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THE ZONE AND NUMERICAL SIMULATION ON THE TUNNEL FIRE

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ABSTRACT: With the development of transition, the mount of road and railway tunnels are more and more in the world. But great loss due to the tunnel fires happened recent years shows that the tunnel fire safety is a problem. Realizing the characteristics of tunnel fires is very important for the tunnel fire protection. In this paper, given a tunnel, the smoke development in different situations was simulated using zone model (CFAST) and field model (FDS). The smoke temperature distribution and smoke layer interface height were discussed. And the comparisons between these two models were made. The harm of fire and smoke to people and tunnel lining at different position was also discussed.

KEYWORDS: Tunnel fire Zone model Field model Smoke development

1. INTRODUCTION

Tunnel is the important traffic and transportation passage to ensure transportation unblock. In China, there are more than 5300 railway tunnels, and total length reaches 2500km. The road tunnel amount is more than 450, and total length reaches 120km.[1] With the development of Chinese transportation, all kinds of tunnel, including view and sea tunnels, will be more and more. In the future ten years, the construction of tunnel will increase quickly.

Because of the narrow inner and sealing sides structure, the vehicle and people are not easy to evacuate in tunnel. Once happens fire, it will develop quickly and cause great people and property loss. In recent 30 years, the tunnel fires happened in the world was common.[2-5] From these cases and the construction of tunnel, we can know that the tunnel fire has the following characteristics:

- difficult to find the fire source, burning situation complex
- air flowing straightway, fire developing quickly
- smoke unable to exhaust and accumulating in tunnel
- the tunnel narrow and long, low visibility
- evacuation and extinguishing difficult
- fire loss large.

The continuous tunnel fires have arisen the researcher's note. Some tests and simulations had been done[6-8]. It is very important for enhancing the fire protection design in tunnel to study the tunnel fire's happening and development. In current fire design code, there have no items to observe how to design the fire parameters and arrange the fire equipment in tunnels. It is often to adopt the demonstration of experts to evaluate the fire design. This is the performance-based design. It is a world hotspot in the fire design[9], especially for the special buildings. In the process of performance-based design, the fire safety objectives will be brought based the actual building. Then the fire detailed performance objectives and fire protection measures will be decided based on the simulation results. At last, an evaluation report will be given to judge if it has reached the safety requirement. In this process, the simulation is a key ring. The fire protection requirement can be suggested pertinently based on the calculation. In many tunnel fire designs, the probable fire developments were predicted using the computer simulation to design the corresponding protection measurements.

In this paper, the tunnel fire was simulated using zone model and field mode. The fire smoke temperature and smoke interface height in different situations were predicted. The fire risk and hazard in different parts of the tunnel was also discussed.

2. ZONE MODEL AND FIELD MODEL SIMULATION

Zone model is a kind of semi-physical model used to study fire process in a confined space.[10] There will be delamination phenomenon in the building fire. The upper layer is hot smoke and the lower layer is cool air. In order to characterize the fire development and simplify the mathematic analysis, the whole space can be divided several zones. In each zone, the state parameters are assumed to be uniform. Using the mass, energy, momentum conservation law and the basic law of chemical reaction to find the influence of each zone, then to get the variation of parameter with time in each zone, this is the basic ideal of zone model. Two-zone model, upper hot smoke layer and lower cool air layer, is most used now. The mass transfer between the two layers is only through the smoke plume. The diffusion and mixture in the interface of the two layers are ignored. The smoke state and the smoke layer height are most concerned. Many programs based on zone model have been developed[11, 12]. Here the CFAST 4.1 was used to simulate the smoke development in tunnel.

Zone model is widely used in actual analysis for its simplicity and convenience. However, for the zone model, only the average value of state parameter with time in some zone can be gotten. It is unable to know the detailed fire and smoke situation in some position. When the tunnel is very long, the whole space is large. If it is only divided into two layers, the results gained from zone model will be the smoke average state of whole tunnel. This will decrease greatly the simulation precision, especially for the fire zone. So the multi-cell concept[13, 14] is adopt to deal with the long and large space when using zone model. In this paper, the whole tunnel is divided into many sections, each section can be considered as a room with large opens at the connections between rooms. Thus, the multi-room fire program can be used to simulate the fire development.

Field simulation is also called computational fluid dynamics model(CFD). It divides the space into many grids. In each grid, the distribution and variation of velocity, temperature, smoke component are gotten using mass, momentum and energy conservation equations. Field model can reflect truly the fire's development with space and time. But the complex control equations and close grid requires high computer speed, large memory and long time. When the detailed fire and smoke development is needed, it is very useful. With the development of computer technology, the CFD model will be used widely in engineering. There are also many field models developed now[15]. The FDS (Fire Dynamics Simulator) developed by NIST[16] was used in this paper.

