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# OPTIMIZATION OF TUNNEL VENTILATION SYSTEMS IN FIRE EMERGENCIES

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**Abstract:** The issue of ensuring safe evacuation conditions from underground structures of subways, railway, and road tunnels remains relevant, as evidenced by statistical data on fires at these facilities. One of the key factors determining human safety in emergencies is the high efficiency and reliability of tunnel ventilation systems during fire emergency modes.

The aim of this work is a comparative analysis of the efficiency of smoke exhaust valves with different orientations relative to the tunnel axis (longitudinal and transverse arrangement) and the development of an optimal activation algorithm for tunnel ventilation devices based on the obtained results, considering various tunnel gradients and distances between smoke valves. Given the significant cost and complexity of full-scale experiments, the research was conducted using developed CFD models implemented in the Fire Dynamics Simulator (FDS) program. The tunnel section model used for numerical experiments consists of a computational domain including a 700-meter-long tunnel section of constant cross-section with variable gradient sections, a fire source, and variable-geometry smoke exhaust valves ensuring the required exhaust flow rate of combustion products. To ensure stable ventilation, the computational domain is connected to two tunnel sections of identical cross-section, modeled using a combined scheme with HVAC elements.

The results of the computational experiments demonstrate a significant (over twofold) increase in smoke extraction efficiency, measured by the reduction in the smoke-filled zone length, when using transversely oriented smoke exhaust valves compared to the longitudinal valve arrangement scheme. The simulation results enable the selection of an optimal activation algorithm for the tunnel ventilation system during a tunnel fire, considering the fire source location and the gradient of the emergency tunnel section, using an addressable fire alarm system.

**Keywords:** tunnel fire, tunnel ventilation, smoke exhaust duct, smoke exhaust valve, smoke-filled zone.

## 1. INTRODUCTION

This article, part of a comprehensive analysis of tunnel ventilation organization in double-track subway tunnels, addresses the optimal arrangement and configuration of smoke exhaust valves for tunnel ventilation system ducts, as well as the selection of a smoke exhaust system activation algorithm integrated with the fire detection system. Analysis of smoke exhaust system modeling results showed that with longitudinal valve installation, due to airflow characteristics near the valve, the smoke front can advance beyond the valve, reducing valve efficiency. This is confirmed by analyzing the distribution of ash particle concentrations across the valve cross-section. Figure 1 shows the 3D distribution of soot mass fraction concentrations in the valve area. The distribution reveals that the central zone of the valve (area of maximum airflow velocity) extracts clean, smoke-free air from the lower part of the tunnel's traffic zone. Only a small peripheral area of the valve effectively removes combustion products. Furthermore, on gradients, the smoke layer front spreads unimpeded along the tunnel ceiling slab between the valve boundaries and the tunnel lining, especially with increasing tunnel gradient. This phenomenon (Plug-holing) has been noted by several researchers [1, 2], but no recommendations for mitigating it were proposed. Only in [3] was it concluded that the area of the smoke exhaust valve has little significant effect on extraction efficiency, while increasing the valve width may improve efficiency. Therefore, numerical modeling of transversely arranged valves, installed across almost the entire width of the tunnel ceiling slab, is of significant interest.

