Study of Natural Ventilation Potential and Performance for the Undergroun Utility Corridor Using Numerical Method

Xiaoyu Zhao[1] *and Yan Wu*[1*]

[1]School of Mechanical Engineering, Tongji University, China.

Abstract. The utilization of urban underground space is a strategic choice to solve land space shortage, traffic congestion and environmental pollution. The underground corridor serves as both commercial and entertainment spaces. Proper natural ventilation system is believed to combine the advantages of good indoor air environment and high energy efficiency. In the present study, field experiments and numerical simulation are performed to compare the natural ventilation performance in the underground utility corridor under different layout of gates and skylights during the transitional season. The results show that the overall Richardson number is calculated to analyze the dominant driving force of the corridor. Second, it has been found that the arrangement of skylights and asymmetric gates can well promote natural ventilation in the corridor. The air exchange rate of the corridor with asymmetrical outlet is 10% higher than that with symmetrical outlet under the conditions in this study. Third, the wind speed at the openings in the middle of the corridor is higher than that of other openings in the corridor with skylights.

1 Introduction

As an important trend of future urban development, the utilization of underground space has played an important role in alleviating urban traffic congestion and solving the shortage of urban land resources [1]. The underground corridor, a long and narrow underground passage with dual functions of commercial space and traffic space (nodes) in large cities, is important and conductive for the compactness and sustainability of cities [2-5].

With the concept of green and ecological building gradually gaining popularity, natural ventilation has received more attention. To making a new expression for calculation of the airflow rate in single sided natural ventilation, Larsen et al. [6] performed a wind tunnel experiment and studied the change of dominant driving force under different temperature difference and wind speed. Chu et al. [7] conducted wind tunnel experiments to study the effects of wind direction, wind speed, and opening area on ventilation efficiency, and proved that two openings on the single wall has better ventilation effect than one opening, and found that buildings with internal partitions has lower exchange rate than buildings with no partition inside. In addition to the factor of openings, factors such as ventilation mode, window type, window area and orientation will affect the performance of natural ventilation, and the most influential factor is the ventilation mode [8].

The natural ventilation of underground buildings has certain particularities. Underground buildings are connected to the external environment only through entrances, exits, ventilation openings, etc., so underground buildings are relatively closed, and the opening of windows is limited. Sim et al. [9] illustrated the advantages and disadvantages of Earth shelter buildings and compared the different designs, locations, and climates of the buildings. Liu et al. [10] analyzed the influence of local heat sources on the natural ventilation of underground space by numerical simulation, and studied the multi-stable problem of airflow movement of buoyant ventilation in underground space. Li et al. [11] conducted a field test in an underground slope tunnel and proposed an equation for predicting the thermal pressure of a sloping underground tunnel, and found that the temperature difference between the air and the wall of the tunnel is the main factor affecting the thermal pressure efficiency. Porras et al. [12]studied the natural ventilation behavior of tunnels, chimneys, and caves at different times of the year and found that ground temperature plays an important role in regulating natural ventilation in underground buildings.It can be seen that the natural ventilation of underground buildings has a certain research basis, and the utilization of buoyancy is very important for the natural ventilation of underground buildings; at the same time, it can be found that the current research on natural ventilation of underground buildings mainly focuses on tunnels.

Although underground corridors are a relatively new building type, the construction of underground corridors is an important trend in future urban development. However, most of the studies on underground corridors so far have been carried out from the aspects of urban planning and road design, and there are few studies on the ventilation performance of underground corridors. In addition, the underground corridor has a long and

* Corresponding author: yan.wu@tongji.edu.cn

narrow structure, and its ventilation characteristics are different from those of ordinary public buildings. At the same time, the ventilation requirements of underground corridors are different from those of tunnel buildings. Therefore, it is necessary to study the natural ventilation performance of underground corridors.

The purpose of this study was to investigate the natural ventilation potential of the underground corridor through field experiment and to analyze the dominant drivers of natural ventilation in the underground corridor. In addition, the airflow distribution under different layouts of gates and skylights is studied through numerical simulation, and an optimal layout scheme is attempted to be designed.

