

Numerical Simulation of Fire Smoke Transport in Underground Spaces of a Pumped Storage Power Station

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Abstract. The present study employs numerical simulation to investigate the transportation of fire smoke within the underground powerhouse of a Pumped Storage Power Station. The obtained results reveal the spatial variation of fire smoke under the smoke exhaust effect inside the facility. For an 8 MW fire occurring on the generator, busbar, and turbine layer floors of the main powerhouse, recommended evacuation times are 86 seconds, 242 seconds, and 298 seconds respectively when utilizing a mechanical exhaust capacity of 85000 m³/h. In case three simultaneous fires occur at these three floor levels, the evacuation time is reduced to 45 seconds. Comparatively, when compared to situations without mechanical smoke exhaust systems, our simulations indicate that escape times for different fire scenarios were extended by only 6 seconds and 91 seconds respectively. These findings underscore the urgent need for optimizing the mechanical smoke exhaust system in order to provide valuable time for personnel evacuation during fire incidents.

Keywords: Pumped storage power station; Smoke prevention and exhaust; Underground building; Fire escape

1. Introduction

The pumped storage power station is a vital component of the power grid, ensuring its efficient operation and stability. By effectively managing the supply and demand fluctuations in electricity consumption, it helps maintain a reliable and consistent flow of energy to meet the needs of consumers[1]. However, operating an underground pumped storage power station comes with unique challenges that need to be addressed for safe and effective functioning[2]. One significant concern is the fire escape difficulties in this closed environment. In case of any fire incidents or emergencies, it becomes crucial to have robust smoke control measures in place. Smoke control measures are essential for several reasons[3]. Firstly, they help prevent the spread of smoke throughout the facility by containing it within specific areas or zones. This containment minimizes potential damage to equipment and infrastructure while also facilitating safer evacuation routes for personnel. Secondly, effective smoke control measures ensure that critical systems remain operational during emergencies. Smoke can impair visibility and hinder access to important equipment or control rooms necessary for maintaining power generation operations smoothly. By implementing appropriate ventilation systems such as exhaust fan systems, operators can mitigate these risks[4]. Furthermore, proper smoke control measures contribute to overall safety by reducing health hazards associated with toxic fumes generated during fires. Underground environments pose additional challenges due to limited natural ventilation options; therefore, relying on mechanical means becomes imperative. To address these concerns adequately, comprehensive strategies should be developed that include early detection systems for prompt response to fire incidents along with well-designed evacuation plans[5].

In Chinese pumped storage power station, various smoke prevention and exhaust systems are implemented based on specific plant characteristics to ensure the safe operation of equipment and human evacuation. These systems effectively manage any smoke generated during a fire incident by

utilizing ventilation and safety tunnel exhaust ducts for its discharge. These systems effectively manage smoke flow during fire events by analyzing the spread of fire smoke within three key areas: the generator layer, busbar layer and turbine layer of the main powerhouse in a pumped storage power station. By understanding how fire smoke behaves in these underground structures through comprehensive research and analysis, valuable insights can be gained for both future design considerations and operational strategies.

Meanwhile, expanding our knowledge about fire smoke spread is vital for enhancing safety protocols within underground buildings. The findings from this study will serve as a valuable reference point for engineers involved in designing similar facilities or improving existing ones. Ultimately, ensuring effective smoke control measures not only safeguards personnel working within these structures but also helps maintain uninterrupted electricity supply to meet society's growing energy demands efficiently.

2. Method

2.1 Physical Model

The main powerhouse in the underground plant have specific dimensions that play a crucial role in determining the effectiveness of smoke control measures. The main powerhouse spans an impressive width of 144 m, towering at a height of 24 m, and stretching over a length of 45 m. To ensure safety within these underground plants during emergency situations such as fires or smoke incidents, numerical simulation techniques are employed to calculate smoke diffusion patterns. This study focuses on analyzing how smoke spreads throughout the main powerhouse and evaluates various factors of ventilation systems. By conducting extensive simulations using advanced computational models, researchers can gain valuable insights into optimizing smoke exhaust systems for efficient evacuation procedures. These findings serve as essential references for designing effective strategies to control smoke dispersion within underground plants. Figure 1 visually represents the geometric model diagram specifically designed for this study's underground main powerhouse. It is noted that the fire smoke transport in the main powerhouse is difficult, because once the fire happens, the stairwell will act as not only as a pathway for smoke transport but also a escape route for occupants. It is important to enhance safety protocols in main powerhouse by providing evidence-based recommendations for designing robust smoke control measures. Hence, engineers can effectively mitigate potential risks associated with fire incidents or other emergencies in this environment.