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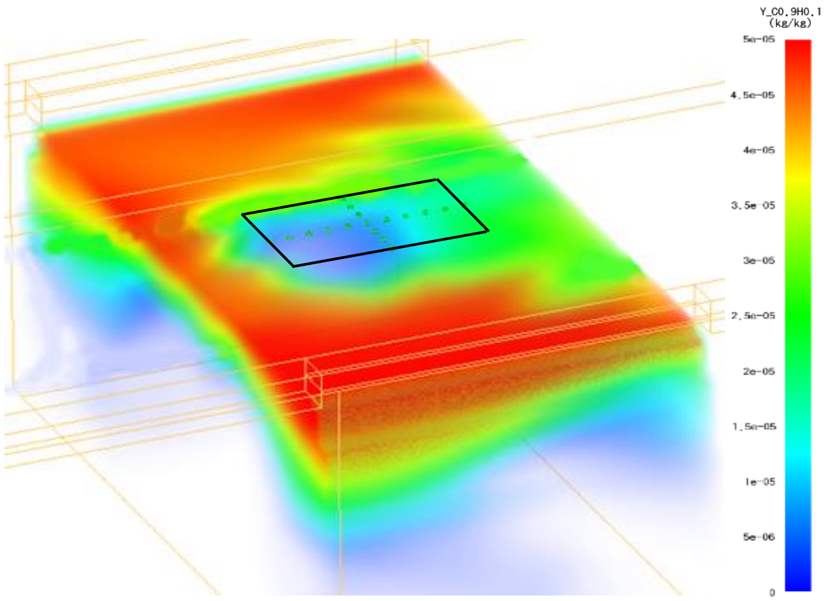
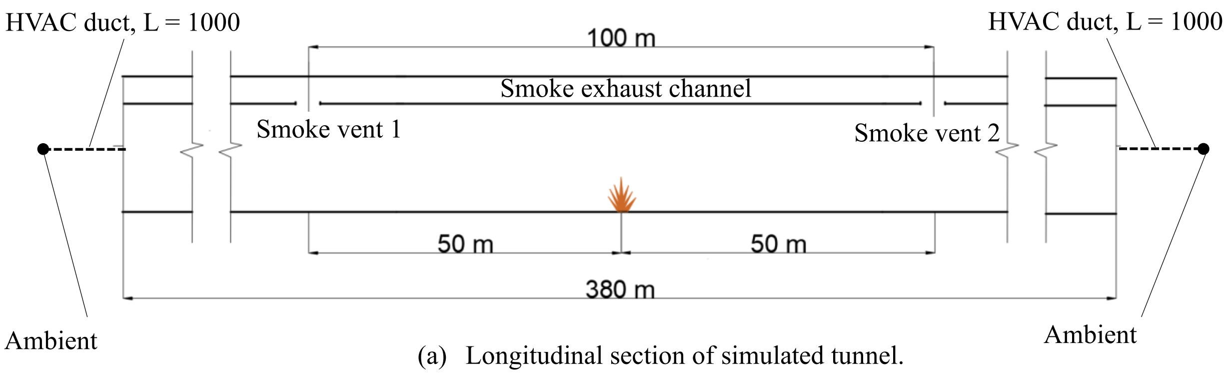



***Figure 1.*** *3D distribution of soot mass fraction in the smoke exhaust valve area.*

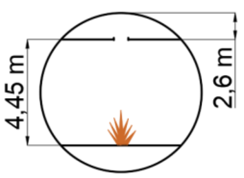
## 2. RESEARCH METHODOLOGY

A double-track subway tunnel with an internal lining diameter of 10.4 m was chosen as the model. Simulations were performed using a combined FDS (version 6.9.1) and HVAC model. The computational domain is 380 m x 10 m x 6.5 m. The grid cell size, following recommendations [4], was set to 0.25 m x 0.25 m x 0.25 m. Two connected tunnels, each 1000 m long, were modeled using HVAC elements to conserve computational resources. The model replicates the configuration of a section between stations. The gradient of the tunnel section within the computational domain can vary from 0 to 40 ‰. Smoke removal flow rate – 50 $m^3 \cdot s^{-1}$.

Fire power was set at 6 MW, and the distance between smoke exhaust valves at 100 m. The schematic of the computational model is shown in figure 2. Smoke exhaust valve dimensions were set to 2 m x 4 m for longitudinal arrangement and 1 m x 8 m for transverse arrangement.




(a) Longitudinal section of simulated tunnel.




(b) Cross-section of simulated tunnel.

***Figure 2.*** *Arrangement of simulated tunnel.*

A preliminary assessment of valve orientation efficiency involved modeling the dynamics of hazardous fire factors propagation under identical initial and boundary conditions (tunnel geometry, fire power, distance between valve axes, exhaust flow rate per valve, valve area, tunnel gradient U = 25‰, L = 50 m). The results indicated a significant reduction (over twofold) in the smoke-filled zone length when using transverse valve orientation (Figures 3, 4).

