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Ventilation and environmental control of underground spaces: a short review

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Abstract. More and more underground spaces were used in 21st century because of rapid urbanization, traffic problems, etc. Underground city, metro, tunnel, mine, industrial and agriculture engineering, civil air defence engineering need large underground spaces. Underground spaces with different thermal, ventilation and lighting environments may cause comfort, health and safety problems. Concrete problems include excessive humidity, heat transfer specialty, excessive CO caused by blockage in long distance traffic tunnels, difficulty in smoke exhaust and evacuation during fire, harmful microorganism, radioactivity pollutants, psychological problems, and so forth. Air quality control technologies for underground spaces, including ventilation technology, dehumidification technology, natural energy utilization technology, smoke extraction technology and ventilation resistance reduction technology, will be reviewed. Ventilation for smoke-proof/evacuation and ventilation will also be reviewed.

1 Diversity of underground and semi-underground spaces

The development and utilization of underground spaces has a long history. From caves of primitive society to drainage facilities of slave society; from underground tombs of ancient monarchs to metro spaces of industrial society; from underground air-defense shelters of the 20th century war periods to underground cities of modern society, the utilization of underground spaces becomes more and more common.

With rapid urbanization and population densification, development of underground spaces becomes necessary. Modern underground spaces are mainly used in the following aspects.

- Underground dwellings,
- Underground commercial facilities and some public buildings,
- Underground public transportation facilities, such as subways, underground tunnels and garages,
- Municipal facilities, such as utility tunnels,
- Underground industrial buildings, such as underground power stations and mines,
- Underground air-defense shelters, coalmine refuge chambers,
- Underground spaces for agricultural engineering,
- Underground storage spaces.

2 Unsolved problems in underground spaces

2.1 Moisture transfer

Compared to spaces above ground, one of the distinguishing features of underground spaces is high humidity especially in summer. Humid environments in underground spaces have important impacts on human health and comfort, safe operations and service life of equipment. Humid underground spaces can cause microbial growth, and lead to corrosion and damage of building surfaces and equipment. Therefore, it is important and necessary to control the moisture, which mainly comes from wall dampness, and hot and humid air. The dampness of the wall is caused by the following reasons.

2.1.1 Evaporation of construction residual water

In the construction process, water is needed for constructing walls and grounds. Most of the water will be evaporated into underground spaces, which can reach

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95% relative humidity in the first two years after construction.

2.1.2 Groundwater penetration through the coating layer

Under gravity effects, groundwater can flow through rock cracks to middle spaces of rocks and coating layers. Without careful design and construction, groundwater may penetrate through the coating layer under osmotic pressures. The influence is more serious in rainy season when groundwater is strong and groundwater level is high.

2.1.3 External humid air penetrates into the interior

When partial pressure of water vapour inside the constructed spaces is smaller than that outside the constructed spaces, water vapour outside envelop will diffuse into interior which is a common moisture transfer process in underground spaces. The amount of wall moisture is directly related to local geological and hydrological conditions, rock ruptures, seasons, structural forms of the coatings, building materials, temperature and humidity of indoor air, air change rates and moisture from construction process.

2.2 Heat transfer

When air flows through underground tunnel, the heat exchange between airflow and isothermal surfaces is a complicated and unstable heat transfer process in most cases. Mihalakakou et al. [1] and Li et al. [2] proposed models validated by long-term measurements to describe thermal influences of key variables such as length, diameter and air velocity. Ben Jmaa Derbel and Kanoun [3] studied cooling and heating effects of underground heat pipes using a thermal resistance method to evaluate the thermal capacities. Krarti and Kreider [4] used a simplified analytical model, which assumed that all variations are periodic functions of time. Wu et al. [5] also proposed a numerical model to predict the thermal performance and cooling capacity of underground soil to air systems. Hokoi et al. [6] developed an approximate two dimensional model of an underground rectangular tube to produce a solution nearly equal to that of a three dimensional model.

There are many factors affecting tunnel heat transfer, such as the tunnel shape (rectangular, horseshoe, ellipse, round, etc.), tunnel size, air inlet temperature, wall roughness, airflow rate and mass transfer (moisture condensation, evaporation).

