Theory and Practice of Science and Technology
2025, VOL. 6, NO. 11, 66-75
DOI: 10.47297/taposatWSP2633-456913.20250611

Analysis of the Impact of Fire Source Location on Visibility in T-shaped Utility Tunnels Under Different Ventilation Schemes

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ABSTRACT
T-shaped utility tunnels are long, narrow confined spaces with intersections. During a fire, smoke can propagate through multiple pathways, and ventilation schemes can influence smoke flow direction, thereby increasing fire accident risks. To investigate how changes in fire source location affect visibility in T-shaped utility tunnels under different ventilation schemes, a model was established using Pyrosim software. The result show that under ventilation scheme *a*, fire source position 1 has the greatest impact on visibility; under ventilation schemes *b* and *c*, fire source position 4 has the greatest impact on visibility; under ventilation scheme *d*, fire source position 3 has the greatest impact on visibility.

KEYWORDS
Ventilation method; Fire source location; T-shaped utility tunnel; Cable compartment fire; Visibility

1 Introduction

Underground utility tunnels, while enabling the centralized installation of multiple municipal pipelines and facilitating maintenance management, also present new challenges for fire prevention and control. Cable compartments—sections where high-voltage and communication cables are concentrated—are particularly prone to fires caused by equipment failures, short circuits, or aging insulation layers [1]. Statistics show that fires in cable compartments account for more than 70% of all utility tunnel fires. Once a fire occurs, smoke rapidly accumulates within the narrow, enclosed tunnel space, causing temperatures to rise and toxic gas concentrations to increase. This dramatically reduces visibility and poses severe challenges to personnel evacuation and rescue operations.

Visibility is one of the key parameters for assessing fire hazards, as it directly affects whether individuals can identify evacuation routes and emergency exits. In underground utility tunnels, limited lighting conditions combined with suspended carbon particles and water vapor lead to significant light scattering and absorption, resulting in a rapid decline in visibility [2]. When visibility drops below 2 meters, personnel have difficulty recognizing the path ahead, substantially slowing evacuation and increasing the risk of poisoning or heat injury. Furthermore, visibility variation reflects the distribution and movement of smoke, serving as a critical indicator for evaluating smoke exhaust system performance and overall fire control effectiveness [3]. Therefore, investigating how fire source location affects visibility not only helps elucidate smoke propagation mechanisms but also provides quantitative guidance for emergency lighting layout, monitoring point placement, and evacuation strategy design.

To date, scholars have conducted extensive research on smoke behavior in enclosed conduits, including utility tunnels. Zhao et al. [4] constructed a rectangular tunnel model to analyze how fire source location and longitudinal ventilation velocity influence smoke temperature distribution and backflow length. Liu et al. [5] used FDS+EVAC numerical simulations to examine smoke control strategies and lateral passage spacing. Zisis et al. [6] analyzed the effect of fire source power on smoke flow in rectangular ducts. Lei et al. [7] investigated smoke stagnation, backflow length, and temperature distribution at junction zones in cross-shaped tunnels. Chen et al. [8] studied smoke control and critical wind speed in intersecting passages, offering insights into smoke induction and stagnation control in cross-shaped utility tunnels. Liang et al. [9] quantified smoke backflow and retention length under multiple fire conditions through both numerical simulations and experiments, showing stronger smoke retention and longer clearance times at cross-intersection nodes. Guo et al. [10] developed a CFD model to explore smoke diffusion in L-shaped tunnels with small curvature radii, finding that curvature radius and ventilation velocity significantly influence the spatiotemporal evolution of smoke. Shi et al. [11] analyzed how smoke outlet location and exhaust volume affect control effectiveness in L-shaped utility tunnels, comparing visibility, temperature, and smoke exhaust efficiency.

However, research on smoke propagation in T-shaped enclosed passages remains limited, with few systematic studies addressing the influence of fire source location on visibility. This study aims to address this gap by establishing a fire model of a T-shaped utility tunnel using FDS. Under different ventilation conditions, fire sources are placed at four positions: the left side of the main corridor, the intersection, the right side of the main corridor, and the branch corridor. The study analyzes visibility patterns associated with various fire source locations, providing a reference for fire protection

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design and rescue operations in T-shaped tunnel junctions.

2 Simulation Approach

2.1 Model Setup

This study focuses on a T-shaped section of the cable chamber within an underground utility tunnel located in the High-Tech Zone of Hefei City, Anhui Province, China. A full-scale (1:1) model of the cable chamber was developed using FDS software. The internal dimensions of the tunnel are 2.8 m in width and 3.4 m in height, with concrete as the construction material. On the left side, three layers of 35 kV cables and four layers of 110 kV cables are arranged, while the right side contains three layers of 10 kV cables and four layers of 110 kV cables. The vertical spacing between adjacent layers is 0.3 m, and the horizontal spacing is 0.45 m. The bottom layer is positioned 0.5 m above the tunnel floor, as illustrated in Figure 1. The X-axis represents the main corridor, with the left and right portals spaced 200 m apart, whereas the Y-axis denotes the branch corridor, extending 100 m from the intersection. The computational grid size is 0.2 m × 0.2 m × 0.2 m. The domain is divided into two regions along the X- and Y-axes, comprising a total of 357,000 grid cells. A simplified schematic of the tunnel model is presented in Figure 2.

