# Simulation of Smoke Flow in a Longitudinal Ventilated Tunnel in Macau

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## Abstract

In the past decades, tunnel fire safety has been highly concerned since tunnels were widely installed and utilized as transportation links for people and cargos worldwide. In order to achieve a fire safety purpose, smoke extraction system should be well designed and built to extract or control the smoke effectively. The objective of this paper is to investigate the heat and smoke flow behavior based on CFD simulation in a longitudinal ventilated tunnel, Tunel do Monte da Guia (TMG tunnel) in Macau SAR, China. The dimension and the inclination angle of the existing roadway tunnel are of 285m (L) x 10.5m (W) x 7m (H) and 2.45˚, representatively. In this study, a single fire source caused by a vehicle is considered. The smoke flow in the tunnel model is simulated with the CFD program, FDS. In results, the critical velocities are obtained with the tunnel models arranged in the horizontal and inclined positions. Moreover, the smoke temperature is also analyzed in this study.

Keywords: **Smoke Flow, Simulation, Longitudinal Ventilation, Tunnel**

## Introduction

Tunnel ventilation is an important part in a modern tunnel. In the normal traffic condition, the ventilation can keep an acceptable level of contaminants produced by the vehicles. During a fire scenario, the emergency ventilation can remove or control the smoke in order to ensure the life and fire safety in tunnel. Regarding tunnel ventilation, natural ventilation or mechanical ventilation can be selected to use. Natural ventilation is mainly effective for a short and low traffic volume tunnel. For a long and high traffic volume tunnel, mechanical ventilation system is required. Mechanical ventilation is basically classified into three types: full transverse ventilation, semi-transverse ventilation and longitudinal ventilation. Longitudinal ventilation system is the most effective in cost in comparison with the full transverse and semi-transverse systems as the longitudinal system does not require additional space for ducts and requires lower maintenance cost [1]. However, longitudinal ventilation is suitable for a tunnel with unidirectional traffic.

In a longitudinal ventilated tunnel, jet fans are usually directly installed along the longitudinal direction. When the jet fans are activated in the emergency mode, the ventilated air forced the smoke flow from upstream to downstream direction to make a safe route for road passengers to evacuate and fireman to fight the fire. However, if the supply capacity of the ventilation system is not enough or the system is wrongly designed, the smoke will spread to the upstream direction. In such case, people inside tunnel is difficult to escape due to the blockage of evacuation route and inhalation of excess smoke and toxic gases. The upstream movement of hot smoke and gases is so called the “Back-layering” phenomenon. To prevent the back-layering phenomenon, the minimum ventilation velocity, so-called the critical velocity, provided by the ventilation system is required.

Experiments for the smoke flow in tunnels can be found in the open literature [2-5]. Based on the experimental studies, the critical velocity can be calculated by the empirical equations in terms of the heat release rate and tunnel geometry. Wu and Bakar [2] developed the equations, Eqs. (1-4), which utilized the hydraulic tunnel height $\bar{H}$ to replace the tunnel height as the experimental results showed that the tunnel temperature decreases when the tunnel width increases:

$$V'' = \frac{V}{\sqrt{g\bar{H}}} \quad (1)$$

$$Q'' = \frac{Q}{\rho_0 C_P T_0 \sqrt{g\bar{H}^5}} \quad (2)$$

$$V'' = 0.4[0.20]^{-\frac{1}{3}}[Q'']^{\frac{1}{3}}, \text{ for } Q'' \leq 0.20 \quad (3)$$

$$V'' = 0.4, \text{ for } Q'' > 0.20 \quad (4)$$

where V is the ventilation velocity, $ms^{-1}$; Q is the fire convective heat release rate, kW; $V''$ is the dimensionless critical velocity based on hydraulic tunnel height; $Q''$ is dimensionless heat release rate based on hydraulic tunnel height; g is gravitational force, $ms^{-2}$; $\rho_0$ is ambient air density, $kgm^{-3}$; $C_P$ is specific heat capacity of air, kJ $kg^{-1}$ $K^{-1}$; $T_0$ is ambient temperature, °C;

Lee and Ryou [3] introduced the effect of aspect ratio and tunnel, *As*, into the correlations proposed by Wu and Baker [2]. The new equations are shown as Eqs. (5-7):

$$V'' = \frac{V}{{A_S}^{0.2}\sqrt{g\bar{H}}} \quad (5)$$

$$Q'' = \frac{Q}{\rho_0 C_P T_0 \sqrt{A_S g\bar{H}^5}} \quad (6)$$

$$V'' = 0.73[Q'']^{\frac{1}{3}}, \text{ for } Q'' \leq 0.20 \quad (7)$$

where *As* is the aspect ratio;