2.3 Pollutants

Pollutants in underground spaces mainly include TVOC, CO, PM_{10}, radioactive Rn, and so on. Concentrations of formaldehyde and TVOC in underground malls are higher than that of outdoor environments. Tao et al. [7] investigated concentration levels of formaldehyde and TVOC in 9 underground malls in Xi'an, China. Mean mass concentrations of formaldehyde and TVOC range from 0.05 mg/m^3 to 0.26 mg/m^3 and from 0.34 mg/m^3 to 3.56 mg/m^3, respectively. Chow et al. [8] investigated indoor CO concentrations in a large underground car park in Hong Kong. CO concentration does not necessarily increase when the total number of cars increase. Braniš [9] compared PM concentrations recorded on streets, in underground spaces and inside underground trains. The highest PM_{10} concentration was recorded inside the Metro trains (113.7 mg/m^3 and 1.44 mg/m^3), the second highest in the underground spaces of stations (102.7 mg/m^3 and 1.29 mg/m^3), followed by outdoor environment (74.3 mg/m^3 and 0.85 mg/m^3). Li et al. [10] investigated the daily and seasonal variations of radon concentrations in underground buildings in major cities of China. Radon concentrations in the underground buildings change through two cycles each day. Radon concentrations in the underground buildings in winter are lower than those in summer, which is opposite to the situation above ground level.

Under construction periods, common harmful components in underground spaces are CO, CO_2, NO_2, SO_2, dust and exhaust gas from construction equipment. Construction ventilation, used for comprehensive control of underground space construction environments, has a direct impact on body health and construction efficiency of tunnel construction workers. Sasmito et al. [11] studied several ventilation scenarios in cross-cut regions where active mining took place and found that combination of brattice–exhausting system yields best performance. During excavation, right-cut scenario can be considered and implemented to minimize presence of recirculation zone. Further, additional auxiliary ventilation is required during excavation to enhance gas control. Liu et al. [12] studied construction ventilation in deep diversion tunnels using Euler–Lagrange method. Aiming at the construction ventilation of deep diversion tunnels with construction branch tunnels and transverse passageways, a three dimensional unsteady Euler–Lagrange two phase turbulence model was utilized with considering air leakages, gas–solid heat exchanges, gas–solid interaction forces and particle collisions.

2.4 Smoke control and exhaust

There are several characteristics when fire happens in underground buildings. Firstly, hot smoke fume can not be discharged in time, space temperature rises fast, heat dissipation is difficult, and flashover occurs. Secondly, the amount of smoke is large and build up for a long time. Insufficient combustion happens because of insufficient ventilation. Concentrations of toxic gases such as carbon monoxide and carbon dioxide increase rapidly, and smoke layer is thick and easily spreads to other areas. Last, underground buildings have limited entrances/exits and long evacuation distances, which makes evacuation and fire fighting difficult.

Once a fire breaks out in an underground space building, it often brings huge losses. For examples, subway fire happened at Daegu, Korea once killed 198 persons and injured 147 persons. Another subway fire happened at Baku, Azerbaijan, killed 289 persons and injured 265 persons [13].

Fire-induced smoke is the main reason of huge casualties and property loss when fire happens in underground spaces. Characteristics of fire-induced smoke in uniform environments and thermal stratified environments have been studied for many years. Temperature of smoke released by fire sources is much higher than ambient air temperature. Buoyancy caused by the temperature difference can drive smoke upward. During the rising process, smoke plume entrains surrounding air with lower temperature. The amount of smoke generated in a fire is mainly determined by the amount of air entrained by the plume. Cetegen et al. [14] measured entrainments in near and far fields of fire plumes rising from fire sources with different diameters and heat release rates. Experiments indicate the presence of three regions above the fire source. Heskestad [15] proposed a model of virtual origins and a rationale for temperature correlations. Hu et al. [16] studied the rise time of buoyant plume front at three different positions (at the center, near a wall and in the corner of the atrium floor) by full scale burning tests. Early fire smoke movements and detection in large volume spaces with stratified environments inside was also studied.