2 Field experiment

2.1 Test objects and method

In order to understand the wind speed level of the natural wind near the underground corridor during the transition season and provide boundary conditions for numerical simulations, a field experiment was carried out in an underground corridor in Shanghai. There are shops on both sides of the corridor, with 14 gates. The wind shaft is set up on the roof of the corridor, and the skylight can be closed or opened, as shown in Fig. 1. The total length of the corridor is about 480m, the width is about 8.5m, the height of roof is 6m, and the height of the wind shaft is 1.6m.

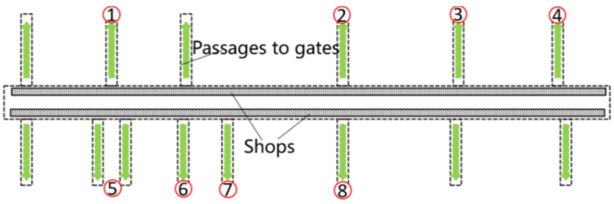

Fig. 1. Floor plan of the underground corridor and measuring points location.

Fig. 2. Street View of the Underground Corridor.

Table 1. Measuring probes.

Sensor type	Measuring range	Measuring accuracy
Hot-wire Anemometer	0~+20m/s -20~70℃	±(0.2m/s+1%x) ±1.8℃
Indoor Air Quality Probe	0~10000ppmCO_2 0~+50℃	±75ppmCO_2 ±0.5℃

The wind speed near each gate of the corridor and the temperature difference between the corridor and the outdoor environment can reflect the natural ventilation potential of the underground corridor driven by wind and buoyancy. Use testo480 tester to measure wind speed and temperature. The specifications of the sensors used are shown in Table 1. The incoming wind speed was measured near the gates, and the temperature was measured inside and outside the corridor, and these parameters were measured at a height of 1.6m. Considering that the parameters of each location in the same block do not change much, only the wind and heat parameters of several representative locations are measured, which are shown in Fig.1. According to the weather data provided by the nearby meteorological station, the test condition is that the wind speed is of level 2 (1.6-3.3m/s) and the temperature is 15℃, which meets the temperature and wind speed requirements for natural ventilation in the building.

2.2 Test results and analysis

The wind speed of the measuring point obtained from the test is shown in Fig.3. The wind speed of different measuring points varies greatly, and the wind speed of the same measuring point also has large fluctuations, which may be caused by the distribution differences of surrounding buildings, trees, etc. and the instability of natural wind; however, most of the average wind speed of the measuring points is about 0.5-1.5m/s. In addition, since the built corridor has already started operation, and the indoor air conditioning system is on, So the indoor temperature under natural ventilation cannot be measured correctly.

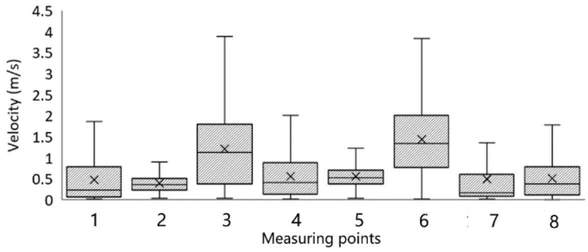

Fig. 3. Wind speed at each measuring point

The Richardson number (Ri) of the underground corridor is calculated in order to evaluate the dominant driving force of natural ventilation in the underground corridor. Ri is the ratio of the Grashof number (natural convection) to the Reynolds number (forced convection), and in general, neither natural convection nor forced convection can be ignored when $0.1 < Ri < 10$. According to the general requirements of the indoor thermal environment, take 25°C as the natural temperature during natural ventilation, that is, the temperature difference between indoor and outdoor is 10°C; the wind speed is 0.5m/s, and the characteristic length is the height of the corridor, which is 6m. The obtained Ri is about 8, which means that it is necessary to consider the combined effect of thermal pressure and wind pressure in the natural ventilation of the underground corridor.