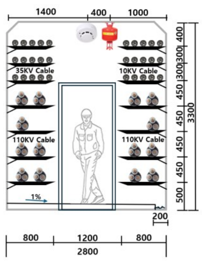

Figure 1 Cable Compartment Layout Model (Unit: mm)

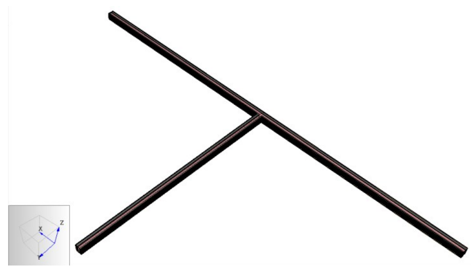

Figure 2 Schematic Diagram of T-shaped Utility Tunnel Model

2.2 Ventilation Methods

According to GB 50838—2015, Technical Specifications for Urban Utility Tunnels, cable compartments within utility tunnels should adopt a ventilation system that combines natural air intake with mechanical exhaust. The airflow velocity at tunnel ventilation outlets should not exceed 5 m/s [12]. In this study, the ventilation system is simplified in the model by representing the air inlets and outlets as ports. The T-shaped utility tunnel is configured under two ventilation modes: "two inlets and one outlet" and "one inlet and two outlets."

Four specific ventilation schemes are defined as follows:

· Scheme *a*: Air enters through the left and right ports and exits through the branch port.
· Scheme *b*: Air enters through the left and branch ports and exits through the right port.
· Scheme *c*: Air enters through the branch port and is exhausted through both the left and right ports.
· Scheme *d*: Air enters through the right port and is exhausted through both the left and branch ports.

2.3 Fire Source Configuration

Four fire source locations are defined in the model, denoted as Fire 1, Fire 2, Fire 3, and Fire 4 (Figure 3).

Each fire source is positioned on the bottom-layer cable at a height of 0.5 m above the floor level, with a surface area of 1 m × 1 m.

The center coordinates of the four fire sources are as follows:

· Fire 1: (−50, 1.4)
· Fire 2: (0, 1.4)
· Fire 3: (50, 1.4)
· Fire 4: (0, 52.8)

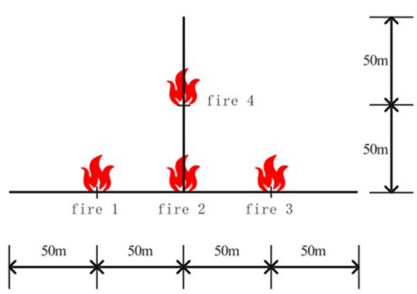

Figure 3 Fire Source Location Layout Diagram

2.4 Visibility Measurement Point Setup

According to the typical human eye height [13], visibility measurement points are positioned 1.6 m above the floor along the centerline of the tunnel width. These points are spaced at 5 m intervals along the tunnel's longitudinal axis. In addition, visibility slices are defined at X = 0 m and Y = 1.4 m within the tunnel.

2.5 Simulation Scenario Design

Fourteen simulation scenarios were designed based on the utility tunnel configuration, fire source location, and ventilation scheme, as summarized in Table 1.

Table 1 Simulated Operating Conditions Table

Operating condition	Ventilation method	Ventilation scheme	Location of the fire source	Airflow velocity at the outlet
1			1	
2		*a*	2	
3			4	
4	two inlets and one outlet		1	3 m/s
5		*b*	2	
6			3	
7			4	
8			1	
9		*c*	2	
10			4	
11	one inlet and two outlets		1	1.5 m/s
12		*d*	2	
13			3	
14			4	

3 Analysis of Simulation Results

3.1 Effect of Fire Source Location on Visibility under Ventilation Scheme *a*

Figure 4 illustrates the variation of visibility within the utility tunnel over time when the fire source is located at Position 1. Along the main corridor, visibility begins to decline noticeably at the −40 m position around 50 s after ignition. At 100 s, 150 s, and 200 s, the visibility reduction initiates near −50 m, while at 250 s and 300 s, it extends further to −60 m and −65 m, respectively. During the first 50 s, only a small amount of smoke generated at the fire source was carried forward by the airflow entering from the left inlet, causing visibility to drop slightly near −40 m. Between 100 s and 200 s, as the fire stabilized and smoke production increased, visibility decreased significantly near the fire source. By 250 s, smoke backflow became apparent, shifting the visibility degradation region toward the left inlet.

In the branch corridor, visibility remained largely unchanged during the first 50 s, as the weak smoke flow did not penetrate the branch duct. As combustion progressed, visibility in the branch corridor decreased rapidly. However, during the first 150 s, the smoke layer remained relatively thin, leading to only a minor visibility reduction near the branch outlet. After 150 s, the smoke flow stabilized, and the outlet maintained a steady exhaust, resulting in minimal further visibility variation in the branch direction.

