Influence of the Positive Slope of the Fire Source on Smoke Control of Tunnel Lateral Smoke Exhaust System

Yuejing Chen¹, Li Zhang², Xuefeng Han³*

¹College of Safety Science and Engineering, Nanjing Tech University, Nanjing, China
²College of Safety Science and Engineering, Nanjing Tech University, Nanjing, China
³College of Safety Science and Engineering, Nanjing Tech University, Nanjing, China

* Xuefeng Han’s e-mail: safety@njtech.edu.cn

Abstract—In order to study the influence of the positive slope of the fire source on the smoke control effect of the lateral smoke exhaust system of the tunnel, this paper established a tunnel fire model, reasonably divided the grid, and controlled variables such as the scale of the fire source, the amount of smoke, and the smoke outlet. Using FDS simulation software, by changing the forward slope of the fire source, study the temperature distribution, CO concentration, and smoke settlement height of the tunnel fire. The simulation shows that the effect of the tunnel lateral smoke exhaust system is different when the fire source is located on different slopes.

1. INTRODUCTION

Due to the narrow interior space of the tunnel, the poor ventilation, the variety of vehicles traveling in the tunnel and the complexity of the cargo, and the cables and wires of the tunnel itself, the cause of the fire are variable [1-2]. Once a fire accident occurs, it is easy to cause high temperature in the tunnel, smoke deposition, and low visibility, which will greatly hinder the rescue work. The main causes of highway tunnel fires are: vehicle breakdowns, traffic accidents and so on [3].

In 2001, Shu Ning and Xu Jianmin of South China University of Technology conducted simulation experiments on the southern part of the Jingzhu Expressway as the research object. They studied the characteristics of tunnel fire smoke flow under the action of longitudinal ventilation, and the influence of smoke in the upward tunnel on the downward tunnel and the impact of the horizontal hole [4]. In 2015, Li Mingxuan and others conducted experiments in the completed ring road tunnel, and studied the effect of centralized smoke exhaust system in controlling tunnel smoke spread during ring tunnel fire [5].

Through the use of numerical simulation and experiment methods, Li Junmei and others have studied the influence of different tunnel slopes (0%±5%) and ventilation wind speed (0-3m/s) on the maximum temperature of the tunnel ceiling [6]. Xia Zhengwen and others studied the flow of fire smoke in the tunnel under the conditions of 0%, 3%, and 5% slopes of the reduced-size tunnel model test and the longitudinal ventilation wind speed of 0.8-6m/s [7].

In this paper, by changing the positive slope of the fire source, controlling variables such as the scale of the fire source, the amount of smoke, the smoke outlet, etc., the changes in the temperature distribution of the tunnel fire, the CO concentration, and the height of the smoke deposition are studied from the longitudinal dimension. The control effect of different positive slope on smoke control scheme
was analyzed along the tunnel longitudinal, and the best smoke exhaust scheme under different positive slope was obtained.

2. ESTABLISH TUNNEL MODEL AND SIMULATE WORKING CONDITION SETTINGS

In this paper, a highway tunnel is taken as an example, and the physical model of the tunnel is constructed in FDS at a ratio of 1:1. Select one of the sections for research, and there is an independent flue exhaust duct on the wall on one lateral of the tunnel. The interval of the electric smoke exhaust vents on the exhaust duct is 67.5m, and each group of exhaust vents has 3 small exhaust vents, the spacing is 2m. The smoke exhaust vent is 2m long and 1m wide. The distance between the lower end of the smoke exhaust vent and the tunnel is 4.6m. The schematic diagram of the tunnel model is as Fig.1.

