Underground Spaces

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Underground spaces with varying thermal, ventilation, and lighting environments can face problems of comfort, health, and safety. High temperatures, high humidity, difficulty in flue gas emission, harmful microorganisms, radon, and physical and psychological problems are examples of issues.

underground space ventilation environment control

1. Diversity of Underground and Semi–Underground Spaces

Underground space development and utilization has a long history. The use of underground spaces has increased, from caves in primitive society to drainage facilities in slave society, from catacombs of ancient emperors to subway spaces in industrial society, from underground air raid shelters in the twentieth century to underground cities in modern society.

The development of underground spaces is becoming increasingly important as urban population density rises. In recent decades, underground spaces have been shown to provide an additional 25–40% livable space [1]. Furthermore, as the problem of urban land scarcity worsens, underground spaces show great promise in alleviating urban land scarcity [2][3]. Underground spaces in modern times have primarily been used in the following ways.

- Underground residential buildings;
- Underground commercial facilities and some public buildings, such as underground shopping malls and underground hotels;
- Underground public transport facilities, such as subway, underground tunnels and garages;
- Municipal facilities, such as utility tunnels;
- Underground industrial buildings, such as underground power stations and mines;
- Underground air raid shelters, coal mine refuge rooms, agricultural engineering underground spaces;
- Underground storage spaces.

2. Unsolved Problems in Underground Spaces

2.1. 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 those in outdoor environments. Tao et al. [4] 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. Liu et al. [5] investigated patterns of pollutant concentrations and their sensitivities to traffic volume in naturally ventilated underground parking garages. They found that the $PM_{2.5}$ concentrations in underground parking garages were slightly higher than in ambient environments, but PM_{10} concentrations were significantly higher. Chow et al. [6] investigated indoor CO concentrations in a large underground parking garage in Hong Kong. CO concentration does not necessarily rise when the total number of cars increases. Oh et al. [7] investigated the exposure of particulate matter and TVOC in underground parking garages under various ventilation modes and their impact on health. The levels of inhalation exposure to PM and TVOC as well as the health effects associated with them, are affected by the ventilation types used in underground parking garages. For most residential underground parking garages in China, natural ventilation is the most popular ventilating mode, when construction and operating costs are considered. Therefore, more effective ventilation systems are required depending on the traffic–volume and indoor air quality (IAQ). Yang et al. [8] investigated IAQ in an underground shopping mall. Although the CO_2 concentration can meet the requirement stipulated in the standard, people also recommended that IAQ, the maximum acceptable CO_2 concentration stipulated in the standard, should be investigated further. Li et al. [9] investigated the combined effect of elevated temperature, RH and CO_2 concentration on human responses. They found that high RH and CO_2 concentration degrade air quality, and that the combined effects of high air temperature, RH and CO_2 concentrations result in a variety of human responses. Braniš [10] compared PM concentrations measured on streets, in underground spaces and within subway trains. The highest PM_{10} concentrations were found inside Metro trains (113.7 mg/m^3 and 1.44 mg/m^3), followed by underground station spaces (102.7 mg/m^3 and 1.29 mg/m^3), and outdoor environments (74.3 mg/m^3 and 0.85 mg/m^3). In Europe, related agreements stipulate that subway air-conditioning filters should be replaced regularly every month [11]. However, Moreno et al. found that filters could maintain air quality for at least 3 months, and if pathogens can also be maintained within the standard range during this period, then the current agreement needs to be changed. They also pointed out that the WHO should give additional and equally important attention to improving underground air quality [11]. "Construction specifications on underground excavation engineering of hydraulic structures" stipulates that the minimum air velocity used when calculating the ventilation of large underground spaces is 0.15 m/s [12]. Li et al. found that the air velocity could control the dust level, provide the required oxygen concentration and control the temperature within an acceptable range, but it was not enough to reduce the CO concentration below the acceptable safety limit [13].