Kennedy and his coworkers [6] proposed the equations, Eqs. (8) and (9) to calculate the critical velocity and average temperature of fire gases, which assumes Froude Number of 4.5. These equations were also quoted in NFPA 502 [7].

$$V_C = K_1 K_g \left(\frac{g \cdot H \cdot Q}{\rho \cdot C_P \cdot A \cdot T_f}\right)^{1/3} \quad (8)$$

$$T_f = \frac{Q}{\rho \cdot C_P \cdot A \cdot V_C} + T \quad (9)$$

where $V_C$ is the critical velocity, m/s; $K_1$ is 0.606 which is the Froude number factor ($Fr^{-1/3}$); $K_g$ is the grade factor; g is gravitational force, $ms^{-2}$; H is height of tunnel, m; Q is heat release rate, kW; $\rho$ is average density of approach (upstream air), $kgm^{-3}$; $C_P$ is specific heat capacity of air, kJ $kg^{-1}$ $K^{-1}$; $A$ is area perpendicular to the flow, $m^2$; $T_f$ is average temperature of the fire site gases, K; $T$ is temperature of the approach air, K;

Nowadays, with the help of the powerful computer and the CFD simulation [2, 8- 9], the smoke flow and heat transfer characteristics in a tunnel fire can be clearly observed and analyzed. Regarding the simulation tool, Fire Dynamic Simulator (FDS) is commonly used for various types of fire engineering problems. Fire Dynamics Simulation (FDS), which is developed by National Institute of Standards and Technology (NIST), has been verified as a reliable tool by a number of tests and experiments in the references [8, 10]. Result of FDS can be displayed in the Smokeview program for analysis of the smoke and heat behavior of tunnel fire.

In this study, FDS is applied to simulate the smoke flow in the tunnel located in Macau. The main objectives of this paper are listed below:

- ✧ Build an accurate tunnel model based on the existing tunnel in Macau - Tunel do Monte da Guia, hereafter called TMG tunnel, with the FDS;
- ✧ Analysis of smoke flow and determine the critical velocity with the tunnel arranged in a horizontal position;
- ✧ Compare the critical velocity obtained from the tunnel models in the horizontal position and in an inclination position;

## Description of Tunnel Model

In Macau peninsula, see Figure 1, Tunel do Monte da Guia (TMG tunnel) has been built under the Guia Hill since 1990 and the longitudinal ventilation system has operated for than 28 years. TMG tunnel is built to connect the areas of central residential and outer harbour. Usually, the passenger cars and the medium-sized vans pass through the tunnel. The traffic volume is high daily, especially, during the rush hours. Table 1 lists the geometry of the tunnel.

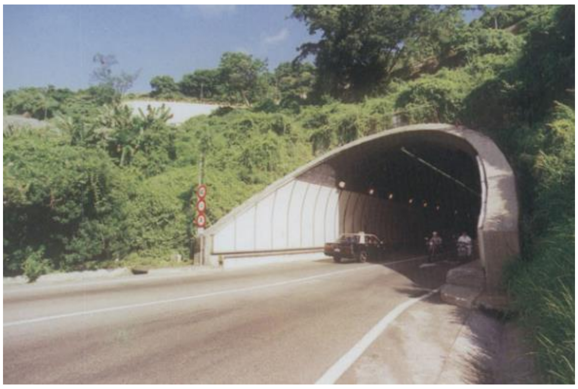


**Figure 1. Tunel do Monte da Guia (TMG Tunnel)**

**Table 1. Parameters of TMG Tunnel**

| Parameters | Description |
|---|---|
| No. of lane and direction | Two lanes, bi-directional |
| Dimension | 285m (L) x 10.5m (W) x 7.2m (H) |
| Height-to-width aspect ratio | 0.69 |
| Tilt angle | 2.45 ˚ |

Figure 2 shows the TMG Tunnel model developed for the FDS simulation. Total length of the TMG Tunnel model is 285 m. In the model, a cubic fire source is arranged at 60 meters after the tunnel inlet and the constant heat release rate (HRR) is set as 14.8MW which is equal to a van fire [11]. Only the top surface of the cube is set as a 'fire' surface. As seen in the figure, seven horizontal thermocouples are set 0.4 m under the ceiling along the downstream direction with a 20 m spacing. To measure the vertical temperature from the ground to the ceiling, eleven vertical thermocouples, with 0.5m spacing vertically, are set at 60 meters downstream from center of fire source (see Figure 3). All the locations of the horizontal and vertical temperature sensors and the fire source of the full scale model is referred to [3].