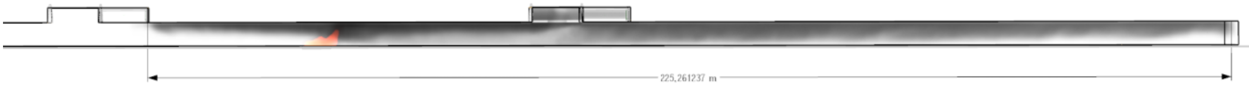



***Figure 3.*** *Smoke spread in tunnel (longitudinal arrangement of smoke exhaust valves, t = 200 s).*

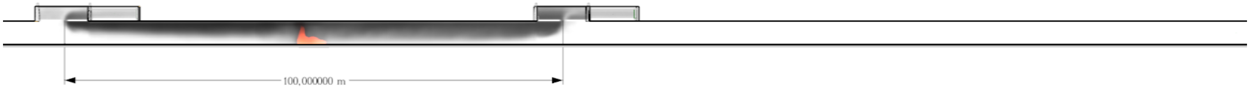



***Figure 4.*** *Smoke spread in tunnel (transverse arrangement of smoke exhaust valves, t = 200 s).*

Based on these preliminary results, additional studies were conducted to evaluate the proposed solution's effectiveness and its impact on the overall smoke exhaust system algorithm. The extent of the smoke-filled zone was chosen as the efficiency criterion. This extent is considered a function of the tunnel section gradient and the distance from the valve axis to the fire source.

The following model was adopted for processing experimental results:

$$y(a,x) = a_0 + a_1 \cdot x_1 \cdot x_1 + a_2 \cdot x_2 \cdot x_2 + a_3 \cdot x_1 + a_4 \cdot x_2 + a_5 \cdot x_1 \cdot x_2 \quad (1)$$

where:
y (a, x) - function value;
ai - model coefficients;
x1 - dimensionless gradient value;
x2 - dimensionless distance from the smoke exhaust valve axis.

Model coefficient determination, adequacy assessment, and coefficient significance evaluation followed algorithms described in [5]. Numerical experiments also monitored gas flow rate changes at the left and right boundaries of the computational domain and velocities within the grid. Simulations covered the following parameter ranges: tunnel gradient – 0 – 40 ‰, distance from Valve 1 axis to fire source – 10 – 90 m.

## 3. RESULTS

A series of computational experiments yielded the following results:

1. Using:

$$x_{1i} = \frac{U_i - 0.5(U_{max} + U_{\min})}{0.5(U_{max} - U_{\min})}; \qquad x_{2i} = \frac{L_i - 0.5(L_{max} + L_{\min})}{0.5(L_{max} - L_{\min})}; \quad (2)$$

where:
$U_i$ - current tunnel section gradient value, ‰;
$U_{max} =$ 40 ‰ – maximum gradient value;
$U_{min} =$ 0 ‰ – minimum gradient value;
$L_i$ - current distance from Valve 1 to fire source, м;
$L_{max} =$ 90 м – maximum distance value;
$L_{min} =$ 10 м – minimum distance value.

Substituting the experimentally derived coefficients into function (1) yields:

$$L_s = 273{,}4847 + 22{,}9572 \cdot x_1 \cdot x_1 - 10{,}619 \cdot x_2 \cdot x_2 + 155{,}642 \cdot x_1 + 48{,}8189 \cdot x_2 + +21{,}7516 \cdot x_1 \cdot x_2 \quad (3)$$

where:

$L_s$ - smoke-filled zone length, м.

Graphical representation is shown in Figure 5. The above results pertain only to longitudinal valve arrangement. For transverse orientation, the smoke-filled zone did not exceed the distance between valves (≤ 100 m).