Radon is a major environmental carcinogen identified by the World Health Organization, and it is primarily emitted by soil and building materials. In reality, the radon risk is primarily caused by short-lived radon progeny. The increased exposure caused by short-lived radon progeny in underground mines is primarily due to inadequate ventilation and increased radon exhalation from surface materials [14]. Li et al. [15] investigated the daily and seasonal variations of radon concentrations in underground buildings in major cities of China. Radon concentrations in the underground buildings fluctuate in two cycles per day. In winter, radon concentrations in the underground buildings are lower than in summer, which is the opposite of the situation above ground level. The primary external factor causing this phenomenon is seasonal variation in outdoor temperature [16]. Jin et al. [17] summarized the characteristics of underground indoor radon, its progeny, and the source to those of unequilibrium radon and its progeny. Underground indoor radon levels are influenced not only by building materials, but also by geological structure, air tightness of houses, indoor ventilation rate, people's living habits, and other factors.

During the construction phase, common harmful components in underground spaces are CO, CO_2, NO_2, SO_2, dust and exhaust gas from construction equipment. Ventilation during the construction phase, which is used for comprehensive control of underground space construction environments, has a direct impact on the body health and construction efficiency of tunnel construction workers.

2.2. Smoke Control and Exhaust

When a fire breaks out in an underground building, several characteristics emerge. First, hot smoke fumes cannot be discharged in a timely manner, space temperature rises rapidly, heat dissipation is difficult, and flashover occurs. Second, a lot of smoke builds up for a long time. Incomplete combustion occurs as a result of insufficient ventilation. Toxic gas concentrations, such as CO and CO_2, rapidly increase. The layer of smoke is thick and easily spreads to other areas. Finally, because underground buildings have few entrances and exits and long evacuation distances, evacuation and firefighting are difficult. When a fire breaks out in an underground space building, massive losses are often the result. A subway fire in Daegu, Korea, for example, killed 198 people and injured 147 others. Another subway fire killed 289 people and injured 265 in Baku, Azerbaijan [18]. A fire will result in significant losses and casualties.

When a fire breaks out in an underground space, the main cause of casualties and property loss is fire-induced smoke. For many years, researchers have studied the characteristics of fire-induced smoke in both uniform and thermally stratified environments. The temperature of smoke emitted by fire sources is significantly higher than the temperature of the surrounding air. The buoyancy caused by the temperature difference can propel smoke upward. During the rising process, the smoke plume entrains cooler air from the surroundings. The amount of smoke produced by a fire is primarily determined by the amount of air entrained by the plume. The maximum gas temperature beneath the tunnel ceiling is proportional to heat release rate (HHR), longitudinal ventilation rate, and ceiling height [19]. Cetegen et al. [20] measured entrainments in near and far fields of fire plumes rising from fire sources with different diameters and HHR. Experiments show that there are three regions above the fire source. Heskestad [21] proposed a model of virtual origins and a rationale for temperature correlations. Hu et al. [22] used full-scale burning tests to investigate the rise time of a buoyant plume front at three different locations (center, near a wall, and corner of the atrium floor). Early fire smoke movement and detection were also investigated in large volume spaces with stratified environments inside. A thermally stratified environment accelerates the decreases in axial temperature and velocity of a fire smoke plume until it reaches a maximum height [23]. In long and narrow structures, a ceiling jet would be constrained by vertical walls, resulting in smoke backflows and an increase in smoke temperature under the ceiling [24]. Li et al. [25] investigated smoke properties in a reduced scale (1:12) corridor model of an underground hydraulic machinery plant under natural filling conditions. When the HHR is less than 1500 kW, the maximum smoke temperatures under the ceiling are all less than 200 °C. Ji et al. [24] used two sets of small-scale experiments to conduct theoretical and experimental research on the maximum smoke temperature under the ceiling. They developed a relationship to determine the maximum smoke temperature. The method is appropriate for subway station fire engineering designs. Ventilation is the most effective way to control fire-induced smoke. Traditional ventilation systems used to control fires include the longitudinal ventilation system, supply air semi-transverse ventilation system, exhaust air semi-transverse ventilation system, full transverse ventilation system, and natural ventilation system [26][27][28][29][30][31]. The temperature distribution of fire-induced flow along mechanically ventilated tunnels was investigated by Li et al. [32]. To predict the temperature distribution of a fire flow with enough accuracy for engineering use, a model was proposed that took tunnel ventilation velocities and fire heat release rates into account. Khattri [33] investigated the effect of ventilation velocity on variables such as maximum ceiling temperature, maximum floor temperature, maximum ceiling flux, maximum flux on the floor and fire growth rate. Gao et al. [34] pointed out that hybrid ventilation can prevent smoke dispersion more effectively than conventional mechanical ventilation. Hybrid ventilation is an effective way to exhaust fire induced smoke with a 3 × 3 m or larger roof window in an atrium ceiling. Hu et al. [35] suggested that in an emergency scenario involving a train on fire stopping beside the platform of a subway station, the most effective strategic cooperative ventilation mode is only to activate the over track exhaust system of the tunnel rail track area with the aid of the activation smoke exhaust pattern of a platform ventilation system. Natural ventilation through vertical shafts or roof openings has the benefits of saving space, lowering costs, simplifying maintenance, and saving electricity. Because of the benefits listed above, the use of vertical shafts for natural ventilation has gained popularity. The effect of tunnel smoke exhaust on shaft geometry, shaft height, shaft cross-sectional area, and shaft aspect ratio has been extensively studied [36][37]. Vertical shafts connected at oblique angles provide better natural ventilation. The height of shafts has a critical value. To avoid entrainment of fresh air, the shaft's large section length and width should be divided into several smaller shafts. The phenomenon of smoke layer separation and blockage in shaft smoke extraction results in low smoke extraction efficiency [36]. Cong et al. [38] proposed a method of the board-coupled shaft to alleviate the blocking effect (BCS). The results show that this method can improve smoke extraction efficiency, but special consideration should be given to the size of the plate and the distance from the well. Despite extensive research into natural ventilation of vertical shafts, there are still many challenges to overcome. Gao et al. [39] investigated the effects of domes on the confluence, storage, and suppression of fire-induced smoke control in subway stations. Preliminary findings indicate that when the fire source is located beneath the dome, the CO concentration in the hall of a subway station is significantly lower. As a result, some architectural features aid in smoke control.

