke barrier

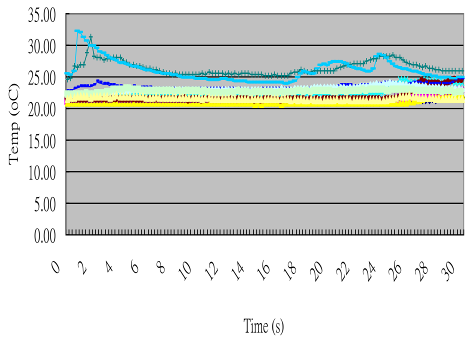
(a) Stage 1



(i) 0° inclined with 0.5 ms^{-1} ventilation



(ii) 10 ° inclined with 0.55 ms^{-1} ventilation



(iii) 20° inclined with 0.7 ms^{-1} ventilation

(b) Stage 2

Fig. 5: Air temperature measured

6. CONCLUSIONS

To secure safety, appropriate smoke management system must be set up in tunnels. There are different methods to control smoke movement, such as smoke barrier and longitudinal ventilation system. Different types of systems can offer different levels of protection to users. In this experiment, the observations of smoke movement in a scale model are useful in the design of a good system. However, using scaled modeling, the situation in the real case cannot be accurately predicted, as there are many uncertainties in this stage, and further investigation on the smoke movement should be continued.

Two types of smoke management systems, smoke barriers and longitudinal system, have been studied in this experiment. For the tunnel installed with longitudinal ventilation fan, the critical velocity of ventilation has been found. This critical velocity is very important for fire safety in the tunnel, as it is the minimum value required to stop back-layering. If the velocity is lower than the critical one, smoke would spread to the protected area inside a tunnel.

In stage 2 of the experiment, the critical velocity of ventilation has been found. The critical velocity of a tunnel with 10^o inclined angle is 0.55m/s and the critical velocity of a tunnel with20^o inclined angle is 0.7m/s. The reason of different velocities is that smoke buoyancy in a tunnel with 20^o inclined angle is greater than in a tunnel with 10^o inclined angle. Consequently, higher ventilation velocity should be provided. This velocity is tested by using ventilation fan only. Moreover, if the smoke barrier and ventilation fan have been installed in tunnel together, the result of critical velocity will be reduced drastically. It is because smoke upward movement can be limited by the smoke barrier. In this case, the critical velocity of ventilation can be lowered. Both systems can be used in a real tunnel, but further investigation is needed.

ACKNOWLEDGEMENT

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