3. CASES DESIGN

A cuboid road tunnel with the size of 200m long, 8m wide and 5m high was assumed. The ceiling and wall were built using concrete. For the zone simulation, the tunnel was divided into 21 sections. The two sections at the ends were 5m long, and the other 19 sections were 10m long. The centre section was named sec.0, and the sections at its left were named sec.-1 to sec.-10 in turn, and the right sec.1 to sec.10, as shown in figure 1. Each section was like a room, 10m × 8m × 5m, with two large opens with size of 8m × 5m. When the tunnel caught fire, the fire source was not easy to find and people were difficult to evacuate when it was far away from the end. So it was most dangerous when fire happened at center of the tunnel. In the simulation, the fire was set at the sec.0, center of the tunnel. In the road tunnel, fire source was usually oil, such as the explosion of tank truck, the gasoline tank fire. For the road tunnel design fire, the World Road Association recommended some value for various tunnel fires from 4MW (Bus) to 100MW(Gasoline tanker)[17, 18]. Here, a tank truck was assumed to catch fire. The area of the tank was 4m×5m. The fire power was taken as $1MW/m^2$, then the total heat release rate was 20MW. The steady fire was adopted.

Generally, there will have air flow in the tunnel for the running of vehicle and environment wind. This air flow can bring some influence on the fire and smoke development. Two environment conditions were designed to study the effect of wind: 1) there was no wind; 2) one uni-directional wind with the velocity of 1m/s flowed through the tunnel. The ambient temperature was 20˚C. In zone model, the wind was designed to flow from outside into sec.-10, and flowed from sec.10 to outside, the flow was steady velocity of 1m/s. In field model, the wind flowed into the tunnel from sec.-10 and flowed out from sec.10 with the steady volume of $40m^3/s$ calculated by the wind velocity and cross-section area of tunnel. The tunnel was partitioned into 800 × 32 ×20 grids.

4. RESULTS AND DISCUSSIONS

4.1 Zone model results

Figure 2 was the development of smoke layer height calculated by CFAST in tunnel when there was no wind. For the fire source was set at the center of tunnel, the smoke development towards two ends was same completely, so only the smoke layer height development of one direction was given in the figure. Figure 3 was the variation of smoke layer height calculated by CFAST when there was a wind of 1m/s. Figure 3 (a) was the result of within 55m away from the fire source, and (b) was the result of beyond 55m away from the fire source. It can be seen from the figures that the results without wind and with wind had small difference. The smoke layer height of windward section was slightly higher than that of the corresponding leeward section. This showed that the wind had some delay for developing to the windward, but this effect was not obvious.

It could be observed the time of smoke spread to the tunnel end was about 50s, the movement velocity was about 2m/s. The smoke layer height was keeping above 2.5m in the tunnel. The smoke layer height of sec.0 descended to 3m at 40s, and 2.7m at 300s. In sec.2 and sec-2, the smoke descended to 3m at 60s, and 2.5m at 300s. In sec.5 and sec-5, the smoke descended to 3m at 120s, and 2.7m at 300s. For the two end sections, the smoke kept above 3m always. This indicated that the smoke descended quickly at the beginning period. When smoke reached 3m, it descended slowly. After 200s, the smoke layer height of fire source was not the lowest. The smoke layer of 4 sections besides of the fire section was lower. The temperature of fire section was higher, the smoke was not easy to descend. And for the sections close to the end, the smoke flowed outside of the tunnel, difficult to accumulate. So the smoke near the fire section was lowest. It can be know from above results that the danger caused by smoke layer was most within 50m away from the fire source. Evacuation towards to windward could reduce the hazard from smoke layer.

Figure 4 and figure 5 was the temperature variation of different sections calculated by CFAST without wind and with wind, respectively. It showed that the highest temperature reached 500˚C at the fire section. This temperature can make hazard to the tunnel structure.[19] The temperature of two sections besides of the fire section reduced to about 350˚C, and that of end sections was about 75˚C. The temperature decreased with the distance away the fire source. The temperature in sec.0 rose to 450˚C at 10s. And the temperature of sec.10 and sec.-10 had obvious increasing at 50s. This indicated that the smoke reached the tunnel end at 50s. When the temperature rises to 180˚C, it will have threat to the safety of people. Seen from the figures, the temperature within the sec.4 and sec.-4 reached 180˚C, so it was dangerous to people in these zones. It could also be seen that the wind's effect on smoke temperature was small in the zone model simulation, the temperature of windward was little higher than that of the corresponding leeward.

