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Feasibility analysis on natural ventilation scheme for large underground spaces based on the top cover design

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ABSTRACT

A natural ventilation scheme was proposed for large underground spaces based on the top cover design. This is regarded as a design towards 'green' or 'sustainable' building. The main factors influencing the natural smoke extraction efficiency were studied by using orthogonal design method and CFD technique. A new model was built to estimate the feasibility of the natural ventilation scheme in case of fire accidents. Results show that when fire occurs in underground part of the building, smoke can be exhausted to the interlayer, which is added between the underground part and its top cover, and then the smoke spread along the ceiling of the interlayer to its open boundaries. When working together with smoke shafts, smoke screens can limit the spread of smoke and improve the smoke exhausting efficiency of shafts. In addition, whether the smoke can be vented above specified safety height both in underground part and in the interlayer can be theoretically estimated by the judging model constructed. In order to ensure safety smoke layer height, the size of the underground part is limited when the fire power is determinate. And it showed linear relationship between critical underground part size and critical fire power. The slop of the line decreases when smoke screens are added.

1. Introduction

With land resources decreasing in compact cities, the demands for underground spaces increase. And even the urban underground buildings are constantly transformed to those of the multi-layered and large-scaled styles. In order to satisfy the requirements of different functions of use, spatial structures such as underground comprehensive vehicle depots, underground parking lots and subway stations are becoming increasingly complicated and diverse. Different from the above-ground buildings, underground buildings mainly rely on the mechanical smoke exhausting systems to control smoke since it is impossible for them to have sufficient openings for natural ventilation.

There are many researches on smoke exhaust and ventilation schemes of underground buildings with different structures. Domingo et al. studied mechanical ventilation inside a typical two-storey traffic transfer building by CFD technology. A relatively economical solution was found to maintain the pollutant concentration and temperature inside the building so as to obtain the expected values, and different fire scenarios were designed to verify the reliability of the exhaust system (Domingo et al., 2011). Guo et al. put forward a smoke control scheme in underground passages of CBD by numerical simulation and small-sized experiments, and pointed out that the natural ventilation shaft played a key role in the underground exhaust system (Guo et al., 2013). Hu et al. studied mechanical ventilation efficiency of underground corridor through full-scale experiments, and analyzed the influence of different locations of air supply outlets and exhaust fan operating time on smoke ventilation efficiency (Hu et al., 2006). Zhang et al. made a research on mine tunnel fire with the Fluent software and created piecewise function to express the evacuation rate of personnel. It is found that CO gas spread evenly at the initial stage of a fire and the installation location of rescue capsule was located (Zhang et al., 2012). Zhong et al. conducted a series of mechanical exhaust experiments, quantitatively analyzed the influence rules of vent velocity and height on mechanical smoke ventilation efficiency, and pointed out that the smoke ventilation efficiency can be improved by increasing vent height and smoke curtain drop height (Zhong et al., 2010).

In order to satisfy the requirements of different functions, underground buildings are often divided into relatively smaller functional areas. For small and medium-sized underground functional areas, mechanical smoke exhaust is acceptable in terms of technical difficulties and fire cost. However, in recent years, many

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large-sized underground functional areas have appeared in China, such as Vehicle Depot of Choking Chemical Plant, Beijing Metro Line 7, Suzhou Taiping Rail Transit Depot and Nanjing Hexi Bus Rapid Transit Line Depot. In order to meet the requirements of practical functions such as parking, cleaning and maintenance, the total area of these underground depots reaches tens of thousands of square meters, and the train overhauling area or rail line throat area reaches 10,000 square meters, which cannot be further separated. Furthermore, all these underground depots have to take the top-cover developments into consideration so as to get the 'high economic efficiency of land use', which may increase fire accident risk if it goes beyond control. Since the ventilation rate requirement conflicts with the blower capacity, large-sized spaces should be divided into partition areas and equipped with multiple sets of smoke exhaust systems in order to satisfy the ventilation requirement in case of accidents. However, large amount of fresh air will be exhausted since it is hard to form adequate smoke layer under exhaust vents in such large spaces, which will drastically increase the technical difficulties and cost. Compared with mechanical smoke exhaust, natural exhaust is more economic and green. Therefore, it is necessary to design a natural ventilation scheme for such complicated buildings.

Currently, the smoke control for large spaces can be made by calculating ventilation volume per hour. However, this method has some shortcomings. When it comes to a little larger space, it is not economic since large amount of fresh air is directly inhaled into the smoke exhaust outlet, which can reduce the mechanical smoke ventilation efficiency. But as for some smaller spaces, the design value of air exchange rate is too low to meet the ventilation requirement. So, it is suggested to make use of another smoke control method available, namely the performance-based design, which focuses on predicting the interface of smoke layer (Zhao et al., 2009). Based on this method, Zhong et al. found the critical height of smoke exhaust outlet so as to achieve the maximum smoke ventilation efficiency under certain conditions (Zhong et al., 2010). This method can also be used to design natural ventilation scheme for large spaces.