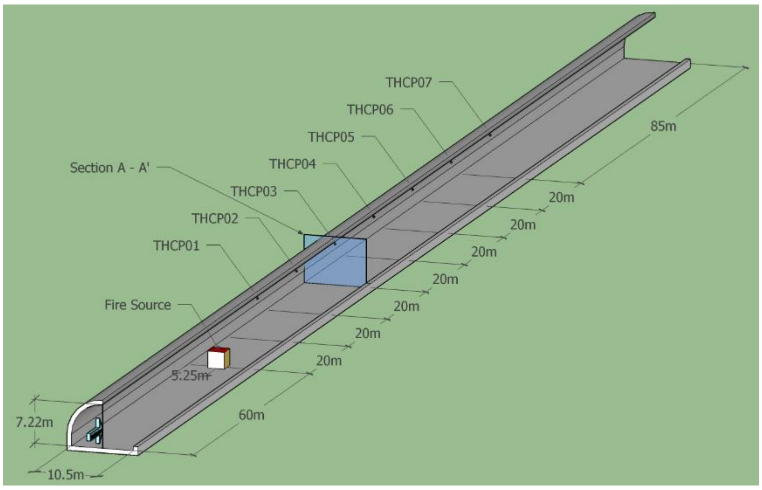



**Figure 2. TMG Tunnel Simulation Model**

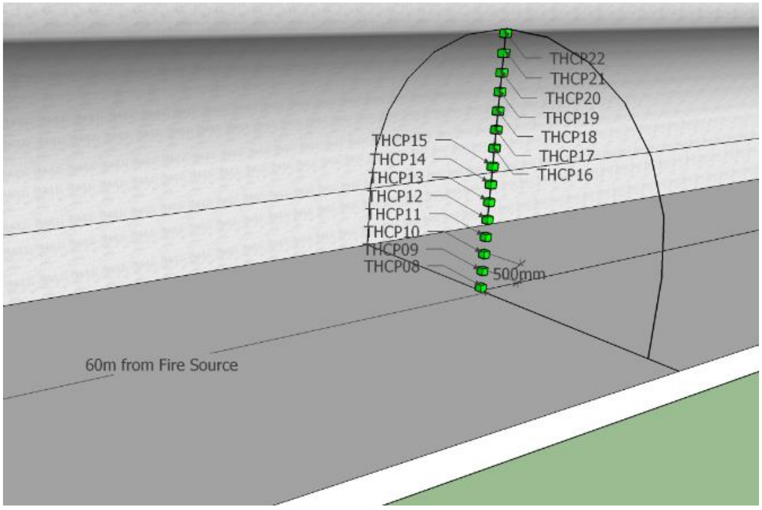



**Figure 3. Vertical temperature sensors arranged in the model (Section A-A')**

In this study, the electromechanical facilities such as the jet fans are neglected. The ventilation flow is directed obtained from the tunnel inlet. In Table 2, it shows the initial and boundary conditions of the model used in FDS. After a sensitivity analysis of mesh size, the mesh size of 0.4 meters is determined. The total number of meshes of the model is 411,800 and the total simulation time is set as 200 seconds.

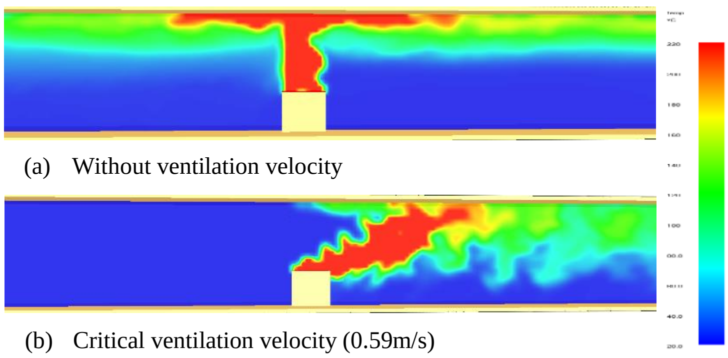
**Table 2. Initial and Boundary Conditions of FDS Model**