3 Computational set-up and numerical method

This section outlines the CFD simulation method used in this paper. The physical descriptions of the studied natural ventilation in the underground utility corridor are first provided in Section 2.1. And then the numerical models and scheme employed in this study are introduced in Section 2.2. Then the boundary conditions of the current simulations are described in Section 2.3.

3.1 Physical models

The size and structure of the underground corridor are shown in Fig.4 and Fig.5, and the total length of the corridor is 500m. The claw-shaped passages lead to the gates of the underground corridor, the size of the gates is 4m×5m, and the size of the top skylight is 30m×2m. Each pair of gates are equally spaced at 100m intervals.

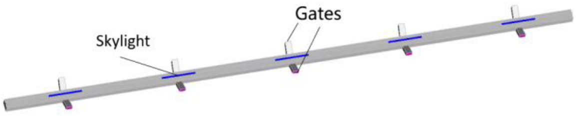

Fig. 4. Schematic diagram of the geometric model.

According to the wind speed obtained by the test, it can be seen that there is a natural wind with an average value of about 0.5m/s at the gates of the corridor in the transition season. The incoming wind direction is one side, as shown in Fig.5. Since the heat source is more complicated in the underground corridor during the operation period, the floor is used as the heat source to simplify the model.

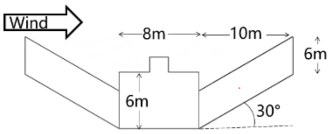

Fig. 5. Schematic of the cross-sectional structure and size of the corridor.

To study the influence of the layout of gates and skylights on the ventilation performance of the underground corridor, underground corridor models with different arrangements of gates and skylights were constructed, as shown in Fig.6.

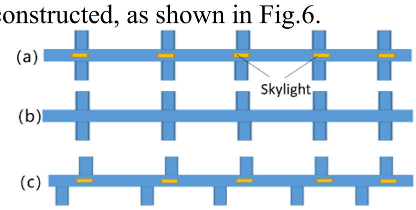

Fig. 6. Schematic of an underground corridor with different arrangements of gates and skylights.

3.2 Numerical models and scheme

Numerical simulations were performed using FLUENT (version 19.0). It is assumed that the airflow in the room is steady, continuous and incompressible, and satisfies the conservation of mass, momentum and energy. Navier-Stokes (RANS) equations and the RNG $k-\varepsilon$ turbulence model are adopted, which are widely used to predict airflow and temperature distribution in buildings. Indoor air is modeled as an ideal gas whose density varies only with temperature and follows the Boussinesq approximation.

The governing equations are solved using a segmented scheme. The coupling of the velocity and pressure is controlled by SIMPLE algorithm. The second-order upwind and central schemes are used to discretize the convection and diffusion terms, respectively, and the pressure term is discretized by a standard scheme. The residual convergence standard of energy is set as 10-6, and of other items are 10-3. In addition, when the monitored data of mass and energy reaches a balance within the allowable range, the calculation result is considered to be converged.

Unstructured automatic body meshes are used. Through the grid independence test, the total number of grids is finally 3.8 million and the maximum mesh size is 0.5 m.

3.3 Boundary conditions

The gates on one side of the corridor are Velocity inlet, and on the other are Pressure outlet; the skylights are Pressure outlet, and all other boundaries are Wall. The floor is set as a wall with the constant heat flux, which is estimated to be 95W/㎡ from the heat balance. The specific parameters of each boundary based on test data, are shown in Table 2, and other parameters refer to the literature (Fluent guidelines).

Table 2. Measuring probes.

Type of boundary	Parameter and Value
Velocity inlet	10m/s；15℃
Pressure outlet	0Pa；15℃
Wall (floor)	No slip；95W/㎡
Wall (others)	No slip；adiabatic

4 Results and discussion

In this paper, the ventilation characteristics of underground corridors with different layouts of gates and skylights are compared from the aspects of indoor airflow characteristics and ventilation rate.

4.1 Airflow characteristics

In order to obtain the airflow distribution in the corridor, three physical models shown in (a), (b), and (c) of Fig.6 are used to calculate respectively. The plane perpendicular to the skylight and passing through the central axis of the skylight is selected as the observation plane, and the velocity contour inside the corridors of different structures are shown in Fig.7. The two red boxes on the left and right are located at the positions of the geometrically symmetrical sections of the two pairs of gates and the gates in the middle of the corridor, respectively.