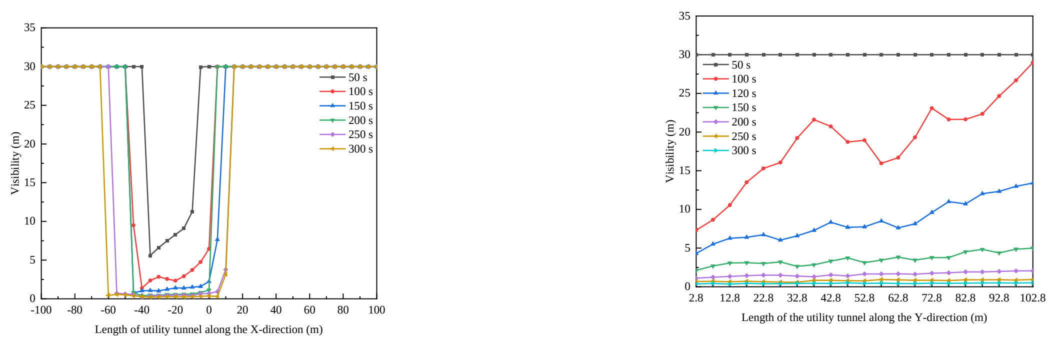

Figure 4 Visibility Changes Under Operating Condition 1

Figure 5 illustrates the variation in visibility within the utility tunnel when the fire source is located at Position 2, i.e., at the intersection. Along the main corridor, visibility fluctuates within a 10-meter range around the fire source. During the first 50 s, visibility remains at normal levels. At 100 s, 150 s, 200 s, 250 s, and 300 s, the visibility at the intersection decreases to 3.7 m, 2.6 m, 1.4 m, 1.1 m, and 0.6 m, respectively.

At the intersection, visibility drops rapidly within the first 50 s after ignition, reaching a minimum of 4.9 m at 17.8 m along the branch corridor. Comparing visibility at different time intervals along the branch shows that the point of minimum visibility gradually shifts forward—from 17.8 m at 50 s to 7.8 m at 100 s, and subsequently stabilizes near 2.8 m.

As time progresses, smoke accumulation near the fire source becomes increasingly dense, which slows its forward spread and results in a downward settling phenomenon of the smoke layer.

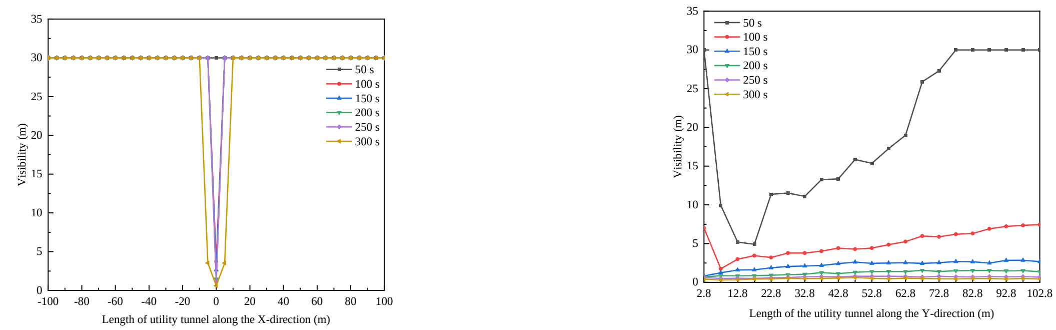

Figure 5 Visibility Changes Under Operating Condition 2

Figure 6 illustrates the variation in visibility within the utility tunnel when the fire source is located at Position 4. In this scenario, the fire source is relatively distant from the main corridor, and the exhaust outlet is situated at the end of the branch corridor. Within the first 300 s, no smoke backflow occurs, resulting in minimal impact on visibility along the main corridor. Consequently, visibility in this section remains close to normal environmental levels.

Along the branch corridor, the point at which visibility begins to decline shifts progressively closer to the fire source as combustion time increases—occurring at 82.8 m at 50 s, 57.8 m at both 100 s and 150 s, and 52.8 m at 200 s, 250 s, and 300 s. During the first 150 s, smoke primarily moves toward the terminal port under the influence of the exhaust fan. However, after 150 s, increasing smoke production exceeds the exhaust system ' s capacity, leading to accumulation near the port. As a result, visibility begins to decrease around the fire source.

Overall, the zone affected by visibility reduction extends approximately 50 m to the right of the fire source.