Generally, traditional ventilation systems reduce average smoke concentration of the entire spaces, which results in high-level smoke concentration in the lower part of the spaces when utilizing traditional ventilation systems.

2.3. Harmful Microorganism

Fungi, bacteria, and viruses are the most common causes of microbial contamination. The underground structure is relatively closed, with a constant temperature and high humidity environment that is ideal for the growth of wall mold [40][41]. Moisture in underground buildings is the main reason for microorganism increases. When there is water ingress or excess condensation within built environments, fungal growth usually occurs [42]. Fifty-one underground spaces were investigated from 1992 to 2004 [43]. It was found that anaerobes in aisles are 4.2 and 3.8 times of those in semi-closed and open aisles, respectively. Appropriate temperature and humidity promote growth of microorganisms on polluted surfaces. Li et al. [44] investigated the effect of air conditioning parameters (temperature, RH and supply air velocity) and deposited dust on microbial growth in supply air ducts. RH is the main influential factor to fungal growth at 3.0 m/s supply air velocity. Yu et al. [41] analyzes the influence of environmental factors on mold present on inner surfaces of Shenyang's underground walls, and found that the mold growth rate is most sensitive to humidity. They suggested that the humidity on the surface of the wall should be controlled below 84% to prevent rapid mold growth. Some microorganism growth shows evident changes related to seasonal and meteorological conditions. Heo and Lee [45] found that bacterial aerosol concentration increased by more than three times from March to April, and decreased by more than two times from October to November. The number of passengers had a small effect on the concentration of bacterial aerosols in the subway station. However, fungal aerosols are relatively unaffected by seasonal changes and a human presence. By contrast with underground stations, a field investigation indicated that the bacterial concentration in the utility tunnel was similar to that of underground stations with few passengers, and the fungal concentration was 3.2 times higher than that of underground stations [46]. Studies of aerosol microbiology in subway environments have focused on culture-dependent techniques, and the current study may have found only a small fraction of the actual microbial content, because the vast majority of microorganisms are not cultured by standard techniques [47].