The effective way to control the fire induced smoke is ventilation. Li et al. [17] studied the temperature distribution of fire-induced flow along mechanically ventilated tunnels. A model was proposed, which considered tunnel ventilation velocities and fire heat release rates, to predict the temperature distribution of the fire flow with enough accuracy for engineering use. Khattri [18] quantified the influence of ventilation velocity on the parameters including the maximum ceiling temperature, the maximum floor temperature, the maximum ceiling flux, the maximum flux on the floor and the fire growth rate. Gao et al. [19] pointed out that hybrid ventilation can inhibit the smoke dispersion more effectively than conventional mechanical ventilation. With 3 m × 3 m or larger roof window in atrium ceiling, hybrid ventilation is an effective method to exhaust fire-induced smoke. The confluence, storage, and suppression effects of domes on fire-induced smoke control in subway stations were also investigated [20]. Preliminary results suggest that CO concentration in the hall of a subway station is significant lower when the fire source is located under the dome. For a subway station without a dome, there is a linear relationship between the average CO concentration and the distance from the coordinate origin. Li et al. [21] studied the characteristics of smoke in a reduced scale (1:12) corridor model of a underground hydraulic machinery plant under natural filling conditions. Maximum smoke temperatures under the ceiling are all lower than 200 ℃ when heat release rates are less than 1500 kW.

2.5 Harmful microorganism

Microbial contamination is mainly caused by fungi, bacteria and viruses. Moisture in underground buildings is the main reason for microorganism increases. Appropriate temperature and humidity promote growth of microorganisms on polluted surfaces. 51 underground spaces were investigated from 1992 to 2004 [22]. It was found that anaerobes in aisles are 4.2 and 3.8 times of those in semi-closed and open aisles respectively. Li et al. [23] investigated the effect of air conditioning parameters (temperature, relative humidity and supply air velocity) and deposited dust on microbial growth in supply air ducts. Relative humidity is the main influential factor to fungal growth at 3.0 m/s supply air velocity.

To guarantee the good environmental quality of underground spaces, comprehensive control measures should be taken including keeping underground space dry and clean, disinfection of underground spaces with disinfectant, using moisture proof coating/hygroscopic material, correct design, operation and maintenance of ventilation and air conditioning systems, using ultraviolet lamps to disinfect air, and so forth.

2.6 Comfort and psychological problems

The underground space environment often has great negative impacts physiologically and psychologically such as psychological depression, boring, a sense of fear. The reasons belong to lack of sunlight and visibility to the outside, high humidity, closeness, poor air quality, and so forth.

Ventilation technologies, temperature and humidity control technologies, noise control technologies, daylight transmission technologies, as well as environmental quality requirements in underground spaces have been extensively studied. Han et al. [24] selected 6 subway stations in Seoul for physical environment measurements and performed a survey of 5,282 passengers. Based on standard equivalent temperature (SET*), comfort range is 16.1 to 31.2 ºC for concourses and 15.9 to 31.5 ºC for platforms. Li et al. [25] conducted both thermal comfort field measurements and questionnaires surveys in different underground air-defence basements in 95 cities in China. Thermal acceptable temperature range is unsymmetrically distributed with respect to the thermal neutral temperature and changes with the ground temperature.

Psychological problems caused by underground spaces are more complicated. Research results show that even if the inner space environment of underground buildings reaches the same comfort level as that of above ground buildings, psychological obstacles still exist. Other investigations show that people ignore actual situations although some underground buildings have sufficient artificial light sources, good mechanical ventilation and humidity control. In underground buildings, it is easy to lose a sense of direction, and cause tension, anxiety and fear because of invisibility of building forms and lack of external reference points provided by windows. Long stay in underground buildings leads to the fact that subjective perception of time increases, sight and memory worsen, fatigue increases, working capacity and protective functions of an organism decreases, and hallucinations [26]. Psychological recognition of underground spaces is an important issue, which need in depth and comprehensive research.

2.7 Natural energy utilization technology

Because of thermal inertia, soil temperature at a certain depth (usually 8-10 meters) is lower than air temperature in summer and higher than air temperature in winter. Air flowing through underground spaces is cooled in summer and heated in winter. Therefore, underground tunnels can be used as a natural cooling/heating source. Tunnel ventilation and air conditioning technology are widely used in air defense shelters, water power station and similar underground constructions. Its high cooling and heating potential result in a major reduction in energy consumptions and initial investments. When using underground tunnels for air pre-cooling and pre-heating, it is necessary to take wall temperature, air velocity, tunnel structure, depth and other factors, as well as local meteorological conditions into consideration.