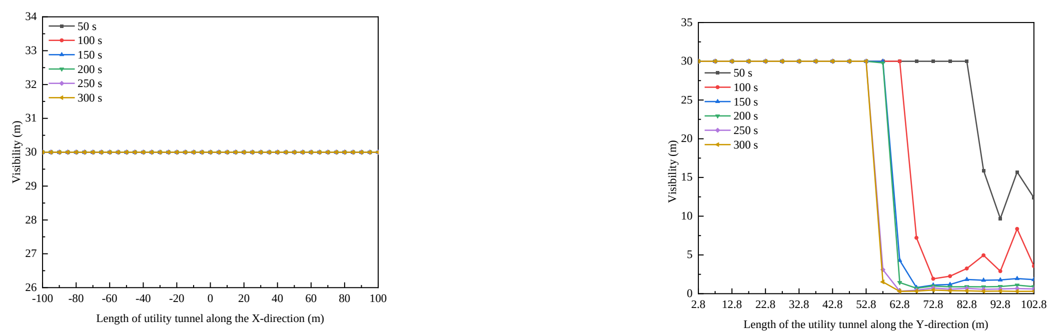

Figure 6 Visibility Changes Under Operating Condition 3

A comparison of visibility variations at different fire source locations reveals distinct patterns. When the fire source is located at Position 4, it exerts no influence on visibility along the main corridor, while its impact on the branch corridor extends approximately 50 m. When the fire source is at Position 2, visibility deterioration along the main corridor is confined to a 10 m range, whereas the entire branch corridor experiences a significant reduction in visibility. When the fire source is at Position 1, the visibility impact extends 50 m along the main corridor but is less pronounced in the branch corridor compared with Position 2.

Therefore, under Ventilation Scheme *a*, the overall visibility conditions are worst when the fire source is located at Position 1.

3.2 Effect of Fire Source Location on Visibility under Ventilation Scheme *b*

Figure 7 illustrates the visibility variation within the utility tunnel when the fire source is located at Position 1. Along the main corridor, visibility near the fire source remains largely unaffected during the first 100 s, as smoke has not yet accumulated at the source. Instead, smoke is carried forward by airflow from the left inlet, causing visibility to begin decreasing on the right side of the fire source.

Between 100 s and 200 s, smoke gradually accumulates at the fire source, leading to a decline in visibility at that location. From 200 s to 300 s, the smoke layer thickens significantly. While part of the smoke continues to move forward, another portion reverses direction, resulting in reduced visibility on the left side of the fire source.

Along the main corridor, visibility changes at key time points are as follows:

· 100 s: visibility at 5 m reaches 25.5 m

· 150 s: visibility at 5 m decreases to 2.89 m

· 200 s: visibility at the intersection decreases to 1.5 m

· 250 s: visibility at the intersection decreases to 1.1 m

· 300 s: visibility at the intersection decreases to 0.57 m

The location and magnitude of visibility reduction are closely related to smoke density and movement. Early in the fire, with lower smoke accumulation and faster flow, visibility reduction is more pronounced near the right side of the intersection. As smoke accumulates and flow slows, visibility reduction shifts toward the intersection itself, resulting in lower values. For the branch corridor, when the fire source is at Position 1, visibility impact is limited to approximately 10 m. At 300 s, visibility at the intersection reaches a minimum of 0.68 m, before gradually returning to normal environmental levels at 12.8 m.

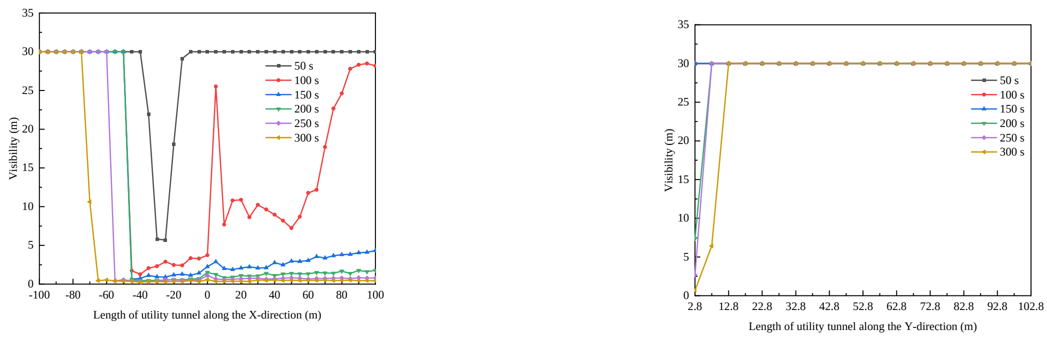

Figure 7 Visibility Changes Under Operating Condition 4

Figure 8 illustrates the variation in visibility within the utility tunnel when the fire source is located at Position 2, i.e., at the intersection of the main and branch corridors. Based on the visibility data, smoke does not flow back toward the upwind direction within the first 300 s. Visibility along both the main and branch corridors to the left of the fire source remains within normal levels, with the impact confined primarily to the downwind direction.

In the downwind direction, visibility fluctuates noticeably during the first 100 s, exhibiting abrupt increases and decreases. This behavior is primarily due to the transition of the fire from the ignition stage to the development stage, which induces unstable smoke flow. After 100 s, visibility stabilizes at low levels, with an average value of approximately 0.8 m.