Ventilation has been shown to be an effective method of controlling airborne microorganism contamination in underground spaces. Hwang et al. [48] measured the concentrations of culturable airborne bacteria (CABs) in the underground environment of 16 subway stations in Seoul, South Korea and found that CAB concentrations in stations with ventilation systems were significantly lower than those in stations without ventilation systems ($p < 0.001$). Zhang et al. [46] found that after ventilation for 1.0 h, 86.0% of airborne bacteria and 28.7% of airborne fungi were removed in an urban utility tunnel. In underground spaces with no ventilation systems, it is critical to reduce harmful microorganism concentrations and improve IAQ.

2.4. Comfort and Psychological Problems

Underground space environments frequently have significant physiological and psychological consequences, such as psychological depression, boredom, and a sense of fear. The reasons include a lack of sunlight and visibility to the outside world, high humidity, close proximity, poor air quality, and so on.

Extensive research has been conducted on ventilation technologies, temperature and humidity control technologies, noise control technologies, daylight transmission technologies, and environmental quality requirements in underground spaces. Racz and Petrilean [49] found that underground mines face the issue of condensate which drips down on the walls of the underground work especially in summer periods, thereby substantially changing the comfort of working conditions.

Fanger proposed predicted mean vote (PMV) in 1970, this model is only suitable for mechanical ventilation and is used to evaluate steady-state thermal environment. Therefore, many new prediction models have been proposed. Nicol and Humphreys [50] proposed an adaptive model in 2002. This model is only suitable for natural ventilation environments under specific conditions. In this environment, there is the possibility of thermal regulation such as opening windows and adjusting clothes. Recent studies have found that there is a “scissors gap” between PMV and thermal sensation vote (TSV) voting. Therefore, Yao et al. [51] used the “black box” theory to adaptively predict the average voting model, which takes cultural, climatic, social, psychological and behavioral adaptation factors into account. The environment of underground spaces is very different from that of above-ground spaces, so the existing thermal comfort model cannot be directly used to evaluate underground spaces. However, the majority of thermal comfort research is based on above-ground spaces, and prediction models for underground spaces are scarce. Li et al. [52] collected 5862 valid questionnaires from typical underground buildings in 249 Chinese cities over an 8-year period.

The psychological issues caused by underground spaces are more complex. 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 barriers still exist. Other studies show that people ignore actual situations, despite the fact that some underground buildings have adequate artificial light sources, good mechanical ventilation and humidity control. In underground buildings, it is easy to lose one’s bearings in underground buildings, causing tension, anxiety and fear because of the invisibility of building forms and the lack of external reference points provided by windows. Long-term exposure to underground buildings causes subjective perception of time to worsen, sight and memory to deteriorate, fatigue to increase, working capacity and protective functions of an organism to decrease, and hallucinations [53]. Ko et al. [54] pointed out that compared with windowless state, people with windows had higher positive emotions (such as happiness and satisfaction) and lower negative emotions (such as sadness and sleepiness). When there were windows, working memory and concentration ability were improved, but there were no significant differences in short-term memory, planning and creativity. As a result, the connection between underground space and the natural environment is an important factor influencing human psychology. Kim et al. [55] investigated the effects of indoor plants and artificial windows in an underground laboratory. Plants have a positive impact on the underground environment, whereas artificial windows have a less significant impact.

2.5. Air Quality Control and Ventilation

Because underground buildings are relatively closed and humid environments, ventilation is especially important. Natural ventilation and mechanical ventilation are the two types of ventilation based on the driving forces of airflow. Depending on the application, ventilation can be classified as general ventilation, emergency ventilation, construction ventilation, and so on.