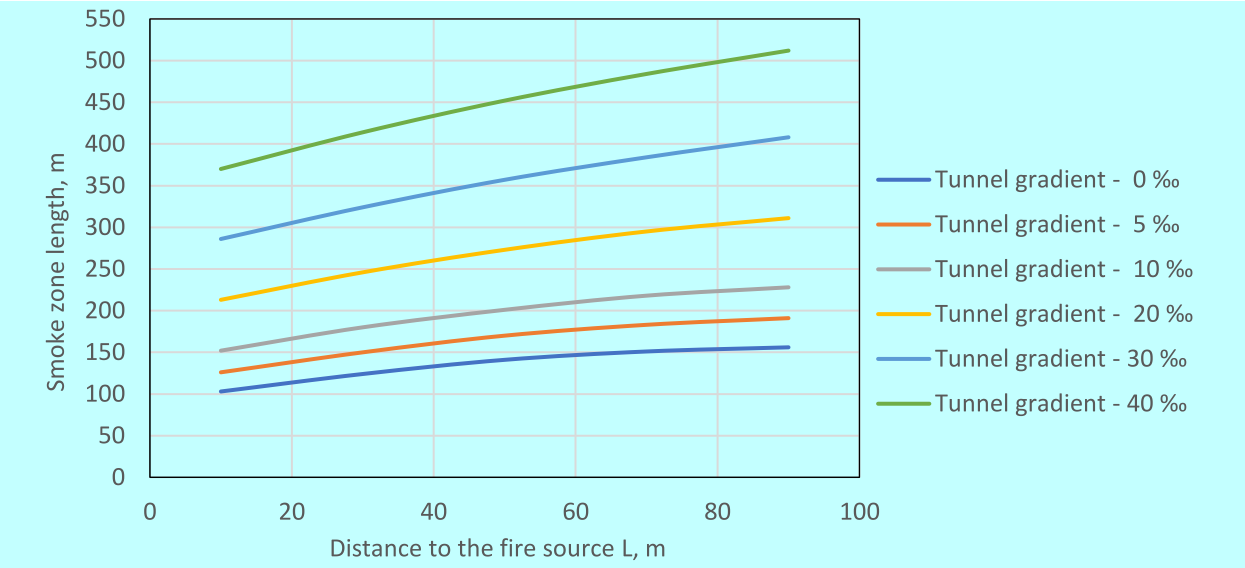



***Figure 5.*** *Dependence of the smoke zone length on the distance to the fire source*

2. Calculations revealed a trend of decreasing gas flow rate in the right branch of the computational domain as the tunnel gradient and distance to the fire source increased. For transversely arranged valves, the average gas flow rate for gradients between 0 and 40‰ was 44.3 -- 35.7 $m^3 \cdot s^{-1}$ (Figure 6).

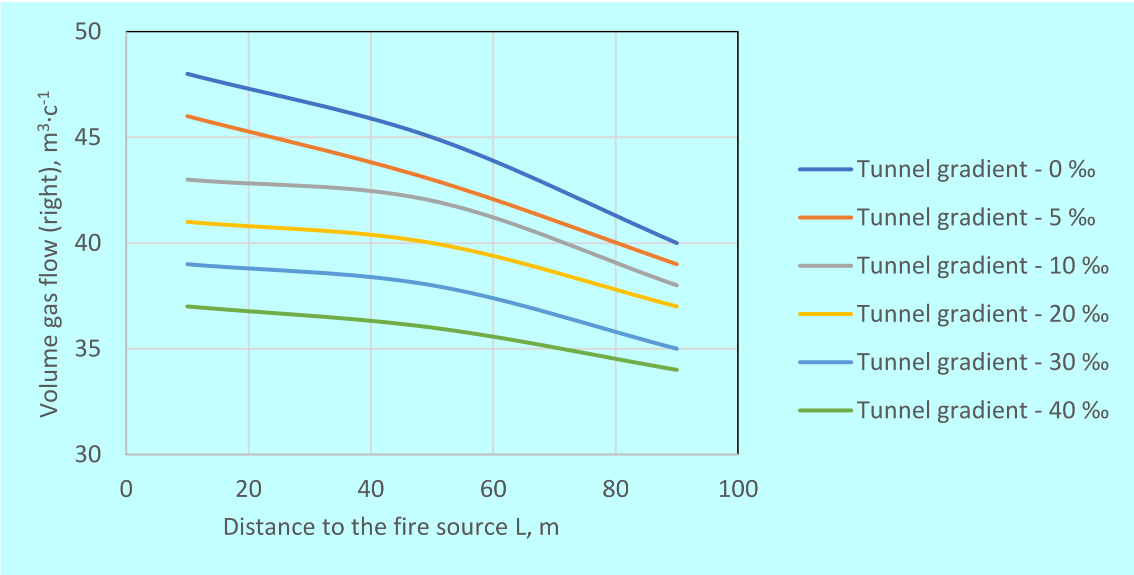



***Figure 6.*** *Dependence of the volume gas flow on the distance to the fire source (transverse arrangement of valves)*

For longitudinally arranged valves, the average flow rate was 44.0 - 21.0 $m^3 \cdot s^{-1}$ (Figure 7).