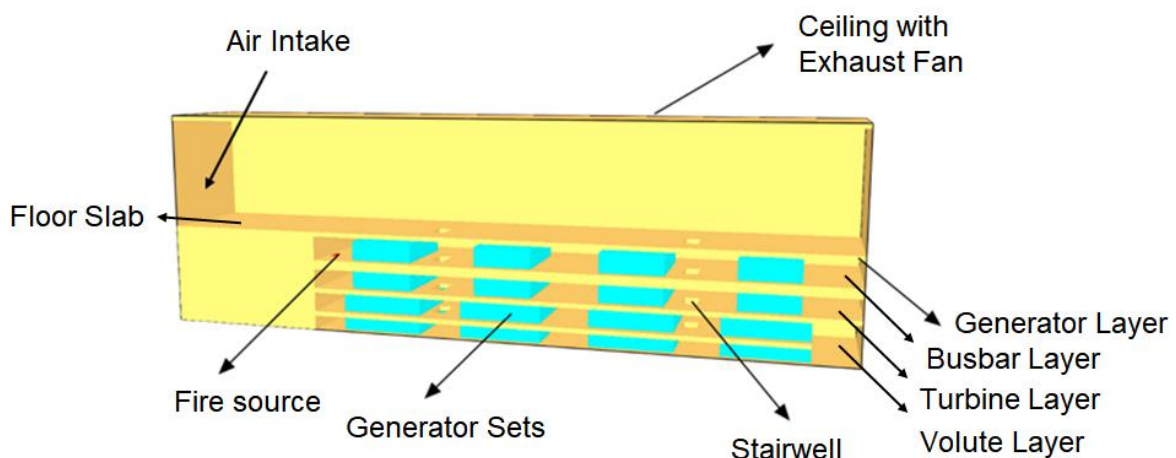


Figure1 Geometric model and boundary setting of main powerhouse

2.2 Fire Source

The simulated fire source is set as liquid fire, which accurately represents a potential fire hazard in the main powerhouse. This ensures that the fire simulation is realistic and can effectively test the safety measures in place. According to the current standard (GB 51251-2017), the heat release rate per unit area (HRRPUA) for buildings with a room height of more than 8 m is determined. In this case, when the fire reaches a steady state, the heat release rate reaches 8 MW with an HRRPUA of 8000 kW/m². This information helps evaluate how well the building's structural integrity and firefighting systems can handle such intense fires. Additionally, it is important to consider other areas within the facility. These figures provide valuable insights into how different sections of the facility may respond to fires and help assess their overall safety preparedness.

3. Results and Discussion

The dynamic simulation in Fig. 2 demonstrates the evacuation of smoke from the main powerhouse over time, considering a fire on the generator floor and simultaneous utilization of mechanical smoke exhaust and prevention at a rate of 8000 m³/h. Although the fire is extinguished after 100 seconds, the mechanical smoke exhaust continues for an additional 900 seconds. Following the outbreak of fire, thermal buoyancy causes gradual upward spread of smoke until it starts spreading horizontally at the top, eventually filling up the upper space of the generator layer. Within 10 seconds after ignition, smoke reaches the top and initiates lateral dispersion. By 100 seconds, approximately half of the generator floor becomes filled with smoke. To ensure safe evacuation, personnel should utilize stairways near the fire source as quickly as possible since when mechanical exhaust is employed, smoke rapidly fills up to a height of 2 m within just 86 seconds after the fire broken out (compared to only 6 seconds without mechanical exhaust). It is crucial for individuals to adhere to this evacuation time limit from the room to the nearest stairwells in the main powerhouse .