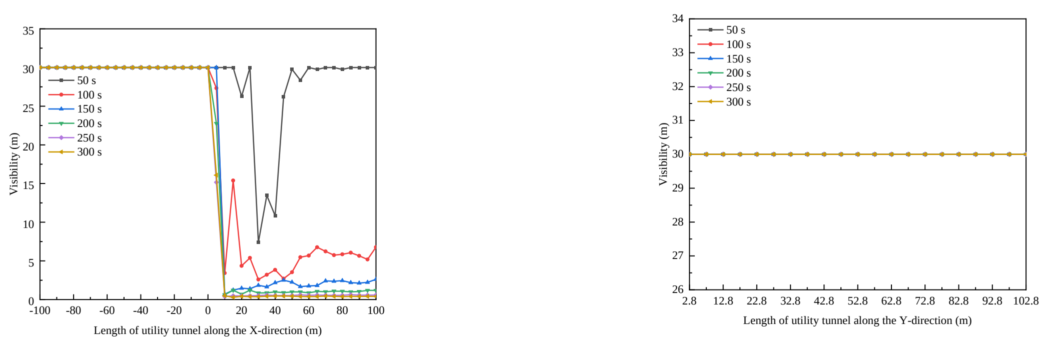

Figure 8 Visibility Changes in Operating Condition 5

Figure 9 illustrates the visibility variation within the utility tunnel when the fire source is located at Position 3. In this scenario, the fire source is situated relatively close to the right-end exhaust vent. Smoke generated by the fire affects visibility only within approximately 50 m to the right of the fire source. The fire does not spread toward the left side of the source or into the branch corridor of the utility tunnel.

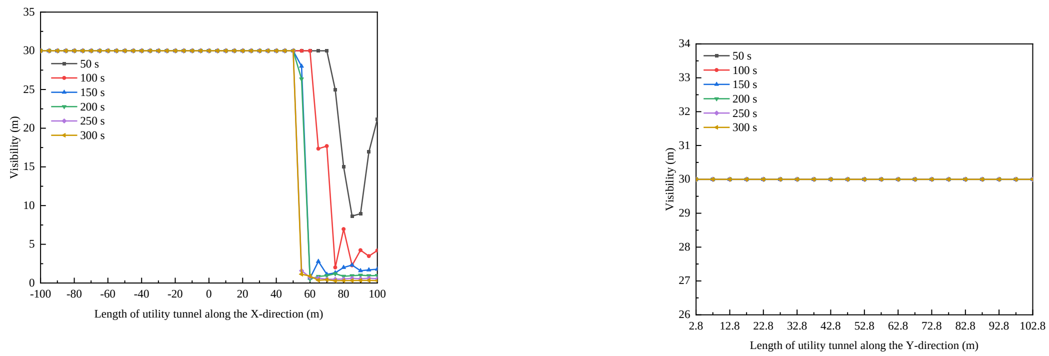

Figure 9 Visibility Changes in Operating Condition 6

Figure 10 illustrates the variation in visibility within the utility tunnel when the fire source is located at Position 4. Along the main corridor, visibility remains largely unchanged during the first 50 s. Between 50 s and 100 s, visibility decreases rapidly, then partially recovers before declining sharply again, finally returning gradually to ambient levels at 75 m. After 100 s, visibility exhibits a similar pattern to that observed between 50 s and 100 s, while near the right inlet, visibility gradually stabilizes at a steady level. A comparison of the positions and heights of visibility recovery points across different time intervals indicates that recovery points progressively shift toward the upstream left, and the height of these points negatively correlates with fire development time. During the early stage of the fire, lower smoke production limits rapid smoke movement toward the tunnel intersection. In the later stage, increased smoke production exceeds the dilution capacity of the makeup airflow. Along the branch corridor, visibility upstream of the fire source remains at normal levels until 250 s. At this point, smoke flow reverses, causing visibility to drop to 0.61 m. Downstream of the fire source, visibility initially decreases but recovers within 50 s, primarily because early smoke production is low, limiting light obstruction to a small area without spreading to the intersection. As smoke production intensifies and makeup airflow moves toward the intersection, visibility decreases further, dropping below 0.5 m.

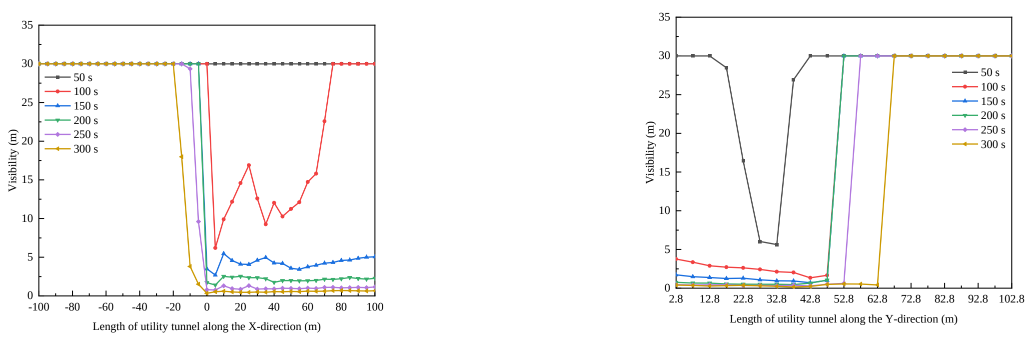

Figure 10 Visibility Changes in Operating Condition 7

A comparison of visibility variations at different fire source locations reveals the following patterns. Fire sources at Positions 2 and 3 have no significant impact on visibility along the branch corridor, whereas the fire source at Position 1 reduces visibility along the branch corridor within approximately 10 m.

