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# Analysis on the influence of the smoke block board on the entrainment phenomena near a mechanical exhaust vent

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ABSTRACT

In this study, the Fire Dynamics Simulator (FDS) numerical simulation method is adopted to analyze the influence of various smoke block board sizes, heat release rates (HRR) and exhaust velocities on the smoke entrainment near a mechanical exhaust vent. The results indicate that the smoke extraction performance of the board-coupled shaft is influenced by the coordination of the smoke block board layout, the heat release rate and exhaust velocity. Besides, the reasonable size of the board can effectively reduce the air entrainment and achieve the best smoke exhaust efficiency. When the board size is smaller than the exhaust vent size, there will be an inefficient exhaust smoke. When the board size is larger than the exhaust vent size, the exhaust smoke efficiency increases rapidly with the increase in the board size. In addition, the exhaust efficiency is insensitive to the HRR under the same board. However, the exhaust velocity exerts a significant effect on the layered stability and smoke extraction performance near the exhaust vent.

## 1. Introduction

Due to the special structure of the tunnel featured with a large aspect ratio, a small cross-section, and a relatively limited space, the fire spreads quickly and the high-temperature toxic smoke can easily accumulate in the event of a fire [1–3]. A large number of tunnel fire cases show that smoke is the main cause of casualties. Therefore, how to effectively extract smoke is an important issue for tunnel fire emergency ventilation and exhaust [4,5]. As an efficient and reliable way of exhausting smoke, mechanical exhaust can effectively control the spread and settlement of smoke, ensure the escape environment in the lane as well as improve the safety of disaster prevention and rescue. However, the smoke exhaust system will disturb the interface between the smoke and the cold air. In the vicinity of the exhaust vent, fresh air will be directly or indirectly sucked into the exhaust vent, and the boundary layer separation and plug-holing will occur, when the smoke exhaust efficiency decreases [6].

In recent years, extensive studies have been conducted on improving extraction smoke performance and reducing air entrainment [7]. Ura et al. [8] found that the shallow road tunnel with roof openings in the ceiling thinned out the smoke more quickly by natural ventilation compared to a normal tunnel without roof openings, because the smoke was actively exhausted through the openings. Zhou et al. [9] conducted experiments in an atrium where smoke was mechanical exhausted, found that forced air flow would increase air entrainment and lead to the phenomenon of plug-holing. It is not the situation that the larger exhaust smoke is, the better the exhaust effect is. Jiang et al. [10] studied the method of calculating the entrainment volume during the horizontal spread of smoke under mechanical smoke extraction and revealed that the heat release rate had no significant effect on air entrainment. Yang et al. [11,12] studied the effects of mechanical smoke extraction on the stratification characteristics of tunnel smoke, and then

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| **Nomenclature** | | *Subscripts* | |
|---|---|---|---|
| m | mass flow rate (kg/s) | cs | smoke flowing of the smoke upstream |
| Q | heat release rate (MW) | cs' | smoke flowing of the smoke downstream |
| u | velocity (m/s) | es | smoke flowing exhaust from shaft |
| A | cross-sectional area ($m^2$) | s | smoke |
| T | temperature | a | fresh air |
| Δ | deviation property | ΔT | smoke temperature rise |
| ρ | density ($kg/m^3$) | | |

proposed the basis for determining the stratification and stability of smoke. Ji et al. [13,14] experimentally studied the influence of the smoke vent height and the exhaust velocity on the mechanical smoke exhaust efficiency in chamber fires. In this case, it was found that through increasing the smoke vent height and decreasing the exhausting velocity, the exhaust process became more effective, thus eliminating the plug-holing and reducing the interference on the smoke interface. Yao et al. [15] investigated the effect of the shaft inclination angle and shaft height on the smoke exhaust capacity, and found that the low and slightly tilted shaft can improve the capacity of smoke exhaust obviously. Fan et al. [16–19] conducted a large number of small-scale experiments and numerical simulation experiments to analyze the air entrainment during the shaft exhaust process [16]. The smoke extraction performance of different shaft sizes [17] and different arrangements of shafts [18] are compared, and the existing shaft structure [19] is enhanced to improve exhaust efficiency.

Cong et al. [20] proposed installing a smoke block board below the shaft, using this board-coupled shaft structure can eliminate the negative effect of plug-holing, thereby promoting the shaft exhaust efficiency to a large extent. Results have shown [21] that when the maximum volumetric flow rate is reached in the shaft, the proportion of air discharged from the board-coupled shaft is 23–27%, which is only half of the traditional shaft (51.3%). However, the above studies were only aimed at the natural ventilation. Besides, when the mechanical exhausting was adopted, the entrainment phenomenon caused by the disturbance of the flow field near the vent was more severe [22,23]. The optimal smoke extraction efficiency of the board-coupled shaft is affected by the size and the position of the board [21], and the phenomenon of entrainment near an exhaust vent under different mechanical exhausting conditions requires further study.

Therefore, in the proposed study, the entrainment phenomenon near an exhaust vent in the tunnel mechanical exhaust smoke is studied; the influence of different heat release rates, exhaust velocities and smoke block board sizes on the air entrainment near the exhaust vent is analyzed, and a reference for the new type of shaft exhaust is also provided.

## 2. Theoretical analysis

During tunnel fires, the smoke movement in the tunnel can be divided into five stages [24] including the rising plume, a turning region near the ceiling, radial spreading under the ceiling, the transition from radial to one-dimensional flow, and one-dimensional flow under the ceiling parallel to the tunnel axis. This study investigates entrainment caused by the presence of a smoke exhaust vent during the fifth stage (one-dimensional horizontal spreading). The flow field of the smoke around the exhaust vent is shown in Fig. 1. During the exhaust process, the smoke mass flow rate through the exhaust vent and in the downstream tunnel section of the exhaust vent can be expressed as follows:

$$m_{es} = m_{es,s} + m_{es,a} \tag{1}$$

$$m_{cs'} = m_{cs',s} + m_{cs',a} \tag{2}$$

where $m_{es}$ is the mass flow rate of the smoke extraction from the exhaust vent, $m_{es,s}$ is the mass flow rate of smoke from upstream, $m_{es,a}$ is the mass flow rate of the entrained fresh air though the exhaust vent, $m_{cs'}$ is the mass flow rate of the smoke in downstream, and $m_{cs',s}$ and $m_{cs',a}$ are the mass flow rates of smoke from the upstream and entrained fresh air in the downstream, respectively.

The temperature rise near the upstream tunnel ceiling and in the shaft can be used to calculate the concentration of fresh air entrained in the shaft [25], which is an important parameter to characterize the smoke exhaust performance.

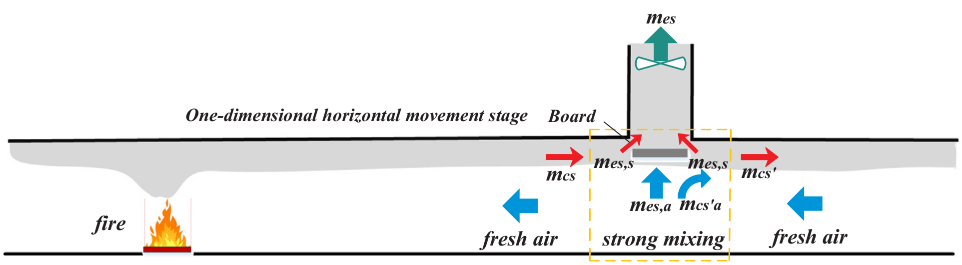


**Fig. 1.** Schematics of the tunnel model with board-coupled shaft.