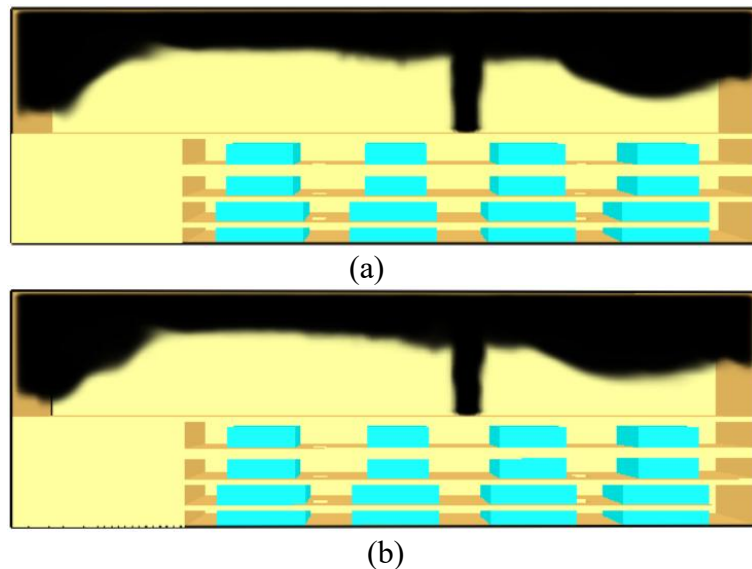


Fig. 2 Comparison of smoke transport during a fire on the generator layer floor (a) without exhaust system after 80 seconds (b) with exhaust observed at 86 seconds

The dynamic simulation in Fig. 3 demonstrates the time-dependent smoke exhaust from the main powerhouse. The fire originates in the busbar layer floor, where simultaneous mechanical smoke exhaust and prevention occur at a rate of 8000 m³/h. Although the fire is extinguished after 100 seconds, mechanical smoke exhaust continues for an additional 900 seconds. Following the outbreak of fire, smoke gradually spreads through stairways to upper floors and horizontally around obstacles. Within 20 seconds, smoke reaches the generator floor, while by 100 seconds, it fills up the entire busbar layer floor with dense fumes. Even after extinguishing the fire source, mechanical

smoke exhaust persists for another 100 seconds, resulting in more than half of the generator floor being filled with thick smoke. Continuing mechanical smoke exhaust for 300 seconds leads to over 80% of space on the generator floor being occupied by noxious fumes. After an additional duration of continuous exhaustion lasting for 600 seconds, all areas on this level become engulfed in dense smoke as it descends through stairwells.

The escape personnel should evacuate from the stairway on the opposite side of the fire source in case of a fire on the busbar layer floor. This is because, after 242 seconds from the start of the fire, smoke gradually descends to a height of 2 m above the generator floor, which is 16 seconds slower compared to when there is no mechanical exhaust system. Therefore, it is crucial for personnel to complete their evacuation within 242 seconds.

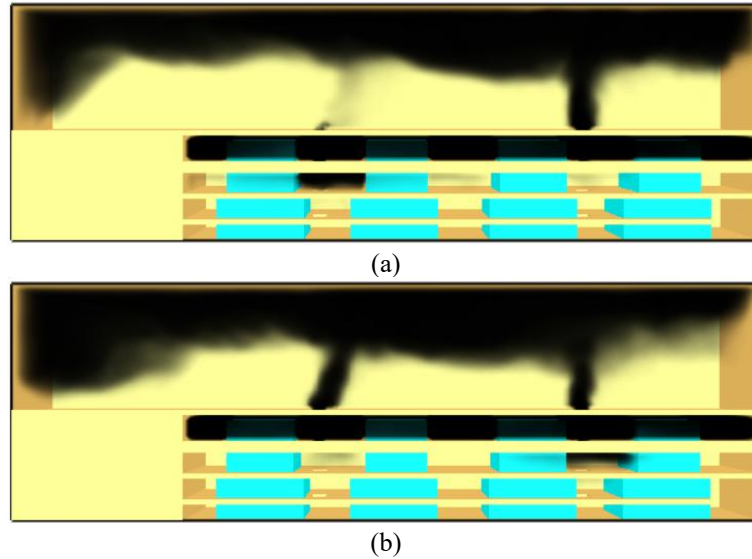


Fig.3 Comparison of smoke transport during a fire on the busbar layer floor(a)without exhaust system after 226 seconds (b)with exhaust observed at 242 seconds