All fire sources at Positions 1, 2, and 3 are located along the main corridor, with their impact on main corridor visibility decreasing in the order: Position 1 > Position 2 > Position 3. The visibility reduction caused by the fire source at Position 1 extends up to 175 m along the main corridor. In comparison, a fire source at Position 4 affects visibility within 120 m along the main corridor and 65 m along the branch corridor. Therefore, under Ventilation Scheme *b*, overall visibility conditions are worst when the fire source is located at Position 4.

3.3 Effect of Fire Source Location on Visibility under Ventilation Scheme *c*

Figure 11 illustrates the visibility variation within the utility tunnel when the fire source is located at Position 1. At 300 s after ignition, smoke has not yet reached the branch corridor, so visibility along the branch remains unaffected, indicating that the branch corridor is relatively safer than the main corridor.

During the first 200 s, smoke primarily moves toward the left-end inlet. This behavior is influenced by two factors: the smoke production rate, which varies with the duration of combustion, and the airflow interaction between makeup air entering from the branch port and exhaust air at the right port. After 200 s, part of the smoke continues toward the left port, while another portion begins to move toward the right port.

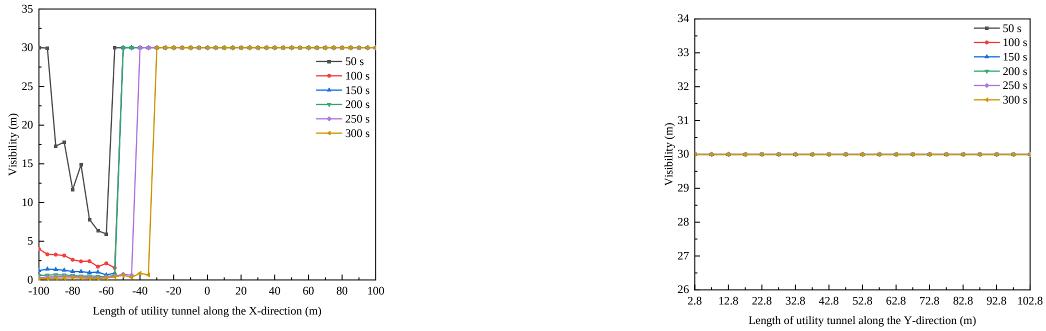

Figure 11 Visibility Changes Under Operating Condition 8

Figure 12 illustrates the variation in visibility within the utility tunnel when the fire source is located at Position 2. With the fire source situated at the intersection, approximately equidistant from the left and right exhaust vents, smoke affects visibility along the main corridor in a relatively balanced manner. During the first 50 s, smoke production is low, and visibility remains largely unaffected. After 50 s, visibility decreases rapidly on both sides of the fire source before gradually recovering. The magnitude of visibility reduction increases with fire duration, whereas the extent of recovery decreases over time. This behavior arises because prolonged burning produces more smoke, leading to progressively greater visibility loss. At a constant outlet air velocity, the smoke extraction capacity is limited by the smoke production rate. Consequently, longer burning times generate more smoke, making extraction less effective and resulting in lower recovery levels. Within the first 300 s, smoke does not form backflow into the branch corridor, so visibility along the branch corridor remains relatively unaffected, indicating that the branch corridor is comparatively safer.

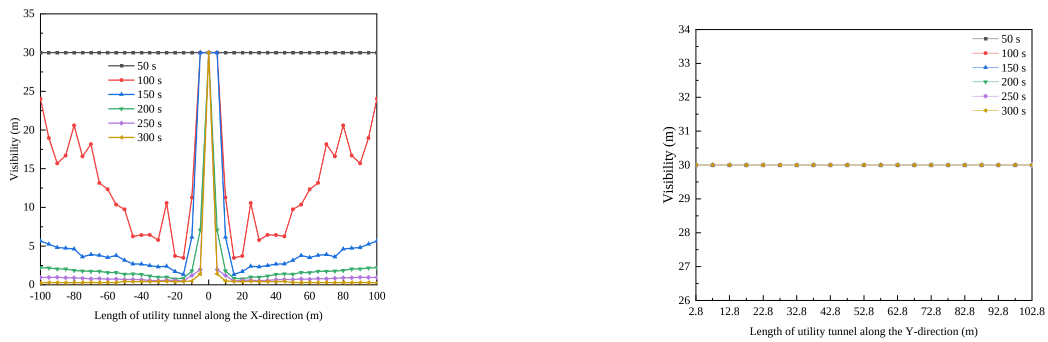

Figure 12 Visibility Changes in Operating Condition 9

Figure 13 illustrates the visibility variation within the utility tunnel when the fire source is located at Position 4. The fire source is situated along the branch corridor on the Y-axis, similar to Position 2, resulting in approximately symmetrical effects on visibility along the main corridor. During the first 50 s, smoke production is sparse and moves slowly, causing no significant reduction in visibility along the main corridor. By 100 s, visibility along the main corridor decreases below 10 m over an 80 m span, returning to normal only near the 15 m port. At 150 s, visibility along the main corridor generally remains below 6 m, and after 200 s, the average visibility drops below 1 m.