After calculation and analysis, based on the consideration of accuracy and computing time, the optimal mesh size of this model is 0.4m × 0.4m × 0.4m. Set up DEVICE (measurement point) in the tunnel to measure the smoke temperature, visibility after a fire; set up SLICE (measurement surface) to observe the distribution range of smoke temperature, visibility. According to the International Road Society (PIARC 1999), the fire scale of different types of vehicles is 2.5-30MW, so the fire source scale is set to 30MW. The Heskestad plume is used to calculate the axisymmetric smoke flow quality. At 30MW, the maximum smoke production rate in the tunnel is 126.51 m³/s. According to the technical measures, the air leakage of the duct system is increased by 10-20%, so the smoke exhaust volume is selected as 160m³/s. 4 groups of smoke exhaust outlets are opened asymmetrically (the fire source is located in the middle of the tunnel), constructing a tunnel model with a positive slope (1.5%, 3.0%). According to the "Road Tunnel Ventilation Design Rules", there is a chimney effect in the positive slope tunnel, which is beneficial to the discharge of smoke. Therefore, this paper chooses the longitudinal wind speed to be 1.0m/s and 1.5m/s to study the best ventilation in the positive slope tunnel Smoke exhaust program.

2.1. Design of fire smoke control conditions for positive slope tunnels

| Slope | Working condition | Fire source Scale (MW) | Exhaust smoke volume (m³/s) | Number of open smoke outlets (Group) | Longitudinal ventilation wind speed (m/s) |
|-------|-------------------|------------------------|-----------------------------|-------------------------------------|-------------------------------------------|
| 1.5%  | C1                 | 30                     | 160                         | 1 3                                 | 1.0                                       |
| 3.0%  | C2                 | 30                     | 160                         | 1 3                                 | 1.5                                       |
|       | C3                 | 30                     | 160                         | 1 3                                 | 1.0                                       |
|       | C4                 | 30                     | 160                         | 1 3                                 | 1.5                                       |
3. STUDY ON FIRE SMOKE CONTROL IN TUNNEL WITH POSITIVE SLOPE

3.1. CO concentration change analysis

According to the measured data of the simulation, select the most unfavorable working condition, and make statistics of the CO under each working condition. Table 2 shows the average value of CO at different locations upstream and downstream from the fire source at each time.

**TABLE 2. AVERAGE CO GAS CONCENTRATION UNDER DIFFERENT WORKING CONDITIONS IN THE TUNNEL**

| Time/s | Working Condition | C1  | C2  | C3  | C4  | C1  | C2  | C3  | C4  | C1  | C2  | C3  | C4  |
|--------|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 100    | The average value of CO concentration at different locations from the fire source (distance from the fire source, where "+" means upstream of the fire source, and "," means downstream of the fire source)/ppm | -200m | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 3   |
|        |                   | -140m | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 3   | 1   |
|        |                   | -90m  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   |
|        |                   | -50m  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
|        |                   | -20m  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
|        |                   | -10m  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
|        |                   | 0m    | 12  | 5   | 9   | 8   | 45  | 38  | 30  | 5   | 112 | 28  | 78  | 6   |
|        |                   | 10m   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
|        |                   | 20m   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |

The CO concentration of each working condition in Table 2 at any time at each position does not exceed the limit concentration of 500 ppm that the human body can withstand, which will not pose a threat to the safety of personnel evacuation. The concentration of CO in the upstream of the fire source is basically close to 0 under various conditions, and the concentration in the downstream of the fire source is basically higher than that in the upstream of the fire source. For a tunnel with a slope of 1.5%, the overall CO concentration when using a slope of 1.5m/s is lower than when using a slope of 1.0m/s. The 3.0% slope is similar to the 1.5% slope, that is, the overall CO concentration is lower when the longitudinal wind speed of 1.5m/s is used.

3.2. Analysis of Settlement Height of Smoke Layer

In this paper, several representative locations are selected by simulation data to study the change of smoke layer height under various working conditions. The height change of the smoke layer at each position in each working condition is shown in the following figure (use x to indicate the distance from the fire source, where "+" indicates the upstream of the fire source, and "," indicates the downstream of the fire source; The safety height of the personnel is 2m, and the smoke layer below this height will pose a threat to the evacuation).