The dynamic simulation in Fig.4 illustrates the smoke exhaust process from the main powerhouse during a fire on the turbine layer floor over time. Mechanical smoke exhaust and prevention measures are simultaneously implemented at a rate of 8000 m³/h. The fire is extinguished after 100 seconds, followed by an additional 900 seconds of continuous mechanical smoke exhaust.

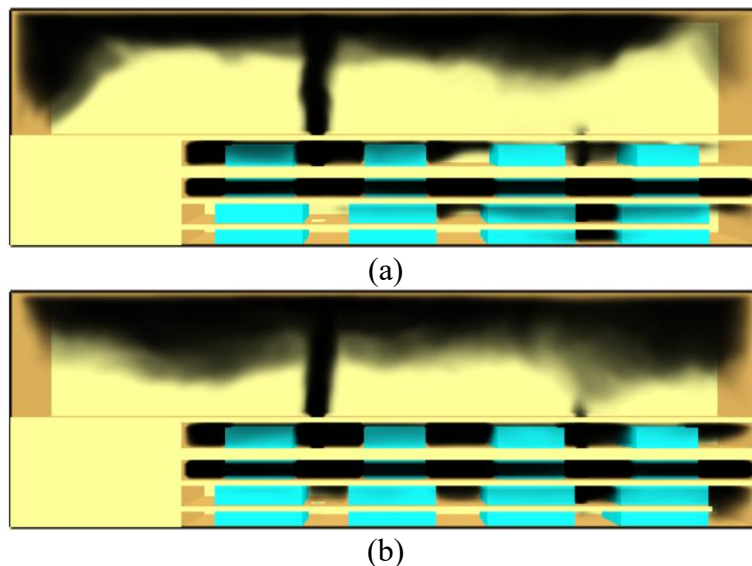


Fig.4 Comparison of smoke transport during a fire on the turbine layer floor(a)without exhaust system after 207 seconds (b)with exhaust observed at 298 seconds

After the fire broken out, smoke gradually spreads vertically through the stairway to upper floors and horizontally around obstacles. Within 30 seconds, combustion-generated smoke ascends to the busbar layer floor adjacent to the fire source; within 50 seconds, it reaches both the busbar and generator layer floors. By 100 seconds, fire-induced smoke permeates throughout the top floor of the generator area while occupying space on the turbine floor. Following fire extinguishment at 100 seconds, more than 70% of the busbar layer becomes filled with smoke. After an additional duration of continued exhaust for another 300 seconds, both busbar and turbine layers become completely inundated with smoke, whereas over half of the generator layer is also affected. After fire extinguishment time point of 600 seconds, all areas on the generator layer are essentially saturated. For fires on the turbine layer floor, personnel should escape from stairways away from the fire source due to slower dispersion without mechanical exhaust—smoke drops to just 2 m above ground level after approximately 298 seconds compared to 91 seconds without mechanical extraction—thereby escape times should ideally not exceed 298 seconds.

The simulation of the most adverse conditions in the main powerhouse is depicted in Figure 5, which show cases with three simultaneous 8 MW fires occurring on the generator, busbar, and turbine layer floor. Under these unfavorable conditions, mechanical smoke exhaust and prevention are implemented at a rate of 85000 m³/h. The fire is extinguished within 100 seconds, while the mechanical smoke exhaust continues for an additional duration of 1700 seconds. The dynamic simulation illustrates the temporal spread of smoke, revealing its gradual propagation through stairways to upper floors and horizontally around obstacles. Within 10 seconds, smoke rapidly ascends to the top of the generator layer and disperses outwardly. After 13 seconds, smoke from both the busbar and turbine layer floors reaches stairways and rises towards the generator layer. By 15 seconds after the outbreak of fire, smoke from lower levels permeates stairways leading to the generator layer, occupying approximately half of its space by 100 seconds when mechanical exhaust system persists even after fire extinguishment. Following another 102 seconds, about 70% of volute layer and roughly 85% of the generator layer filled with smoke. When mechanical smoke exhaust continues for a total duration of 300 seconds, all layers including generator, busbar, turbine layer, and volute layer become saturated with smoke. After 1300 seconds, the concentration of smoke decreases and fills in the volute layer. At 1700 seconds after the outbreak of fire, the main powerhouse remains engulfed in dense smoke without significant exhaustion effect.

