The Effect of Longitudinal Ventilation System on Smoke Movement and People’s Evacuation in Tunnel Fire

Kunhua Xiao1*, Yuyang Ji2
1Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu, Sichuan, 610031, China
2Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu, Sichuan, 610031, China
*Corresponding author: davidxiaox@my.swjtu.edu.cn

Abstract. Smoke movement in a model tunnel controlled by longitudinal ventilation system was studied and in this paper. Smoke movement in a tunnel was studied numerically with some equations reviewed. A numerical experiment with Computational Fluid Dynamics (CFD) was carried out. At the initial stage of tunnel fire, the velocity of ventilation fans can be set up as critical speed to slow down smoke movement and high temperature diffusion. However, in evacuation stage, the ventilation speed should be decreased to prevent smoke transmit too fast and hurt people in the downstream. Without longitudinal ventilation system, smoke is distributed symmetrically in the tunnel. When the tunnel has longitudinal ventilation system, smoke will not distribute in the upstream of the tunnel but it will spread quickly to the downstream. If people still evacuate along the center line of the downstream, they may be threatened by the smoke. This study demonstrated both the advantages and disadvantages of longitudinal ventilation system and showed that the velocity of ventilation fans should be carefully chosen.

1. Introduction
In fire disasters, smoke is the main reason of death, which occupies 80% [1]. Smoke can decrease the oxygen concentration and generate toxic gases, such as sulfur dioxide (SO2) and hydrogen sulfide (H2S). In tunnel fires, generated smoke is produced more than other types of fire [2]. Meanwhile, tunnel fire has these characteristics: high temperature, low visibility, quick spread speed, long extinguishing time; randomness and unpredictability [3]. When a fire occurs in a tunnel, a large amount of oxygen will be consumed in the relatively closed space. When a fire occurs in tunnel, in addition to release carbon dioxide (CO2), some harmful smokes such as CO and SO2 are generated. When the CO2 mass fraction is more than 20% or the fraction of CO is more than 1%, people will be in danger [2]. Furthermore, rapid growing smoke can block people’s sight and make it more difficult for them to evacuate, especially in extra-long tunnels. Nowadays, many researchers have conducted a lot of research on the evacuation time of people in tunnel. Li Chuyun used the theoretical method and evacuation software to propose that the safe evacuation time of tunnel fire should be controlled within 8 minutes [4].

There were 153 big tunnel fires occurring between 2000 and 2015 in China, which has caused 46 deaths and most of them were killed by smoke [3], so the research of smoke spread in tunnel fire is of primary importance. The statistics of injury to human beings caused by tunnel fire accidents [3] is shown by Figure 1.
This study investigates smoke spread in tunnels and people’s evacuation time. Furthermore, some advice and upgrades of tunnel will be given.

**Nomenclature**

- \( \rho \): density \((kg/m^3)\)
- \( u \): smoke velocity \((m/s)\)
- \( v \): ventilation speed \((m/s)\)
- \( \vec{U} \): velocity vector
- \( T \): temperature \((K)\)
- \( \mu \): velocity component \((m/s)\)
- \( F \): other forces
- \( \lambda = -\frac{2}{3} \mu \) \((m/s)\)
- \( S_e \): net work
- \( Q \): number of evacuated people
- \( \mu_l \): vehicles’ proportion (%)
- \( m_i \): number of passengers in a vehicle
- \( \eta_i \): passenger load factor (%)
- \( n_i \): number of vehicles
- \( v_e \): people’s evacuation speed \((m/s)\)
- \( t \): time \((s)\)
- \( X_t \): smoke movement distance

**2. Methodology**

**2.1. CFD simulations**

**2.1.1. Governing equations of smoke simulation**

In CFD, continuity equation, momentum equation and energy equation should be used to simulate smoke. These equations are shown below [5] [6]:

**Continuity equation:**

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0
\]  
(1)

In Equation 1, \( \vec{U} \) is velocity vector.

**Momentum equation:**

\[
\frac{\partial (\rho \vec{U})}{\partial t} + \nabla \cdot (\rho \vec{U} \vec{U} - \mu \nabla \vec{U}) = -\nabla \rho + F
\]  
(2)
In Equation 2, $\mu$ is velocity component $F$ is other forces

Energy equation:
$$\frac{\partial}{\partial t} (\rho e) + \nabla \cdot (\rho \vec{U} e - \lambda \nabla T) = S_e$$

In above equation, $\lambda = -\frac{2}{3} \mu$, $S_e$ is net work. Put three equations together, they can be simplified as [6]:

Continuity equation:
$$\frac{\partial}{\partial t} (\rho \phi) + \nabla \cdot (\rho \vec{U} \phi - \nabla \phi) = S_\phi$$

In equation (4), $\phi$ is generic transportable scalar, $S_\phi$ is rate of change due to sources.