To study dam tunnel cooling/heating effects, Ren et al. [27] conducted 24 hours field measurements continuously in underground multi-tunnels. Both velocity and temperature of inlet air have significant impacts on heat exchange. Compared with 30 °C inlet air temperature, the dam tunnel has better cooling effect when the inlet air temperature is 45 °C. Yuan et al. [28] proposed a new coupled cooling method of latent heat thermal energy storage (LHTES) combined with pre-cooling of envelope (PE), which can meet requirements of safety, no power, stability, reliability and has merits of small occupied volume, no maintenance in peacetime and fully utilization of the external natural cold source. Li et al. [29] studied air temperature variations from inlets to outlets and cooling capacities of underground tunnels. They found that air temperature decreases rapidly with the increase of tunnel length. After a certain length, the air temperature and cooling efficiency do not change any more. Cooling efficiency reaches a stable value at 90 % to 95 %. Experimental results show that both surface roughness and air velocity influence heat transfer of underground tunnels.

3 Air quality control and ventilation

As a relatively closed and humid place, ventilation for underground space buildings is particularly important. According to driving forces of airflow, ventilation can be divided into natural ventilation and mechanical ventilation. According to different use situations, ventilation can be divided into general ventilation, emergency ventilation, construction ventilation, etc.

Natural ventilation systems are usually driven by natural forces such as natural wind, thermal buoyancy and geothermal energy. As mentioned above, the concept of natural ground-coupled ventilation uses stable soil temperature for preheating or precooling of air for buildings. In the early millennium B.C., Iranian architects used wind towers and underground air tunnels for passive cooling and ventilation. Iranian solutions of natural ventilation is integrated with its famous qanat systems usually dug in the slope of a mountain or hillside. The ancient Egyptians already took advantage of pressure differences created by the temperature change between day and night to ventilate construction works of underground tombs and temples [30]. Airflow of natural ventilation in underground constructions is complex which is strongly affected by temperature difference. The influence of outdoor air is increased during autumn and winter. It is significantly reduced in spring and summer. Access tunnel and ventilation chimney, as transition areas, are those which experience highest temperature changes, and play a key role in regulating natural ventilation [31]. Natural ventilation varies throughout the year. Natural ventilation in underground spaces should consider influences of outdoor seasonal wind direction and wind speed, and use wind pressure to enhance natural ventilation. Ventilation outlets and ventilation pipes should be reasonably arranged. The area of ventilation outlets should be appropriately enlarged to minimize ventilation resistance for enhancing natural ventilation.

As an effective way of underground space environmental control, mechanical ventilation has also been widely studied and applied in mines, tunnels, metro stations, hydropower stations, storehouses, etc. To reduce concentrations of harmful substances such as methane and ensure safety of workers in underground coal mining, two auxiliary ventilation systems in dead-end roadways, forcing and exhausting, are used. Air curtain systems for mine refuge chambers prevent harmful gases in the tunnel from entering the chamber. Their barrier efficiency is affected by their structural parameters, installation location and airflow angle as well as size of chamber door. Zhang et al. [32] pointed out that air curtain systems, with air curtains installed on two sides of the door frame behind the door wall that ejected air parallel to the door frame, provide a relatively good barrier effect. An air curtain system that uses pipeline air curtains with a nozzle diameter of 1 mm and a nozzle distance of 15 mm demonstrates a relatively good barrier effect and a barrier efficiency of 55 % to 60 %. For hydropower stations, proper thermal and humid environment is of significance for human safety and steady operation of power generation systems. Ventilation technologies for underground large spaces, i.e. generator floor, are cutting-edge studies. Key factors affecting underground train systems are types of ventilation operating in tunnels and station platforms, which have been widely studied. The train piston effect is also important, which may help to reduce energy consumption. Ventilation design for underground repository should consider architectural design, gradual extension of storage zones, ventilation rates and weather conditions, which are likely to influence ambient conditions along shafts, galleries and storage modules [33].

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