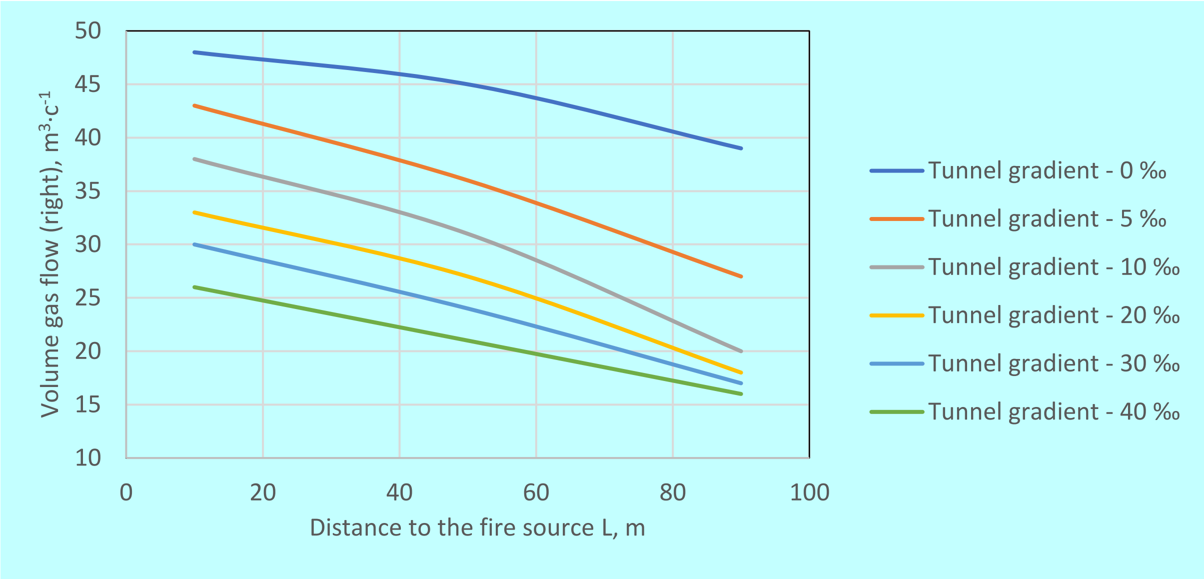
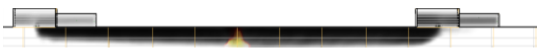



***Figure 7.*** *Dependence of the volume gas flow on the distance to the fire source (longitudinal arrangement of valves)*

Absolute gas flow rates upstream of the fire (against the combustion product flow) were on average 50% higher for transverse valves compared to longitudinal valves.

3. For tunnel gradients exceeding 10‰ with longitudinal valves, activating valves on both sides of the fire source significantly increased (over twofold) the smoke-filled zone and rendered the downstream valve ineffective. For the transverse valve scheme, both valves continued to function effectively, and the smoke-filled zone did not exceed the distance between valves (Figure 8).

a) Longitudinal arrangement of smoke exhaust valves.



b) Transverse arrangement of smoke exhaust valves.

***Figure 8.*** *Smoke spread in tunnel (U = 20 ‰, L = 50 m, t = 500 s).*

4. Comparative analysis of smoke propagation dynamics under identical conditions showed that with transverse valves, smoke did not propagate along the tunnel but was entirely captured by the valve (Figure 9) and contained throughout the simulation period. With longitudinal valves, smoke propagated along the tunnel axis until a steady-state mode was reached (t ≈ 280 s), where further smoke front movement was halted by counter airflow between t = 35...300 s.