2.1.2. Parameter setting
Assume that the pressure in tunnel is equals to one standard atmosphere $P = P_0$, the velocity of smoke $u = 2m/s$, the velocity of air in tunnel $u_0 = 0$, the velocity of longitudinal ventilation system $v = 0$, the temperature of the tunnel $T_0 = 300 K$, the temperature of the fire source $T = 1200 K$, the concentration of smoke at the place of fire source $C = 6\%$, the concentration of smoke in tunnel $C_0=0$. Using carbon monoxide (CO) as the tracer particle of the smoke since CO is the main toxic gas that causes deaths in fires [7], and the distribution of smoke and CO in the tunnel is similar [8].

Commercial CFD package Ansys-Fluent is used to simulate the tunnel fire. The calculation model adopts a rectangular coordinate system, the coordinate origin $(0,0,0)$ is located at the midpoint of the bottom of the tunnel entrance, and the $Z=0$ plane is taken as the ventilation inlet, and it extends 1000m down along the $z$-axis direction that is the length of the tunnel as the ventilation outlet. Choose the width of the tunnel is 10 m and height is 5 m. The parameter of the fire source is 4.9m-length, 1.85m-width and 1.5m-height. Assume the fire source locates on the midpoint of the tunnel and it has reached a steady state of combustion.

2.1.3. Boundary conditions
The tunnel entrance adopts the velocity entrance boundary condition, and the temperature is 300 K. The exit of the tunnel adopts the boundary condition of velocity exit and the temperature is also 300 K. Set the tunnel surface to be insulated.

2.1.4. Working conditions
Perform a three-dimensional steady-state simulation for the tunnel, set the ventilation speed of the longitudinal ventilation system to $v = 0$ (no longitudinal ventilation system), $v = 1 m/s$, $v = 2 m/s$, and $v = 3 m/s$ respectively. The wind direction is from the upstream of the fire source to the downstream. A schematic diagram is shown below [6]:

![Figure 2. Simplified picture for theoretical analysis](image-url)
2.1.5. Data analysis
The result of calculation is loaded in CFD-Post. The smoke spread in the tunnel will be shown in the next part including fraction of CO and temperature in tunnel. After the data being imported into Origin, the graphics will be shown.

2.2. The evacuation times

2.2.1. Determine the number of people evacuated
The number of people need to be evacuated is determined by the proportion of different vehicles, the number of passengers in a vehicle and the passenger load factor [4] as the equation 1 shown below:

\[ Q = (\mu \times m \times \eta) \times n \]  

In above equation, \( Q \) is number of people in the tunnel, \( \mu \) is vehicles’ proportion, \( m \) is number of passengers in a vehicle, \( \eta \) is passenger load factor and \( n \) is number of vehicles.

2.2.2. Determine people’s evacuation speed
According to people’s different age and distance from the fire point, this simulation refers to the evacuation speed provided by the SFPE Fire Fighting Engineer’s Manual [9]. The values are shown in Table 1.

| Types of People | Age Range | Percent | Speed (m/s) |
|----------------|-----------|---------|-------------|
| elderly female | 51-80     | 10%     | 1.04        |
| elderly male   | 51-80     | 15%     | 1.05        |
| adult male     | 17-29     | 20%     | 1.24        |
| adult male     | 30-50     | 10%     | 1.24        |
| adult female   | 17-29     | 15%     | 1.3         |
| adult female   | 30-50     | 30%     | 1.3         |

Evacuation can be affected by many factors including the fire location, the number of vehicles, the number of people. Based on these factors, this study has the following assumptions:
1. People’s reaction time (\( t_{reaction} \)): assume the time between the driver discovers the fire and starting escape is 1 minute [9].
2. Cause of fire and burning condition: the fire is a stable combustion caused by a malfunction of the car engine and the spread of smoke is also stable.
3. Type and number of vehicles: 40 five-seat private car and each of the car is fully loaded.
4. People’s location: people are scattered into 4 groups from 100m to 400m from the fire point. Figure 3 describes this situation below:

![Figure 3. People’s distance from the fire](image)

4. To simplify the calculation, the evacuation time of each group will be calculated first. Then the average of these 4 values is the evacuation time of the people in the tunnel.
5. Assume the smoke movement velocity is 2 m/s in Fluent.

3. Calculation and Result

3.1. The smoke movement and temperature distribution in tunnel
When there is no longitudinal ventilation system in the tunnel \( (v = 0) \), CO mass fraction and temperature around fire source are very high. From the fire source to the upstream, the mass fraction of CO gradually decreases, but it still keeps a high value in downstream. The temperature is distributed symmetrically in the tunnel. When the tunnel has longitudinal ventilation system \( (v \neq 0) \), upstream 100m away from the fire source, the smoke concentration is almost 0. At a downstream location 100 m away from the fire source, the smoke concentration dropped significantly. The change of temperature is similar to smoke.