4.2 Field model results

Figure 6(a), (b), (c), (d) was the development of smoke isotherm of 25˚C, 150˚C, 450˚C at 40s and 60s without wind and with wind gotten from field model, respectively. Figure 7 was the smoke temperature distribution along the altitude without wind at 40s and 60s. And Figure 8 was the smoke temperature distribution along the altitude with wind at 40s and 60s. The number at the icon meant the height above the floor. The figures showed that when there was no wind, the smoke front reached 45m away from the fire source at 40s, and reached the tunnel end at 60s. This result was similar to that of zone model. But when there had a wind of 1m/s, the fire source had an obvious excursion. The smoke development towards windward and leeward had a notable change. The smoke development towards leeward increased greatly and the development towards windward was restrained. At 40s, the leeward smoke had spread to the tunnel end, while the windward smoke just reached about 40m away from the fire source. At 60s, the smoke at windward spread to 60m far away fire source. It was namely that the smoke velocity in leeward was about 3m/s, but the windward is 1m/s. This was very different with the result of zone model. This showed the field model could take into account of wind better. Figure 9 was the flow field near the fire source when there was no wind and with wind, respectively. It could be seen, the flow without wind was very gentle, but when there had wind, the flow was turbulent, the leeward velocity increased.

Figure 10 was the ceiling temperature distribution along the tunnel without and with wind by the CFD model. The number at the icon meant the distance from the fire source. When there was no wind, the temperature of fire location was the highest, about 500˚C, and the time for temperature rising to 450˚C was 10s. This showed the results of zone and field model were similar at the fire source zone. For the temperature of a grid at some time was gotten during the CFD simulation, the temperature was fluctuant before the whole smoke development reached steady. The smoke temperature 10m away from fire source was also 350˚C. The temperature at the tunnel end began to rise obviously at 50s, this indicated the smoke spread to end at 50s. But the temperature was more than 100˚C, higher than the temperature of zone model. Because this was the ceiling temperature, not the average temperature of the smoke layer. When there had wind, the highest temperature was also about 500˚C. But because of the wind influence, the highest temperature was found at the leeward position several meters from the fire source, not above the fire source. For same distance away from the fire source, the temperature of windward was much lower than that of leeward. The windward temperature 10m away the fire was only 240˚C, but the leeward was 450˚C. 50m away from the fire, the windward temperature was about 130˚C, and the leeward was about 200˚C. This illustrated that the windward smoke temperature decreased largely for the inflow wind.

Figure 11(a) was the temperature variation with the altitude and tunnel without wind at 60s, and (b) was the result with wind at 200s. It could be seen that all the temperature except of the fire position increased obviously above the height of 2.5m, and kept 20˚C below 2.5m. This showed that the smoke layer also kept above 2.5m, same as the result of zone model. In addition, the ceiling temperature was not the highest. The temperature 0.5m below the ceiling was highest. Then it decreased with the height reducing. The temperature of whole smoke layer was not uniform. The temperature of upper and lower layer had a difference of 200˚C. When there had wind, the leeward temperature of 1.5m height reached 50˚C. The smoke could descend below 2m. This indicated that the wind hastened the mixing of smoke and air to cause the smoke layer's descending. At the same time, the temperature also reduced. Except near the fire source, the temperature at difference distance was all below 250˚C, which was 50˚C lower than that of no wind.

5. CONCLUSIONS

The smoke development in tunnel fire was simulated by zone model and field model. The temperature distribution, smoke layer height development and flow field variation in tunnel were gained with the situations of without wind and with wind. The results showed that zone model and field model achieved similar results in no wind case. But for wind case, the results of these two models had some difference. The zone model was not sensitive to the wind. While in field model, the wind would have much effect on the smoke development.

The smoke in tunnel spread quickly. In the cases of this paper, the smoke movement velocity was about 2m/s without wind. When there was a wind of 1m/s flowing into the tunnel, the smoke movement velocity of leeward was 3m/s, and the windward velocity was 1m/s. It was namely that the smoke movement velocity of leeward would be the sum of smoke movement velocity of no wind and wind velocity, and the windward velocity was the smoke movement velocity of no wind subtracting wind velocity. The existence of wind would hasten the heat transfer to decrease the smoke temperature. When tunnel happens fire, it is more safety escaping toward windward.

The smoke layer height kept above 2.5m. The temperature was the most threat to people. And the temperature of 40m away the fire source reached 180˚C, it was threaten to the people's safety. The highest temperature would be 500˚C at the 0.5-1.0m below the ceiling. It would damage the tunnel structure.

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REFERENCES

[1] Wang Jianyu, The Technical Advancement of China Tunnel Engineering, China Railway Science, Vol.22, No.1, pp72-78, Feb., 2001.

[2] Du Jianke, Fire Safety Analysis on Railway Tunnel, Safety, No.6, pp1-3, 1998.

[3] http://home.no.net/lotsberg/artiklar/brann/en_tab.html

[4] http://news.bbc.co.uk/hi/english/world/europe/newsid_1858000/1858436.stm

[5] Kunihiko Takeda, Tetsuya Nemoto, Fumi Sato, Present Status and Future Trend of Flame Retardancy in Japan, http://www.mc.mat.shibaura-it.ac.jp/~master/ENG/paper/TAKEDA/4/result.html

[6] Zeng Qiaoling, Zhao Chenggang, Mei Zhirong, Numerical Analysis and Experimental Study on Temperature of Tunnel after Fire, Journal of the China Railway Society, Vol.19, No.3, pp92-98, Jun. 1997.