Natural ventilation is typically powered by natural forces such as wind, thermal buoyancy and geothermal energy. As previously stated, the concept of natural ground–coupled ventilation makes use stable soil temperature to preheat or precool air for buildings. In the early millennium B.C., Iranian architects used wind towers and underground air tunnels for passive cooling and ventilation. Natural ventilation solutions in Iran are integrated with the country's famous qanat systems, which are typically dug into the slope of a mountain or hillside. The ancient Egyptians used pressure differences caused by temperature changes between day and night to ventilate the construction of underground tombs and temples [56]. The airflow of natural ventilation in underground structures is complex and strongly influenced by temperature differences. During the autumn and winter seasons, the impact of outdoor air is amplified. In the spring and summer, it is significantly reduced. As transition areas, the access tunnel and ventilation chimney experience the greatest temperature changes and play an important role in regulating natural ventilation [57]. Underground engineering has a moisture problem due to its unique environment, especially in the summer when natural ventilation is used, because outdoor air humidity is high and easily condenses after passing through the basement. As a result, mechanical auxiliary natural ventilation can not only effectively avoid condensation, but also ensure good underground engineering air quality [58]. Throughout the year, natural ventilation varies. Natural ventilation in underground spaces should take into account the influences of outdoor seasonal wind direction and speed, and wind pressure should be used to enhance natural ventilation. Ventilation outlets and ventilation pipes should be strategically placed. The area of ventilation outlets should be appropriately enlarged to minimize ventilation resistance in order to enhance natural ventilation.

The use of thermal pressure in a solar chimney is an effective way to improve natural ventilation. It uses solar radiation to heat the air in the chimney, causing temperature differences between the air inside and outside the chimney, which causes density differences. As a result, thermal pressure is used to provide additional buoyancy for airflow and strengthen natural ventilation, thereby improving internal thermal environments of buildings and obtaining a better ventilation effect [59]. Guo et al. [60] proposed combining the solar chimney effect with a solar water heater to provide ventilation for underground buildings. Xiang et al. [61] propose technical measures for combining the solar chimney effect with PV/T technology and using the waste heat generated by the PV/T collector to ventilate underground spaces (**Figure 1**). The underground space design strategy of combining natural ventilation and daylighting has grown in popularity in northern China in recent years [62]. The key to the design is to reasonably organize underground spaces and various space forms and elements in the environment, and to design underground spaces by utilizing seasonal changes and plant growth habits, as well as certain artificial auxiliary management and mechanical equipment.

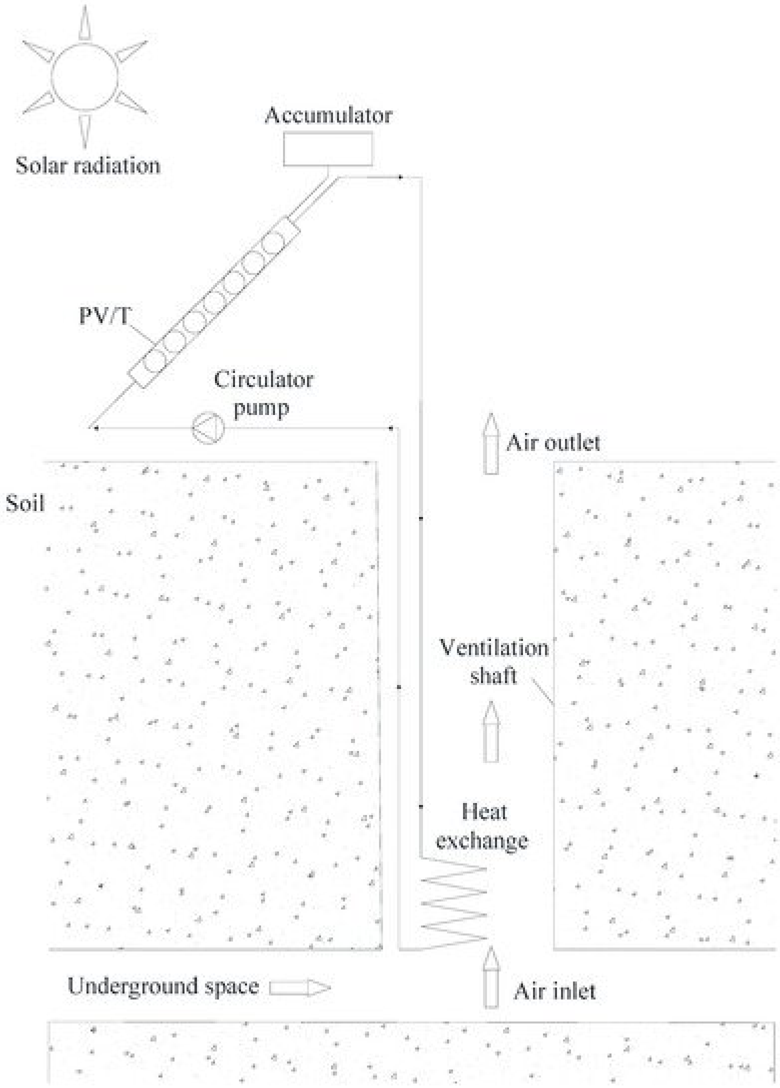

Figure 1. Ventilation system combining solar chimney effect and PV/T [61].