Regarding the branch corridor, smoke generated within the first 300 s moves toward the main corridor through the intersection without forming backflow. As combustion progresses, the forward movement of smoke gradually slows. The location where visibility begins to decrease shifts toward the central port of the duct: 42.8 m at 50 s, 47.8 m at both 100 s and 150 s, and 52.8 m after 150 s.

Comparing visibility at the duct intersection over time indicates that smoke has not reached the intersection within the first 50 s. After 50 s, smoke accumulates at the intersection, reducing visibility below 5 m. This behavior occurs because the exhaust fans at the left and right main corridor ports expel air, while the branch ports near the fire source promptly supply makeup air. Consequently, smoke spreads through the intersection toward the main corridor, accumulating at the junction.

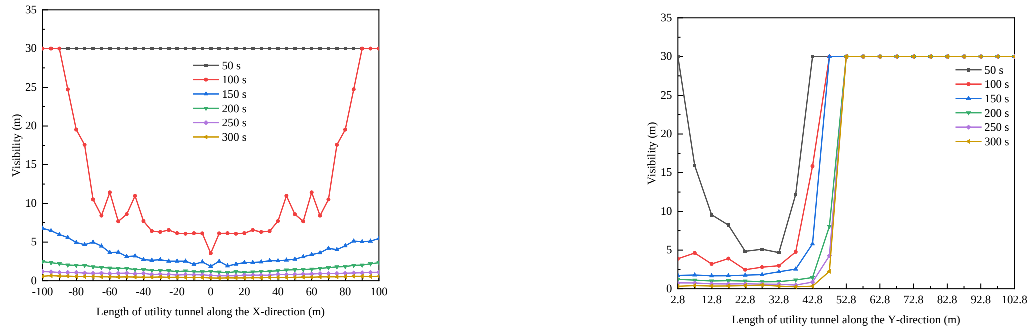

Figure 13 Visibility Changes in Operating Condition 10

Comparison of visibility between fire source Positions 1 and 2: Along the main corridor, the closer the fire source is to the intersection, the greater its impact on visibility. When the fire source is at Position 1, the affected visibility range along the main corridor is 70 m, whereas at Position 2, it extends to 200 m. Under this ventilation scheme, a fire source located on the main corridor has no significant effect on visibility along the branch corridor.

Comparison of visibility between fire source Positions 2 and 4: From the perspective of the main corridor, the farther the fire source is from the intersection, the wider the affected visibility range along both the main and branch corridors. A fire source at Position 4 reduces visibility along the main corridor for 200 m and along the branch corridor for 50 m.

Therefore, under Ventilation Scheme *c*, overall visibility is worst when the fire source is located at Position 4.

3.4 Effect of Fire Source Location on Visibility under Ventilation Scheme *d*

Figure 14 illustrates the visibility variation within the utility tunnel when the fire source is located at Position 1. Smoke does not spread toward the branch corridor, leaving visibility along the branch largely unaffected. Visibility along the main corridor fluctuates between -25 m and -100 m. At 50 s, visibility begins to decrease from -55 m, reaching 5.83 m. At 100 s, 150 s, and 200 s, visibility declines from -50 m to 3.07 m, 1.57 m, and 0.75 m, respectively. At 250 s, visibility decreases from -40 m to 0.7 m, and at 300 s, it decreases from -25 m to 9.8 m. The locations where visibility begins to decline are closely related to smoke production and the positions of ventilation outlets.

During the first 200 s, smoke primarily moves toward the left outlet without forming backflow. This occurs because smoke production is low during the initial fire phase, and inflow at the right port counterbalances outflow at the branch port, creating air mixing. After 200 s, the mixed airflow moves toward the branch port, carrying smoke and generating backflow. At 250 s, the smoke backflow length reaches 10 m, extending to 25 m at 300 s.