When the tunnel slope is 1.5% and 3.0%, the height of the smoke layer upstream of the fire source is always above 2m at different longitudinal ventilation wind speeds. When the slope is 1.5%, the two working conditions at the fire source are both sinking below 2m at the initial stage of the fire; downstream of the fire source, when the longitudinal ventilation wind speed is 1.0m/s, it is obvious that the 160m away from the fire source begins to sink below 2m in the late simulation stage. When the longitudinal wind speed is 1.5m/s, settlement only begins at 200m from the fire source, and when the simulation is about to end. The slope is 3.0%, and the two working conditions at the fire source are in the initial stage of combustion and sink below 2m; Downstream of the fire source, when the longitudinal ventilation wind speed is 1.0m/s, it is obvious that the 160m and 200m from the fire source will begin to sink below 2m at about 450s and 400s respectively. When the longitudinal wind speed is
1.5m/s, settlement begins at about 450s and 300s at 160m and 200m from the fire source, and the degree of settlement is more serious than the former.

(a) Changes in smoke layer settlement height under working conditions C1 (positive slope 1.5% + longitudinal wind speed 1.0m/s) and C2 (positive slope 1.5% + longitudinal wind speed 1.5m/s)
3.3. Longitudinal temperature distribution

Fig. 3 is a screenshot of the temperature diffusion slices of various working conditions at different times (100s, 200s, 300s, 400s, 500s, 600s). Obviously, the spreading distance of the fire source downstream of each working condition is longer than that of the upstream fire source. According to the simulation results, the greater the slope, the shorter the spread distance upstream of the fire source; the greater the longitudinal wind speed, the shorter the upstream spread distance of the fire source. The changes in the downstream of the fire source under various working conditions are less obvious. Moreover, the stratification of the smoke layer at the upstream of the fire source is better for each working condition than at the downstream of the fire source.

Comparing various working conditions, the greater the slope, the shorter the spread distance upstream of the fire source; the greater the longitudinal wind speed, the shorter the upstream spread distance of the fire source. The changes in the downstream of the fire source under various working conditions are less obvious. Moreover, the stratification of the smoke layer at the upstream of the fire source is better for each working condition than at the downstream of the fire source. The contrast gradient is 1.5%. When the wind speed of 1.0m/s is used, the layering effect of the smoke layer downstream of the fire source is better. When the longitudinal wind speed of 1.5m/s is used, it is obvious that the smoke layer is about 20m away from the fire source. More turbulent, this is due to the excessive longitudinal wind speed, the smoke upstream of the fire source is accumulated in the downstream of the fire source near the fire source; but the overall temperature of working condition C1 is obviously higher than that of working condition C2. The contrast gradient is 3.0%. When 1.5m/s longitudinal wind is used, the stratification effect of the smoke layer downstream of the fire source is not as good as the longitudinal wind speed of 1.0m/s, and the smoke layer is more turbulent; the overall temperature of the two working conditions is relatively close.
4. CONCLUSIONS
This paper studies the changes of CO concentration, smoke deposition height, temperature, etc. in the tunnel under the action of different smoke extraction schemes under the lateral smoke exhaust system of the tunnel when the fire source is located on different forward slopes (1.5%, 3.0%) along the longitudinal direction of the tunnel. Determine the fire source scale to be 30MW, the smoke exhaust rate to be 160m$^3$/s, the smoke outlet to open four groups (upstream 1 group, downstream 3 groups), when the fire source is located in the middle of the tunnel, the best smoke control scheme under different slopes (among which Longitudinal wind speeds are along the direction of travel). When the slope is 1.5%, the vertical wind speed of 1.5m/s can achieve the best smoke exhaust effect; when the slope is 3.0%, the vertical wind speed of 1.0m/s can achieve the best smoke exhaust effect.

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