[7] Alexey V. Karpov, Dmitry V. Makarov et al, Fire in Tunnels: Three-Dimensional Numerical Simulation and Comparison with the Experiment, Proceedings of the 4th Asia-Oceania Symposium on Fire Science and Technology. Waseda University, Tokyo, Japan, pp565-576, May, 2000.

[8] O. Vauquelin, O. Mégret, Smoke extraction experiments in case of fire in a tunnel, Fire Safety Journal Vol.37, pp525-533, 2002.

[9] Milosb T. Pucbovsky, Performace-based Fire Codes and Standards, Fire Peotection Handbook, 18th edition, Section11/chapter 9, NFPA, Quincy, Ma. 1997.

[10] Fan Weicheng, Wang Qing'an, Zhang Renjie, Huo Ran, An Introduction to Fire Science(in Chinese), Hubei Science and Technology Publisher, April, 1993.

[11] Huo Ran, Hu Yuan, Li Yuanzhou, An Introduction to Building Fire Safety Engineering, The Publishing House of University of Science and Technology of China, Nov., 1999.

[12] William D. Walton, Zone Computer Fire Models for Enclosures, The SFPE Handbook of Fire Protection Engineering, Chapter 3-7, NFPA, Quincy, Ma. 1995.

[13] W.K. Chow, Fire Hazard Assessment in a Big Hall with the Multi-Cell Zone Modelling Concept, Journal of Fire Sciences, Vol.15, No.1, pp14-28, January/February 1997.

[14] W.K. Chow, On Safety System for Underground Car Parks, Tunnelling and Underground Space Technology, Vol.13, No.3, pp281-287, 1998.

[15] David W. Stroup, Using Field Modeling to Simulate Enclosure Fires, The SFPE Handbook of Fire Protection Engineering, Chapter 3-8, NFPA, Quincy, Ma. 1995.

[16] Kevin B. McGrattan, Glenn P. Forney, Jason E. Floyd, Simo Hostokka, Fire Dynamics Simulator (Version 2)-User's Guide, NISTIR 6784, Nov., 2001.
[17] O. Mégret, O. Vauquelin, A model to evaluate tunnel fire characteristics, Fire Safety Journal, Vol.34, pp391-401, 2000.
[18] D. Lacroix, The New PIARC report on fire and smoke control in road tunnels, Third International Conference on Safety in Road and Rail Tunnels, pp185-197, Nice, France, 1998.
[19] Peng Limin, Liu Xiaobing, Wang Wei, Du Sicun, A Research on the Damage Degree of Tunnel Lining Structure after Fire Accident and Its Detection, Journal of Experimental Mechanics, Vol.14, No.3, pp395-401, Sep. 1999.