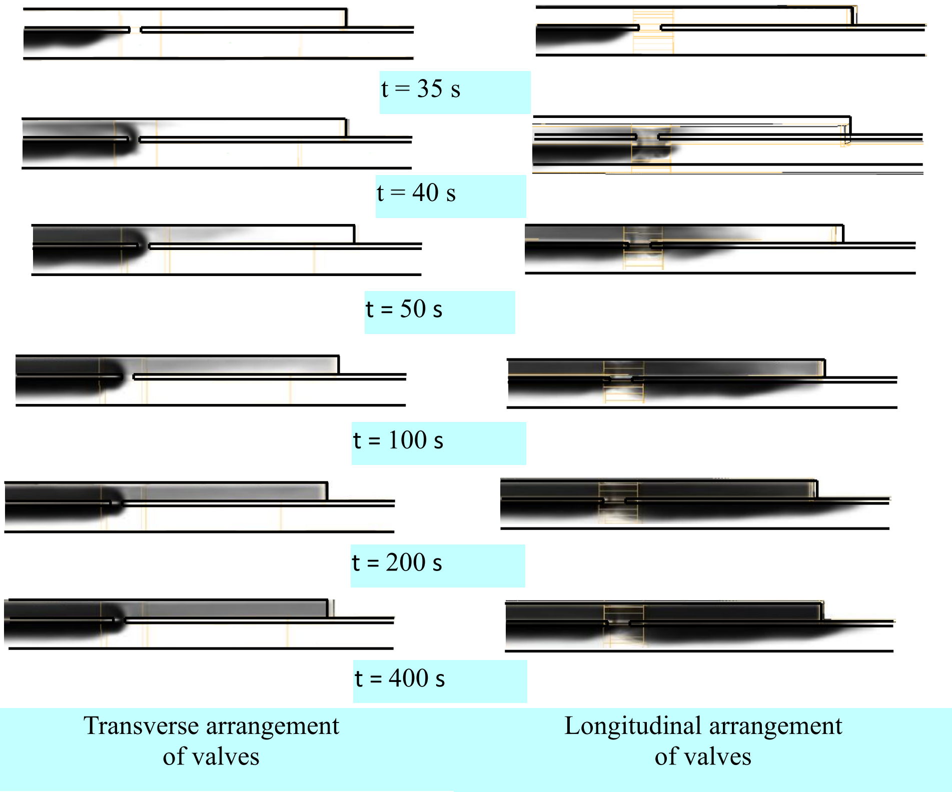



***Figure 9.*** *Smoke layer propagation with different valve orientations*

Velocity fields in valve cross-sections are shown in Figures 10 and 11. For transverse valves (Figure 10), the velocity field in the Y-section shows a nearly uniform distribution of the vertical velocity component across the entire tunnel width (with increased velocities near the lining) -- zone marked by a red line. For longitudinal valves (Figure 11), the zone of stable vertical velocity (red line) constitutes only a small part of the tunnel cross-section (relative to valve width). Areas under the ceiling slab near the tunnel lining (marked blue in Figure 11) allow unimpeded smoke passage along the X-axis.