| **Initial Conditions** | |
|---|---|
| Ambient Temperature ($T_0$) | 20 ˚C |
| Pressure ($P_0$) | 101.325 kPa (1atm) |
| Tunnel Wall | Inert wall, 0.1m in thickness |

| | |
|---|---|
| **Fire Source** | |
| Heat Release Rate | 14.8 MW |
| Dimension | 2.8m (L) x 2.8m (W) x 2.8m (H) |
| HRRPUA | 1888 kW/m$^2$ |
| Location | Refer to Figure 2 |
| Burning material | Polyurethane |
| Burning Time | Fire happens at t = 0s;<br>Burning time = Total Simulation time |
| **Boundary Condition** | |
| Inlet | $T_{inlet} = T_0$;<br>$P_{inlet}$ is varied due to ventilation velocity; |
| Outlet | $T_{outlet} = T_0$;<br>$P_{outlet} = P_0$; |
| Wall and Floor | $T_W = T_F = T_0$ |
| Ventilation Velocity | $u = u_{critical}$; v = 0; w = 0; |

## Results and Discussion

In order to verify the setting of FDS simulation, a reduced scale tunnel model (1040cm (L) x 50cm (W) x 33.3cm (H)) with a height-to-width aspect ratio of 0.67, which is similar to the ratio of 0.69 of the current TMG tunnel simulation is established with the reference of Lee and Ryou [3]. For the reduced scale model, the fire source is reduced from 14.8 MW (for TMG full scale model) to 8.27 kW with the reference to the scaling law [12]. The location of the horizontal and vertical temperature sensors and the fire source of the reduced model is also referred to [3]. After the simulation, as shown in Figure 4, the simulated critical velocity is of 0.59 m/s is almost matched with the experimental critical velocity of 0.58 m/s. Therefore, the same FDS settings for the reduced scale model is applied to the full scale TMG tunnel.

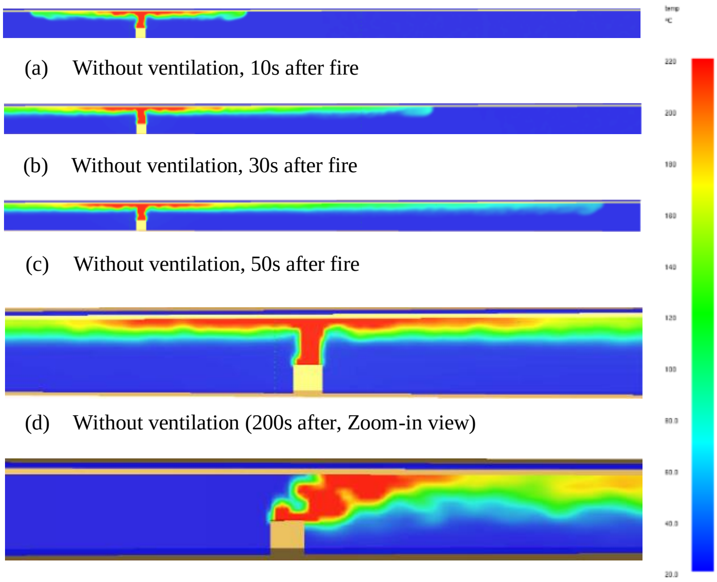


(a) Without ventilation velocity

(b) Critical ventilation velocity (0.59m/s)

**Figure 4. Simulation of the reduced scale tunnel**

For the full scale TMG tunnel, a horizontal case is executed first because it is used as a base case to analyze the effect of slope on the smoke flow and critical velocity in the tunnel. Figure 5 shows the temperature contour plot for the TMG tunnel arranged in horizontal position. From the figure (a) – (d), it can be observed that the hot gases or smoke rise from the fire source to the ceiling. After that, the smoke layer becomes thicker and spread to the both ends of the tunnel. To avoid the back-layering phenomena, as shown in the figure (e), the critical ventilation velocity of 3 m/s can force all the gases to the downstream direction and solve the back-layering problem.