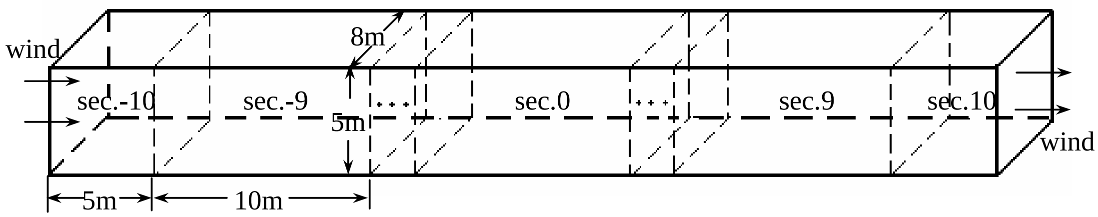


Figure 1. The multi-section design in zone model simulation

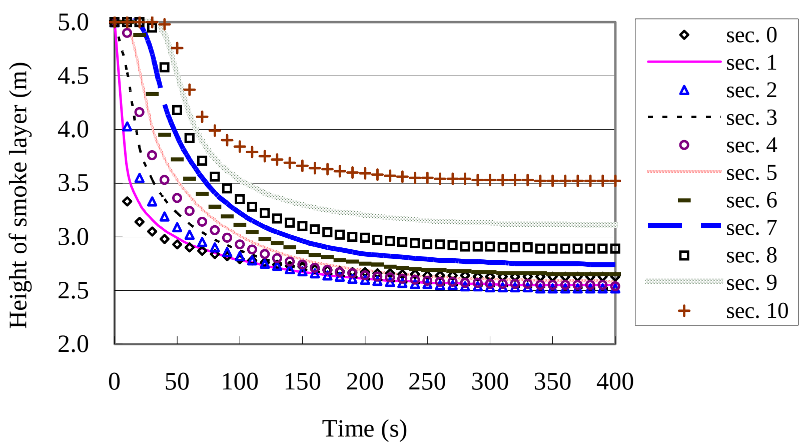
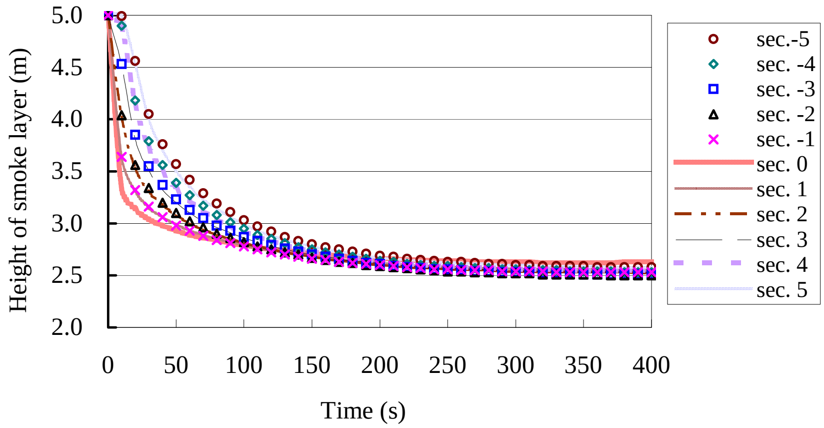
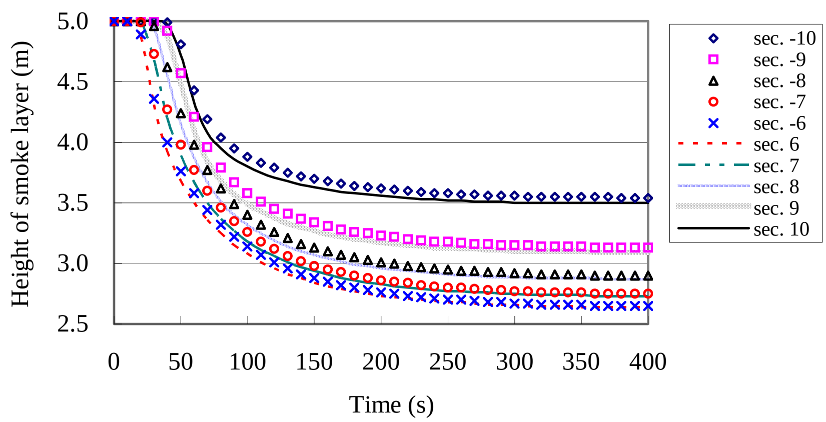