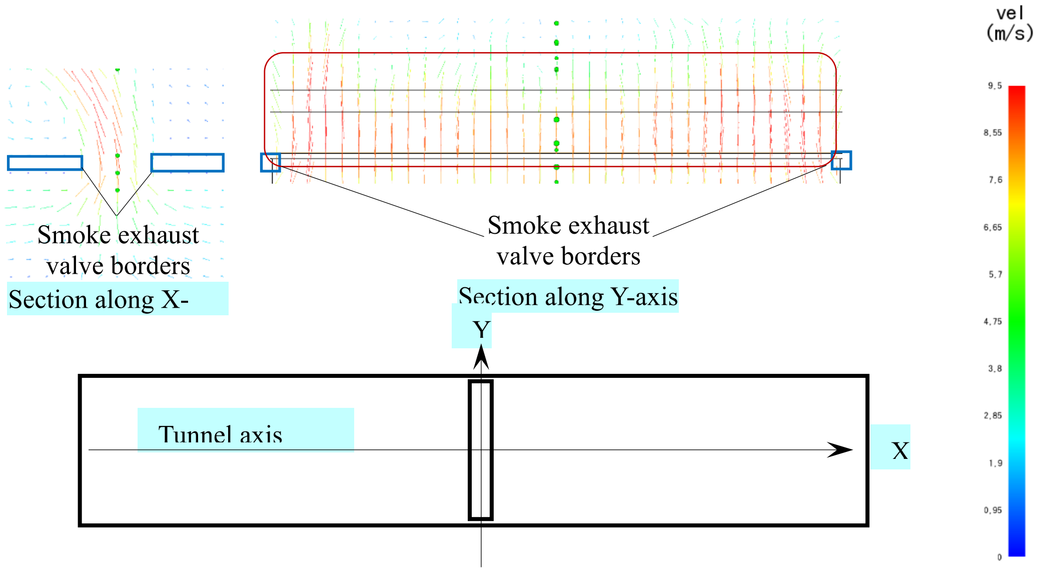



***Figure 10.*** *Velocity fields in the cross-section of the smoke exhaust valve (transverse arrangement of valves)*

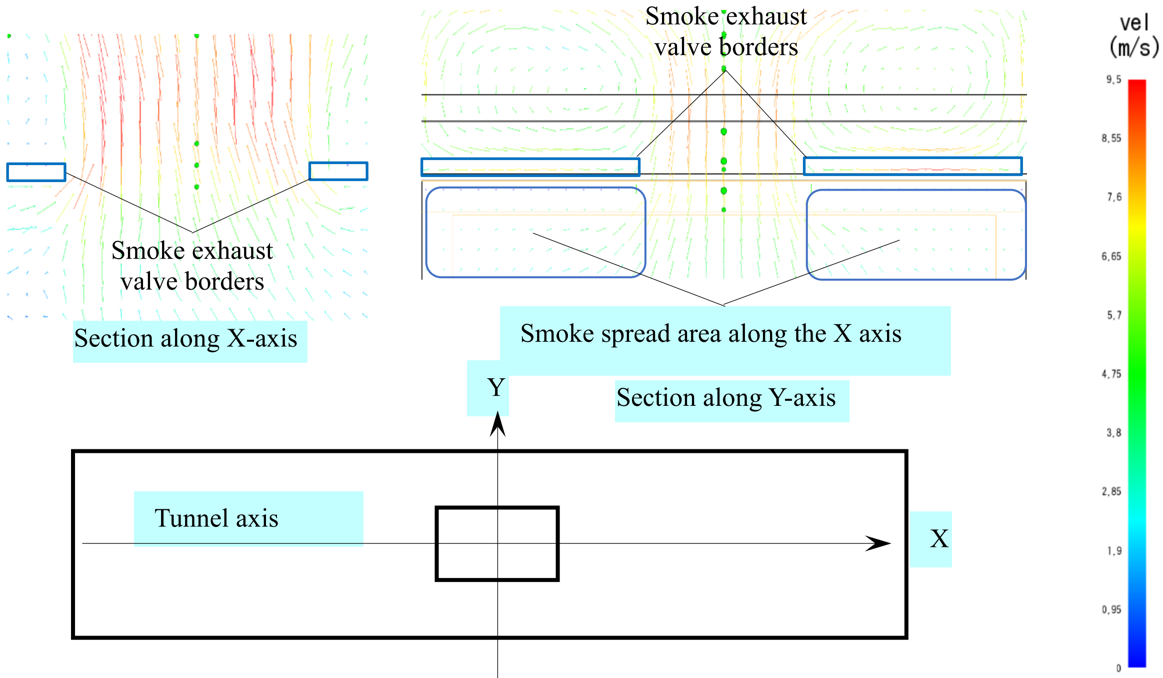



***Figure 11.*** *Velocity fields in the cross-section of the smoke exhaust valve (longitudinal arrangement of valves)*

5. For transverse valves, a steady-state airflow mode formed downstream of the valve (blue rectangle, Figure 12a) shortly after activation, creating a barrier preventing smoke front passage beyond the valves. For longitudinal valves (Figure 12b), this steady-state airflow zone formed significantly later (~100s delay) and was located 40...80 m from the valve (depending on exhaust rate), allowing the smoke front to propagate beyond the inter-valve distance