It can be seen from Fig.7, due to the equidistant distribution of the gates, the airflow distribution in the corridor presents the characteristics of repetition and symmetry. The distribution of the flow field near each pair of gates is basically the same, and the flow fields of two adjacent pairs of gates are symmetrical along the middle section of the two pairs of gates.

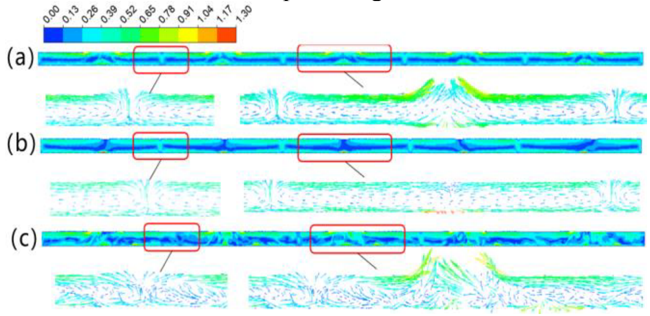

Fig. 7. velocity contour in underground corridors with different structures. (m/s)

According to (a) and (b) of Fig.7, comparing the flow field of the corridor with and without skylights, we find that the air velocity of the corridor with skylights is higher. Especially near the skylights, the effect of buoyancy force promotes the air to be discharged to the height of the corridor, and the effect of buoyancy is hindered when the corridor has no skylight.

Fig.(a) and Fig.(c) of Fig.7 are the velocity contour of the corridors with symmetrical layout and asymmetric layout of gates, respectively. It can be found that the overall flow velocity in the corridor is higher when the gates on both sides are asymmetrically arranged, and the symmetry of the flow field is not obvious. The asymmetry of the gates promotes the flow of air along the length of the corridor and allows for better ventilation.

4.2 Analysis of ventilation rate

The ventilation rate of each pressure outlet of the corridor under the three working conditions is shown in Fig.8, where the positive value is the inflow and the negative value is the outflow. At an ambient wind speed of 0.5m/s, the total ventilation rate in the underground corridor with asymmetric gates is about 118kg/s, which is about 10% higher than when the gates are symmetrically distributed. At the same time, it can also be seen that in the condition of opening the skylight, the gates and skylights in the middle of the corridor bear more ventilation load. This may be due to the fact that the skylights promote the buoyancy effect, which makes the air flow to the middle of the entire corridor.

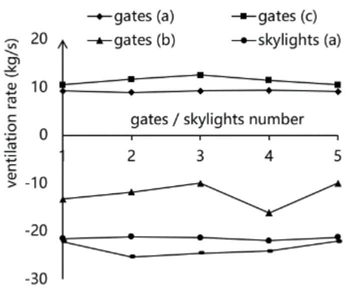

Fig. 8. Ventilation rate of gates and skylights in different cases.

5 Conclusions

In this paper, the natural ventilation characteristics of underground corridors are studied through the methods of CFD numerical simulation and field experiment, and the following conclusions are obtained:

(1) The natural ventilation in the underground corridor belongs to mixed convection, and the effects of wind pressure and thermal pressure cannot be ignored during transitional seasons. In light wind weather, the average natural wind speed around the underground corridors in large cities can reach 0.5-1.5m/s.

(2) The design of skylights and asymmetric gates can greatly promote the natural ventilation in the corridor, which also shows that the effect of heat pressure in the underground corridor is very significant.

(3) Although all the gates and skylights are of the same size in the studied corridor, the gates and skylights in the middle of the corridor have greater ventilation and flow rate. Therefore, the central skylights and gates should be designed to be larger to encourage natural ventilation when possible.

This paper considers the ventilation performance of the underground corridor of different structures, and has a certain reference value for the passive ventilation structure design of natural ventilation in underground corridors, which facilitates low-energy operation of underground corridors and promotes the green development of cities.

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