Figure 2. The development of smoke layer height without wind by zone model



(a) The smoke layer height of sections within 55m away the fire



(b) The smoke layer height beyond 55m away the fire

Figure 3. The development of smoke layer height with wind by zone model

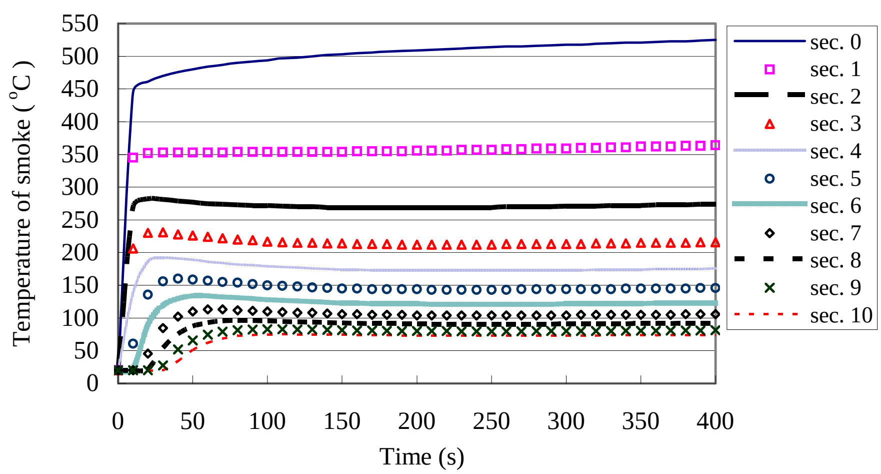


Figure 4. The smoke temperature variation without wind by zone model

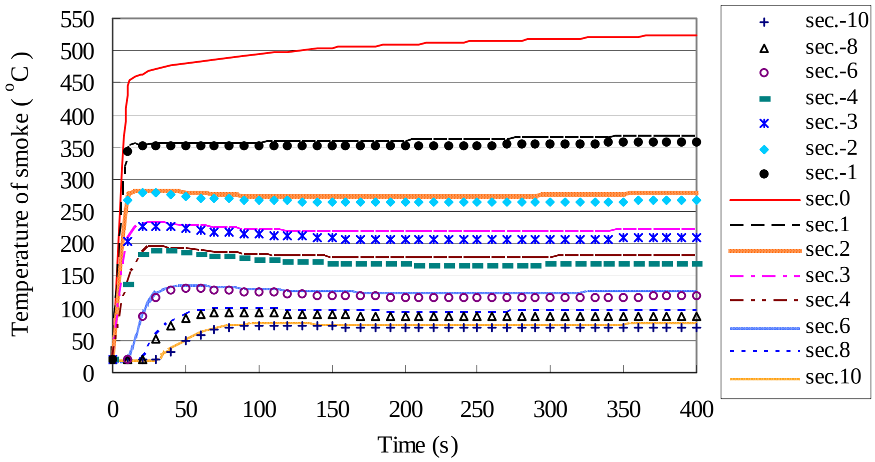
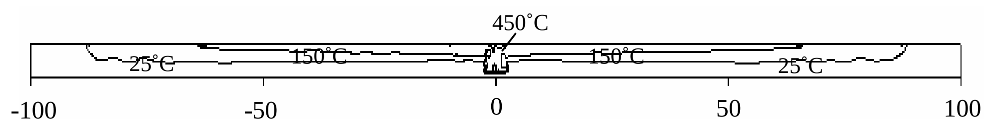
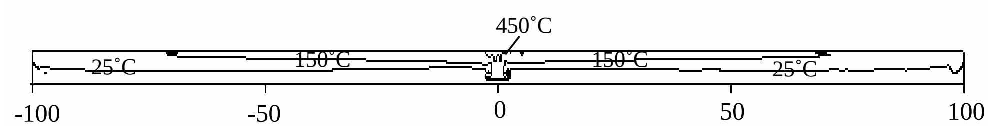


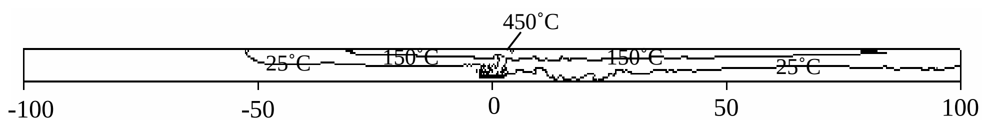
Figure 5. The smoke temperature variation with wind by zone model