However, there are some problems needed to be considered before starting the natural ventilation design process for such large underground buildings. First of all, smoke usually moves quickly in horizontal way driven by thermal buoyancy, which results in thinner smoke layer below the top outlets. As a result, it becomes difficult to use vertical exhaust. What's more, if smoke cannot be exhausted promptly, it needs to move a long way before being exhausted. During smoke movement, due to the heat transfer, on-way resistance and cold air entrainment, the smoke temperature decreases. Then, the insufficient thermal buoyancy and thermal driving force cannot support its suspension. And when smoke layer height descends to unsafe height, it becomes dangerous for personnel to evacuate. In addition, if the dynamic pressure of the smoke is insufficient to overcome the outlet or outdoor resistances, backflow may occur, which leads to low smoke ventilation efficiency (Fan et al., 2014). Finally, thanks to the shortage of land resources in complicated cities, a top cover is adopted, which makes it difficult for people to place enough openings on its top for natural ventilation.

2. Building model and natural ventilation scheme

It is extremely complicated to develop a cover for large underground spaces since it might be a building group with different functions. Fig. 1 shows the cover-based developments of Suzhou Taiping Rail Transit Depot, the cover building group is composed of residential buildings, commercial buildings, complex buildings or even high-rise buildings. So it is obvious that the development of this kind of top cover indeed will increase the risk of its underground part in case of fire accidents, i.e. it brings technical problems to the design of natural ventilation scheme for its underground part. Fig. 2 shows the sectioned partial view of the underground rail transit depot together with the development of its cover. It mainly includes three parts: the underground part used for urban rail transit depot, the first floor used for ground parking and the high-rise buildings located above second floor platform. There are two evacuation platforms in accidents, one is the second floor platform for accidents occurring in its cover part (including the first floor), and the other is the main ring road located on the periphery of its underground part, which is used for underground evacuation and fire rescue. This scheme of evacuation makes it possible to design natural ventilation scheme for its underground part. The first floor can be used as an interlayer between underground part and its cover-based part, which can cut off their linkage in case of fire accidents. So when fire occurs in its underground part, smoke can be exhausted to the interlayer through some connected smoke shafts, and the boundary of the interlayer needs to be open. Besides, some bridges across the main ring road above are needed to connect the interlayer platform with the outside ground, as shown in Fig. 3.

Before starting the feasibility analysis for this natural ventilation scheme, it is quite necessary to obtain the optimum parameters of building for the highest ventilation efficiency in case of fire. The feasibility analysis can become effective on condition of building model with the optimum parameters. In order to make the research results applicable for practical engineering, a building model of 100 m $\times$ 100 m $\times$ 5 m is setup based on field investigation of underground comprehensive depots in China. And the size of the building model is close to the train overhauling subarea, which is the biggest among all the functional subareas. In order to set openings at the top without affecting the development of its cover, an interlayer (first floor) with open boundaries is added between the underground part and its cover-based development, and the elevation of its ground platform is leveled with that of road surface outside. In addition, with proper design of the smoke shaft, dynamic smoke pressure can be enhanced and the efficiency of smoke ventilation can be improved. And a certain high smoke shaft can ensure the safety of smoke layer high in the interlayer. In order to guarantee the maximal distance between natural ventilation opening and smoke control zone not to exceed 30 m (The ministry of public security of People's Republic of China, 2005) and not to occupy too much usable area of the interlayer, either, 16 smoke shafts are evenly arranged at its top. A reasonable natural ventilation scheme requires not only adequate openings on its top for smoke extracting but also sufficient air supply to keep positive pressure within the building, which is significant to keep the smoke ventilation efficiency high. In light of adding air supply and some smoke exhaust functions, a ring road with width of 4 m is designed, which can not only solve the problem of side windows, but also can play the role of fire channel, improving rescue efficiency. As to the side window size, Nanjing Bus Rapid Transit Line 1 was taken for reference, which is 4 $\times$ 1.8 m (width $\times$ height) with space interval of 4 m, as shown in Fig. 4.

3. Influential factors of smoke ventilation efficiency

3.1. Definition of smoke ventilation efficiency

Smoke ventilation efficiency can be defined as a mass ratio between the total smoke extraction level and total yield level during the whole monitoring time. The main combustion product CO_2 is regarded as a reference of smoke. Assuming the combustion is complete (in well-ventilated building), the ventilation efficiency