(a) Without ventilation, 10s after fire

(b) Without ventilation, 30s after fire

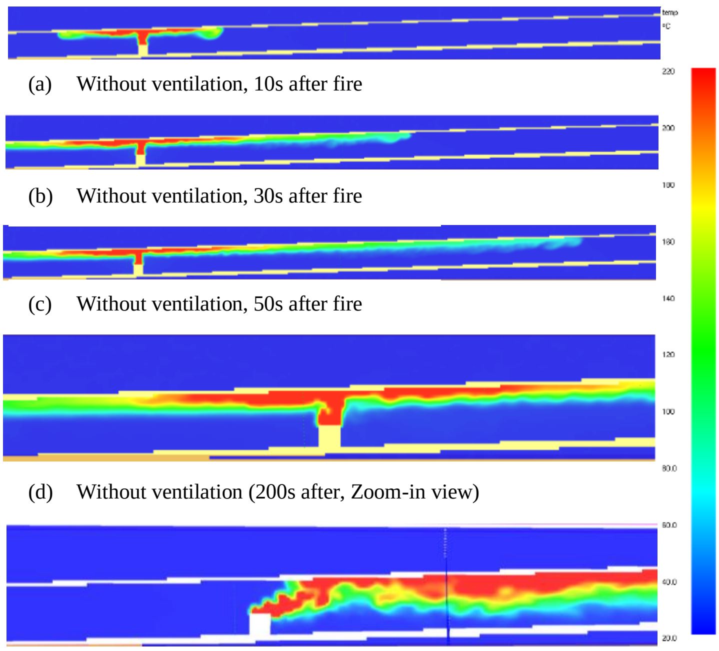
(c) Without ventilation, 50s after fire

(d) Without ventilation (200s after, Zoom-in view)

(e) With ventilation (200s after, $V_{critical}$ = 3m/s)

**Figure 5. Temperature contour plot for the horizontal TMG Tunnel**

Figure 6 shows the temperature contour plot for the TMG tunnel with a upward tilt angle of 2.45°. From the figure (a) – (d), it can be observed that the hot gases or smoke rise from the fire source to the ceiling. After that, the smoke spread to the both ends of the tunnel. However, it seems smoke is faster to spread to the downstream due to a buoyant effect. To avoid the back-layering phenomena, as shown in the figure (e), the critical ventilation velocity of 2.9 m/s can force all the gases to the downstream direction. When compared with a horizontal tunnel, less critical ventilation velocity for inclined tunnel is sufficient to solve the back-layering problem.



(a) Without ventilation, 10s after fire

(b) Without ventilation, 30s after fire

(c) Without ventilation, 50s after fire

(d) Without ventilation (200s after, Zoom-in view)

(e) With ventilation (200s after, $V_{critical}$ = 2.9m/s)

**Figure 6. Temperature Contour Plot of the TMG Tunnel (with a tilt angle of 2.45 °)**

For both of the horizontal and inclined TMG tunnel models, the critical velocities calculated by the FDS simulation are also compared with those predicted by the correlations, Eqs. (1-9) in Table 3. From the table, it is observed that the critical velocities calculated by Wu and Bakar [2] and Lee and Ryou [3] are equal to or larger than 2.5 m/s. Those values are more comparable to the values obtained from the current simulation. As the curved ceiling is used in the current simulation, it is reasonable that there is a discrepancy between the simulation critical velocity values and the values predicted by those correlations. However, the critical velocity is likely under estimated by NFPA 502 [7]. That is only 2 m/s required for the TMG tunnel. As a safety concern, the higher ventilation velocities calculated by the simulation or the correlations [2-3] are recommended for the practical smoke management design.

**Table 3: Comparison of Critical Velocity of the Simulation and Calculated by Correlations**

| Model | FDS Critical Velocity (m/s) | Critical Velocity Calculated by the Correlations (m/s) | | |
|---|---|---|---|---|
| | | Wu and Bakar [2] | Lee and Ryou [3] | NFPA 502 [7] |
| Horizontal TMG | 3 | 2.5 (19% deviation) | 2.7 (13% deviation) | 2.0 (50% deviation) |
| Inclined TMG | 2.9 | 2.5 (15% deviation) | 2.7 (9% deviation) | 2.0 (45% deviation) |

Figure  compares the temperature measured from the eleven vertical thermocouples placed at 60 meters downstream from center of fire source for the horizontal tunnel and the inclined tunnel without ventilation velocity. From the figure, the hot gas layer is maintained to the height of around 3 meters away from the ground regardless of the horizontal or inclined tunnel is observed. It is also observed for both cases that the temperature trends are basically the same until the height over 6 meters. Higher temperature is observed in the inclined tunnel. Perhaps, more hot gases or smoke moves to the downstream due to the buoyant effect caused by the tunnel inclination to the fire source.