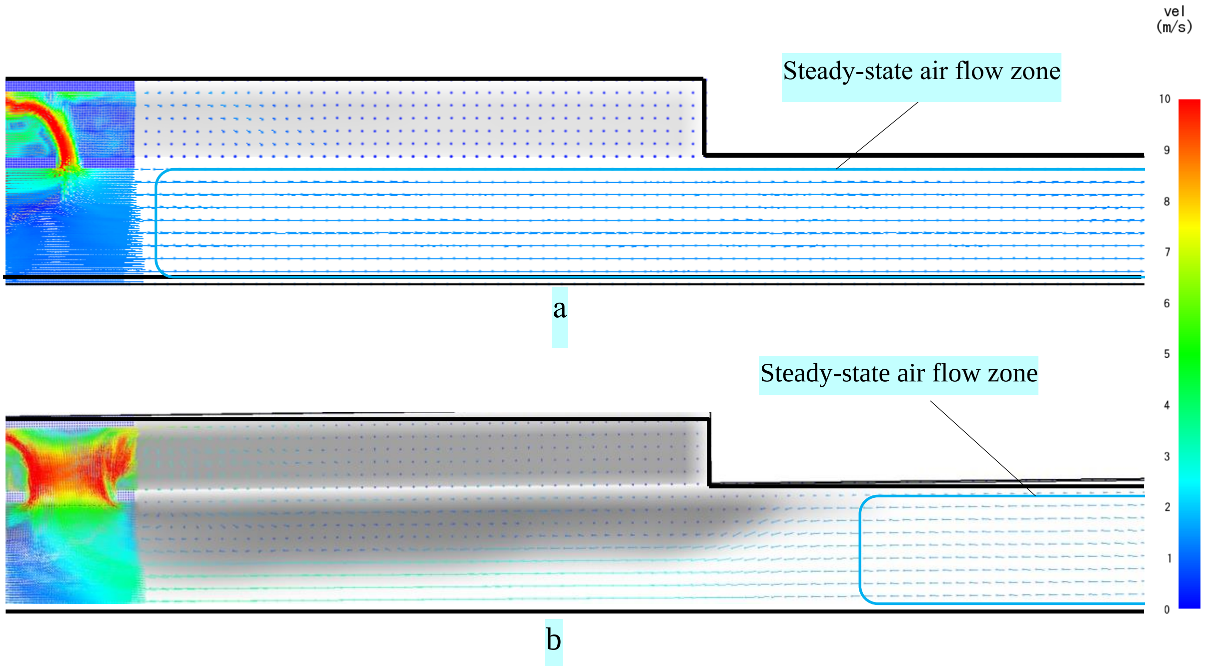



***Figure 12.*** *The structure of air flow distribution in the area of smoke exhaust valves for transverse (a) and longitudinal (b) arrangement of valves*

## 4. DISCUSSION

The results demonstrate that transverse valve arrangement has significant advantages over the longitudinal scheme for the following reasons:

The gas flow structure near transversely oriented valves exhibits distributed exhaust across the entire tunnel width (Fig. 10), eliminating pathways for combustion products along the ceiling edges (Fig. 11).

The flow structure downstream of the valve and higher upstream gas flow rates indicate that transverse valves maintain higher opposing gas velocities against advancing combustion products and preserve smoke layer stratification.

Modeling confirmed that transverse valves limit the smoke-filled zone to the distance between valves.

Containing the smoke layer within the inter-valve distance for gradients >10‰ was unattainable with longitudinal valves.

For longitudinal valves within a detection zone equal to the valve spacing, reducing the smoke-filled zone length requires activating valves downstream (uphill) of the fire, which is often ineffective and complicates the activation algorithm integrated with fire detection.

The activation algorithm for transversely arranged valves simplifies to activating the valves immediately adjacent to the fire source on both sides.

## 5. CONCLUSIONS

The analysis of valve performance parameters for both arrangement configurations validates the obtained results.

The presented smoke exhaust system design will ensure confinement of the smoke-filled zone within the chosen valve spacing while optimizing ventilation equipment costs.

The transverse arrangement of smoke valves relative to the tunnel axis is the optimal solution, with the valve width maximized based on the tunnel's structural constraints. An algorithm for activating valves based on signals from an addressable alarm system, using the criterion of minimizing the tunnel's smoke-filled zone length, has been determined. The obtained results can be utilized in designing ventilation systems for subway, railway, and road tunnels.

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