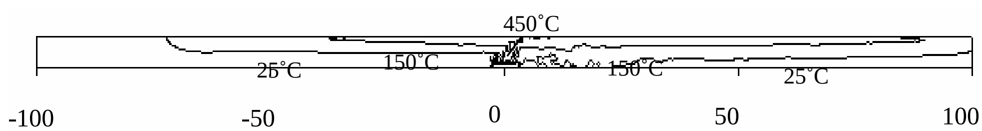
(a) 40s without wind



(b) 60s without wind

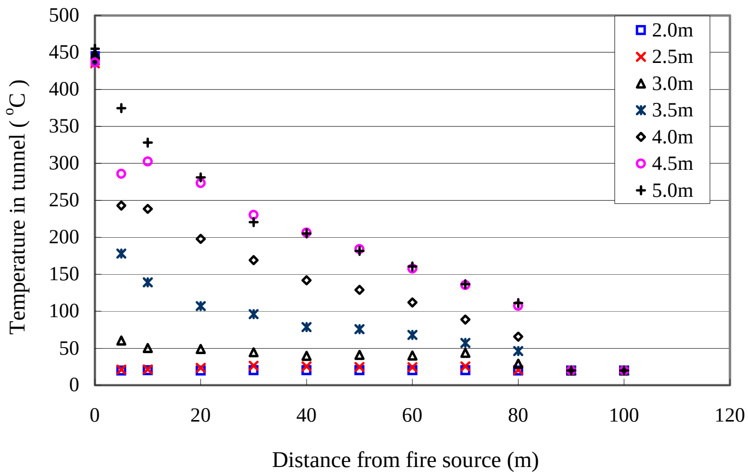


(c) 40s with wind

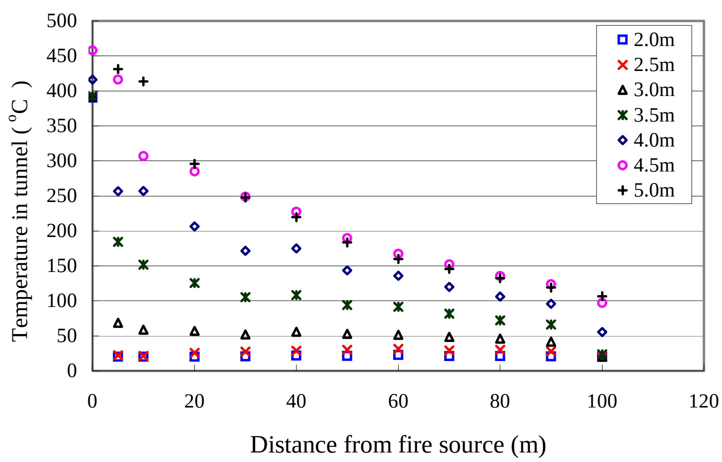


(d) 60s with wind

Figure 6. The temperature development gotten by the field model

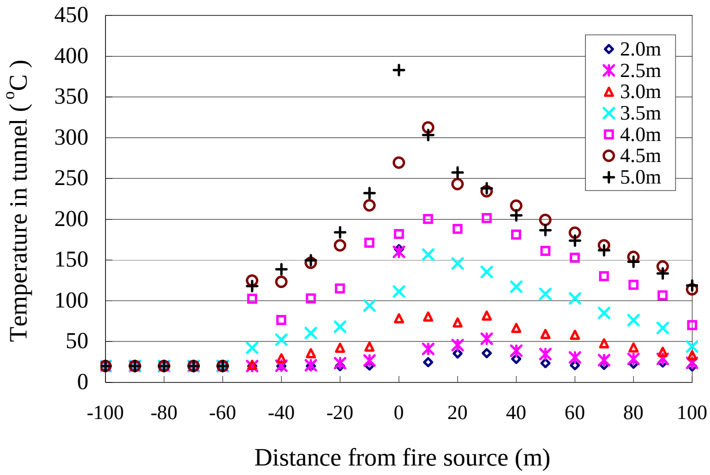


(a) 40s

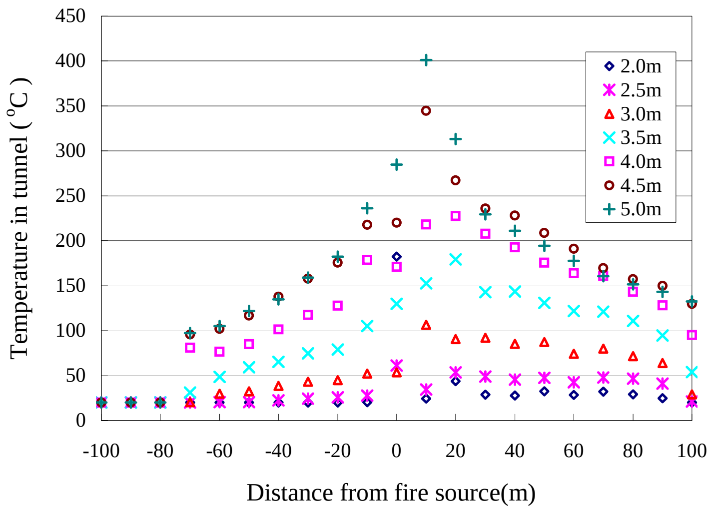


(b) 60s

Figure 7. The smoke temperature distribution along height without wind at 40s and 60s

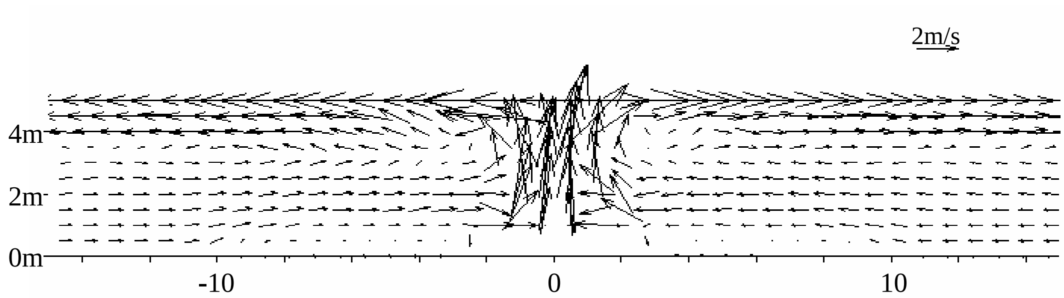


(a) 40s

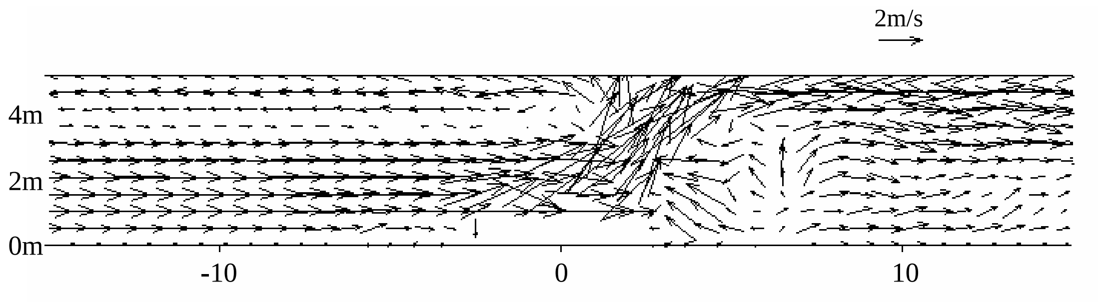


(b) 60s

Figure 8. The smoke temperature distribution along height with wind at 40s and 60s