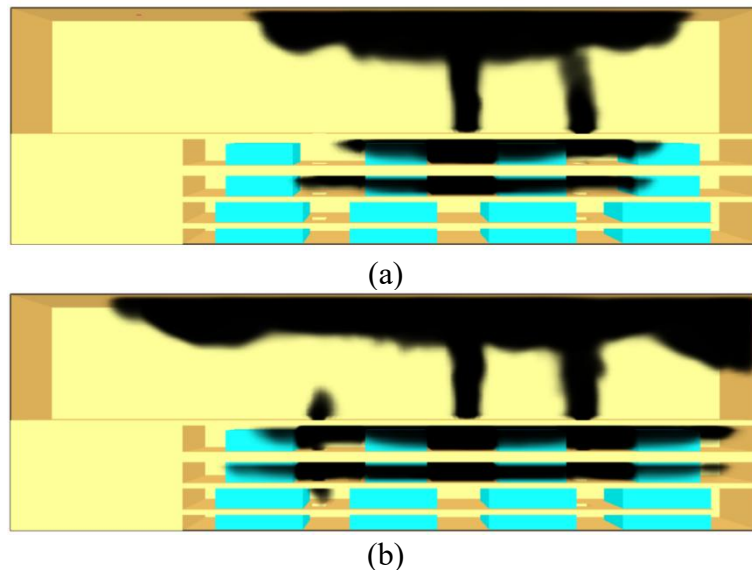


Fig.5 Comparison of smoke transport during three simultaneous fires on the generator, busbar and turbine layer floor(a)without exhaust system after 30 seconds (b)with exhaust observed at 50 seconds

In the event of a fire occurring simultaneously in the busbar, turbine, and volute layer, evacuation personnel should utilize the designated stairway located away from the source of fire.

The gradual descent of smoke from the generator's top to a height of 2 m above ground level is completed within a mere 45 seconds when compared to scenarios without mechanical exhaust systems. Consequently, it is imperative that evacuation time for personnel under worst-case conditions does not exceed this duration, especially for the volute layer when the fire occurs.

The simulation results comparing escape time with and without mechanical smoke exhaust are presented in Tab.1, respectively. The summary of the recommended fire escape time for the powerhouse shows the escape time remains similar whether there is an exhaust system or not when the fire breaks out at the generator layer floor, busbar layer, and three-layer floors. However, there is a difference in escape time at the turbine layer floor. Additionally, the escape times vary depending on the location of the fire.

Table 1 Summary of escape time in main powerhouse with the outbreak of fire at different locations with/without smoke exhaust systems

With/Without smoke exhaust system	Generator layer floor(seconds)	Busbar layer floor(seconds)	Turbine layer floor(seconds)	Three layer floors(seconds)
With	86	242	298	45
Without	80	226	207	44

4. Summary

In this study, we conducted numerical simulations to investigate the transport of smoke in the event of an underground fire at a pumped storage power station. We evaluated the evacuation time from the room of the personal to the closest stairwell. Our specific findings are as follows:

1) For fires with a power output of 8 MW on the generator, busbar, and turbine layer floor of the main powerhouse, along with a mechanical smoke exhaust rate of 85000 m³/h, recommended escape times are estimated to be 86 seconds, 242 seconds, and 298 seconds respectively.

2) In the case of three simultaneous fires at each layer floor with an output of 8 MW each, the recommended escape time is only 45 seconds with or without mechanical smoke exhaust system.

3) Compared to situations without a mechanical smoke exhaust system, escape times can be reduced by up to 6 and 90 seconds respectively. Therefore, it is crucial to optimize the mechanical smoke exhaust system in order to provide valuable time for personnel evacuation during a fire.

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