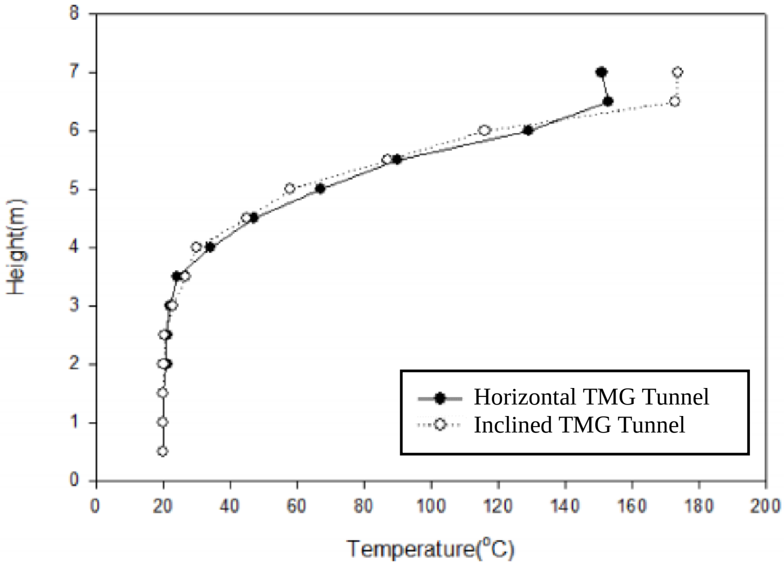



**Figure 7. Vertical Temperature profiles of horizontal and inclined TMG Tunnel (without ventilation velocity)**

Figure  compares the temperature measured from the seven horizontal thermocouples placed under the ceiling for the horizontal tunnel and the inclined tunnel. From the figure, it is observed for both cases that the first thermocouple is much higher because the thermocouple is closer to the fire source. Regardless of the horizontal or sloped tunnel, the temperature curve trend goes downward because the smoke temperature gradually decreases when the smoke moves downstream along the tunnel. For the inclined tunnel, the temperature is higher than that of the horizontal tunnel. It can be explained that more hot smoke is accumulated at the ceiling of the inclined tunnel than the horizontal one.

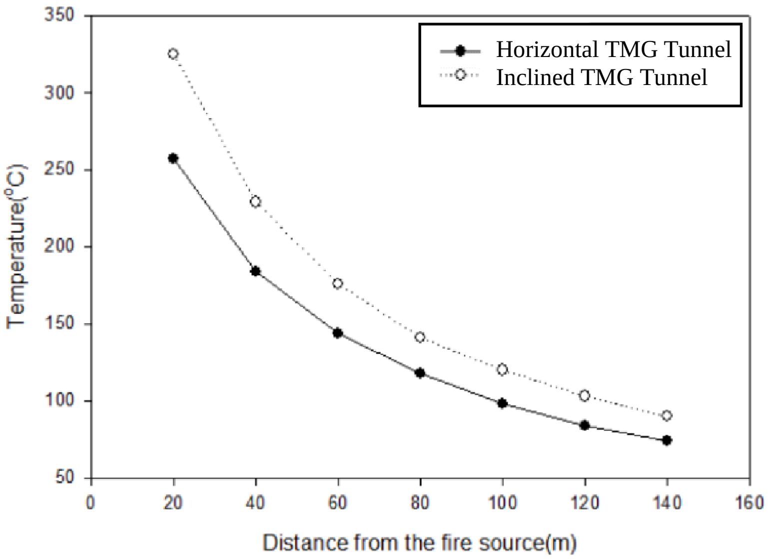



**Figure 8. Horizontal Temperature profiles of horizontal and inclined TMG Tunnel Models**

## Conclusions

In this study, the horizontal and inclined TMG tunnel models simulated by FDS software. From the results, the critical velocity of 2.9 m/s is obtained for the practical TMG tunnel with a tilt angle of 2.45°. That critical velocity is basically matched with the published correlations. From the temperature results, the the hot gas layer temperature in the inclined tunnel is higher that of the horizontal tunnel.

The critical velocity obtained from this study can be used as a reference to verified whether the existing ventilation system has sufficient velocity to ensure the life and fire safety in the practical TMG tunnel in Macau.


## Acknowledgement

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