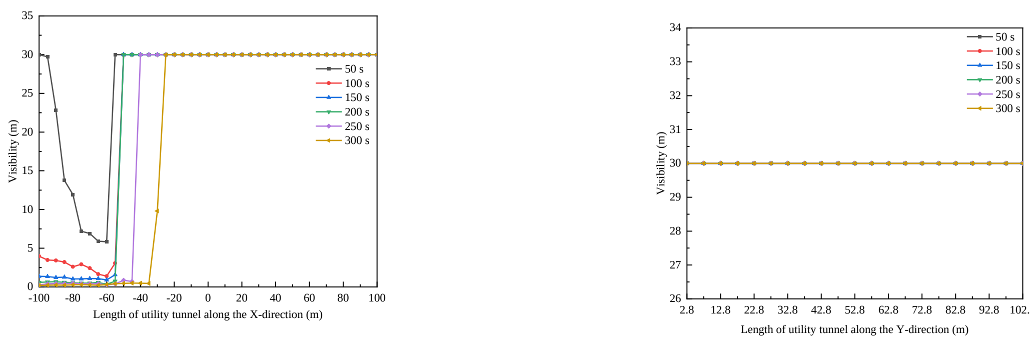

Figure 14 Visibility Changes in Operating Condition 11

Figure 15 illustrates the variation in visibility within the utility tunnel when the fire source is located at Position 2. The fire source, situated at the intersection of the main and branch corridors, affects visibility in both directions for approximately 100 m. Due to angular constraints, natural airflow entering the right port directs smoke toward the left port and branch port at different velocities. Consequently, during the first 50 s after ignition, smoke primarily moves toward the left port. As combustion progresses, smoke production intensifies. Part of the smoke continues toward the left port, while another portion moves toward the branch port. Over time, the smoke layer thickens, reducing its forward momentum and causing it to descend earlier. As a result, visibility decreases more rapidly and significantly in both the main and branch corridors, with the onset of visibility reduction occurring earlier and exhibiting greater severity.

Figure 15 Visibility Changes Under Operating Condition 12

Figure 16 illustrates the variation in visibility within the utility tunnel when the fire source is located at Position 3. The fire source, situated closest to the right-end air inlet, affects visibility along the main corridor within a 150 m range. The entire branch corridor is also impacted by smoke intrusion from the fire. Along the main corridor, visibility decline begins on the left side of the fire source center. The generated smoke does not flow back, and visibility near the left-end port gradually recovers. Along the branch corridor, visibility at the intersection decreases significantly: 12.9 m at 50 s, 5.39 m at 100 s, 1.8 m at 150 s, 1.08 m at 200 s, 0.6 m at 250 s, and 0.35 m at 300 s. Visibility improves toward the branch outlet because the 90-degree intersection with the main corridor creates airflow resistance, slowing the smoke velocity and causing accumulation at the intersection. At the outlet port farther from the intersection, exhaust fans enhance airflow, diluting smoke concentration and restoring visibility.

Figure 16 Visibility Changes in Operating Condition 13

Figure 17 illustrates the visibility changes within the utility tunnel when the fire source is located at Position 4. The fire source is situated closest to the branch outlet. During the first 300 s after ignition, it poses no threat to visibility along the main corridor, affecting only the branch corridor. Comparing visibility at different time points along the branch reveals that both the onset of visibility decline and the location of minimum visibility shift progressively toward the intersection. By 250 s, this point has moved to the left of the fire source, and the minimum visibility continues to decrease as the fire develops further. This phenomenon is primarily influenced by smoke production and airflow velocity. Initially, smoke production is low, but it increases significantly once the fire reaches the fully developed combustion stage. Additionally, the intersecting angle between the main and branch corridors causes a time delay for airflow from the main corridor to enter the branch corridor. Consequently, during the early stage, smoke is primarily discharged through the branch outlet. Later, the left outlet contributes to carrying smoke backflow, although it does not yet affect the main corridor.

Comparing visibility at fire source positions 1, 2, and 3 reveals that along the main corridor, the closer the fire source is

Figure 17 Visibility Changes in Operating Condition 14

to the right-end air intake, the wider the affected visibility range. Specifically, when the fire source is at Position 1, the affected visibility range along the main corridor is 75 m; at Position 2, it increases to 105 m; and at Position 3, it extends to 150 m. From the branch corridor perspective, proximity to the right-end air intake also correlates with a wider visibility impact and longer duration of low visibility. At Position 1, visibility along the branch corridor remains unaffected (0 m). At Positions 2 and 3, the affected visibility range toward the branch corridor is 100 m. However, visibility at Position 3 drops below 5 m after 150 s, whereas at Position 2, it remains above 5 m until 250 s.

Comparing the visibility effects of fire sources at Positions 2 and 4 shows that:

· Position 4 affects visibility along the main corridor by 0 m and along the branch corridor by 70 m.

· Position 2 affects visibility over a greater range than Position 4.

Therefore, under Ventilation Scheme *d*, visibility is worst when the fire source is located at Position 3.

4 Conclusions

A comprehensive analysis of the four ventilation schemes indicates that the distance between the fire source and the air inlets/outlets, as well as the angle between the fire source and the exhaust vent, are critical factors influencing visibility within T-shaped utility tunnels.

(1) Visibility deteriorates when the fire source is closer to an intake vent and farther from an exhaust vent.

(2) Visibility is most severely reduced when the fire source and exhaust vent are both located along the same corridor, whether main or branch.

Based on these findings, cable-dense zones should be positioned away from intake vents. It is recommended to install multiple exhaust vents or top-mounted smoke exhaust shafts along both main and branch corridors to mitigate the risk of global visibility deterioration due to a single vent failure or unfavorable vent placement. Personnel evacuation routes should, whenever possible, be aligned with the direction of the exhaust airflow.

Funding

Anhui Provincial Outstanding Scientific Research Innovation Team (NO: 2023AH010059); University-Level Key Discipline in Safety Science and Engineering (NO: zdxk202101); Anhui Xinhua University Institutional General Research Project (NO: 2023zr020)

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