The result of CFD simulation is shown below:

Figure 4. CO mass fraction in tunnel
3.2. People’s evacuation time in tunnel

3.2.1. People’s evacuation speed
People’s evacuation speed: \( v_e = 1.04 \times 10^\% + 1.05 \times 15^\% + 1.24 \times 20^\% + 1.24 \times 10^\% + 1.3 \times 15^\% + 1.3 \times 30^\% = 1.22 \text{ m/s} \) and the number of people in tunnel: \( Q = 100^\% \times 5 \times 100^\% \times 40 = 200 \), each group has 50 people.

3.2.2. People’s evacuation time
\[ t_1: (500 - 100) / 1.22 = 328 \text{ s or 5.5 min} \]
\[ t_2: (500 - 200) / 1.22 = 246 \text{ s or 4.1 min} \]
\[ t_3: (500 - 300) / 1.22 = 164 \text{ s or 2.7 min} \]
\[ t_4: (500 - 400) / 1.22 = 82 \text{ s or 1.4 min} \]

So the average evacuation time \( t_{average} = (t_1 + t_2 + t_3 + t_4) / 4 = 3.4 \text{ min} \) and the total evacuation time of 4 groups of people in the tunnel is \( t_{total} = t_{average} + t_{reaction} = 3.4 + 1 = 4.4 \text{ min} \) (264 s). The smoke movement distance is \( X_t \approx 2 \frac{m}{s} \times 264 \text{ s} \approx 528 \text{ m} \).

From the calculation of smoke movement and people’s evacuation time, people cannot evacuate from the tunnel in a time period of 264 s. When CO mass fraction is more than 1\%, most of people in the tunnel will be poisoned [2] so they cannot evacuate in time.

4. Conclusion
The main conclusions of this paper are described below:
- By the simulation of CFD, the tunnel has strong air-tightness and poor condition of smoke exhaust so longitudinal ventilation system can decrease smoke spread. When there is no longitudinal ventilation system, people cannot escape the tunnel in time. The smoke movement distance is 528 m, more than 500 m. By Figure 4, CO will transmit most area of the tunnel when \( (v = 0) \). After
using longitudinal ventilation system \((v \neq 0)\), the CO mass fraction decreases sharply. It can increase the probability of people surviving in a tunnel fire and a part of smoke will be absorbed and discharged out of the tunnel.

- As the chart above, the highest temperature in the tunnel is around fire source and decreases towards the surroundings. The high temperature exists in the range of about 100m from the fire source, which will cause harm to people, and the temperature in other places is low and will not directly harm people. High temperature will also cause difficulties for people's evacuation. The longitudinal ventilation system can reduce the high temperature in the tunnel when a tunnel fire occurs to help people evacuate. However, when the ventilation speed increases, its role is not as significant as controlling the spread of smoke.

- Although longitudinal ventilation system can control the smoke well in the upstream of the tunnel, it also has some negative effect. Smoke will quickly move to the downstream of the tunnel with the increase of ventilation speed. It can threaten people in the downstream. By Figure 4 and Figure 5, the greater the inlet ventilation speed, the smaller the influence of the ventilation speed on the smoke concentration and temperature. Therefore, at the initial stage of the fire, the ventilation speed of the fan should be set to the critical ventilation speed to control fire and smoke spread. During the evacuation and rescue time, the ventilation speed should be decreased to avoid the airflow causing the smoke in the tunnel to spread too fast and harmful to the people downstream of the fire source [10].

- The model in this study has limited because it is a steady-state model. To improve this model to an unsteady-state model in further study, smoke exhaust efficiency of the fire source is needed. The efficiency is depended on the heat release rate of the fire source [11]. The smoke exhaust of the fire source was assumed by a symmetrical flow when \(u = 0\). Under this assumption, the model showed the characteristics of the constant smoke movement in the tunnel. However, when the assumption is changed by the people and cars in the tunnel, the influence of the natural air flow, the initial velocity inside the tunnel [11], and other environment conditions, steady-state model may be inadequate to estimate smoke spread. Some improvements that can be made to the model will benefit future research.

- This paper has research about people’s evacuation in tunnel. However, it is hard to simulate people’s behaviors when a fire disaster occurs, so the evacuation time has deviation. Meanwhile, many tunnels have angle, it can also influence smoke movement in tunnel.

Acknowledgments
The authors greatly appreciated the comment from Dr. Xiangdong Li affiliated with Royal Melbourne Institute of Technology University (Australia) who help authors to improve the quality of the paper.

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