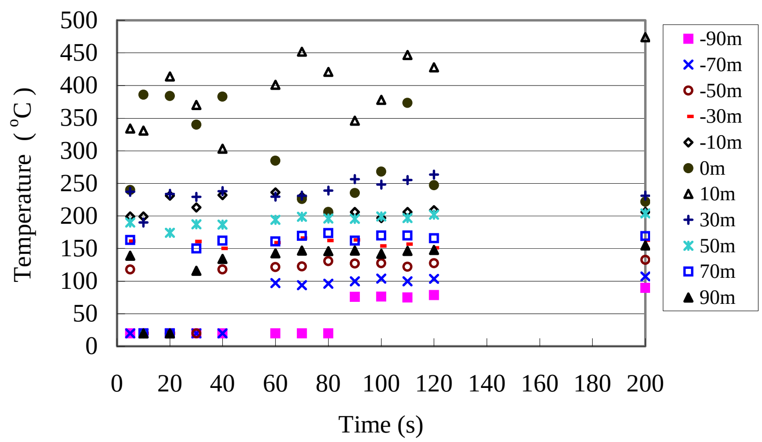


(a) without wind at 60s

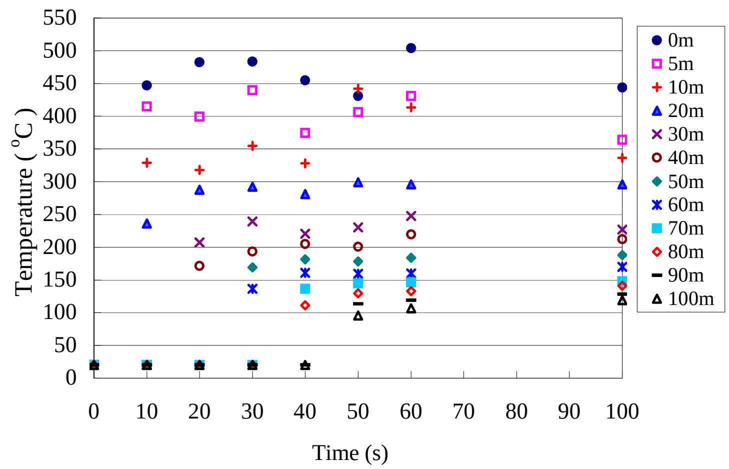


(b) with wind at 200s

Figure 9. The flow velocity vector near the fire source

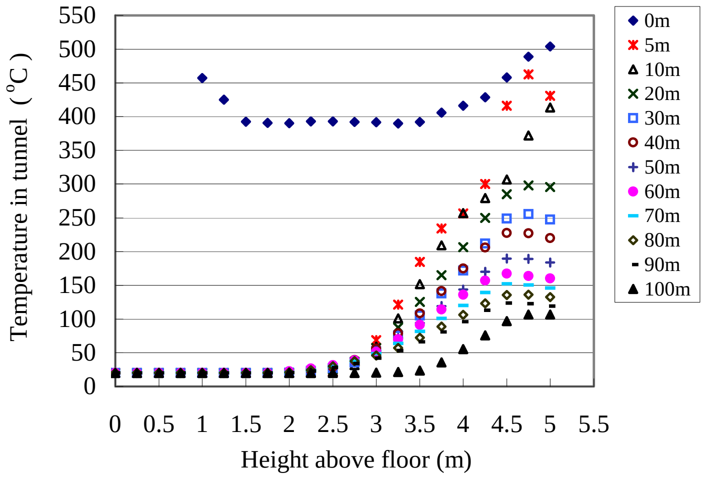


(a) without wind

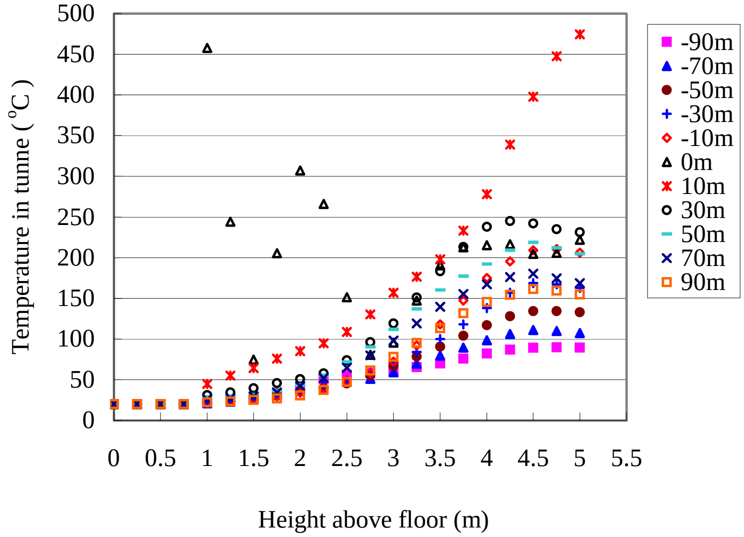


(b) with wind

Figure 10. The ceiling temperature variation along tunnel



(a) without wind (60s)



(b) with wind (200s)

Figure 11. The temperature variation along height