Mechanical ventilation has also been widely studied and applied as an effective method of underground space environmental control in mines, tunnels, metro stations, hydropower stations, and storage facilities, among other places. Two auxiliary ventilation systems, forcing and exhausting, are used in dead end roadways to reduce concentrations of harmful substances such as methane and ensure the safety of workers in underground coal mining. Air curtain systems (**Figure 2**) for mine refuge chambers keep dangerous gases from entering the chamber. Their barrier efficiency is influenced by structural parameters, installation location, airflow angle, and chamber door size [63]. The size of the system's barrier to hazardous gases is referred to as the barrier efficiency. Zhang et al. [63] pointed out that air curtain systems, with air curtains installed on two sides of the door frame behind the door wall and ejecting 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 with efficiency of 55% to 60%. For hydropower stations, a 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. At present, the main air distribution forms of underground generator main workshop of hydropower station are stratified air distribution of generator floor workshop, upper (top) air supply air distribution of powerhouse, air supply air distribution of lower powerhouse, and series direct current ventilation system for an underground powerhouse [64]. 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. When a subway train travels through a relatively narrow tunnel, the positive pressure formed at the head pushes the foul air out, while the negative pressure formed at the tail sucks fresh air in (**Figure 3**).

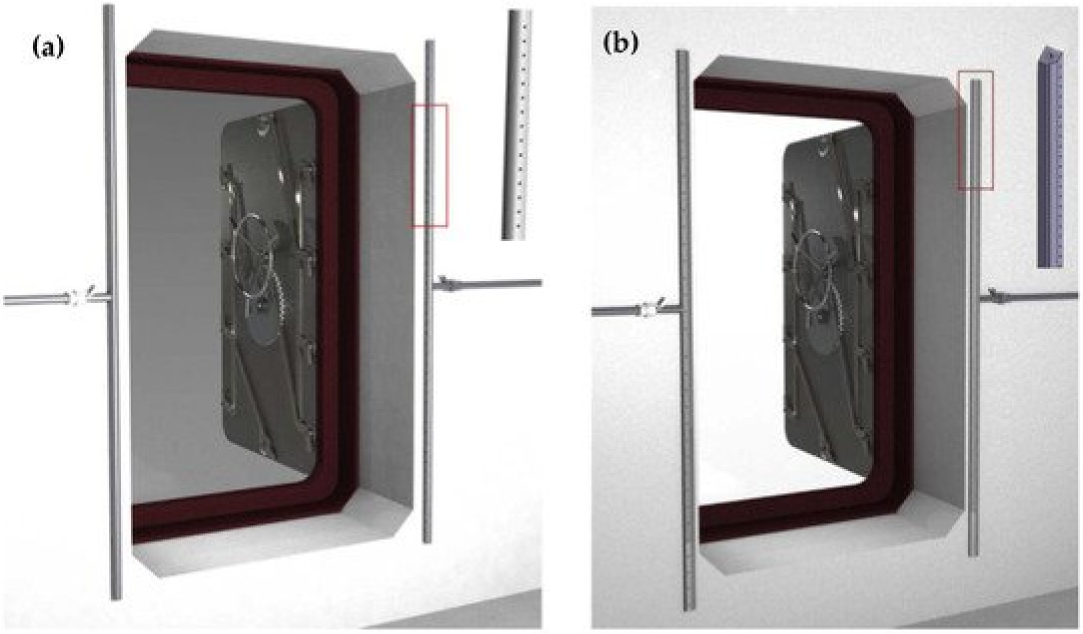

Figure 2. Two main types of air curtain systems for mine refuge chambers in China [63]. (**a**) Pipeline air curtain. (**b**) Air knife.

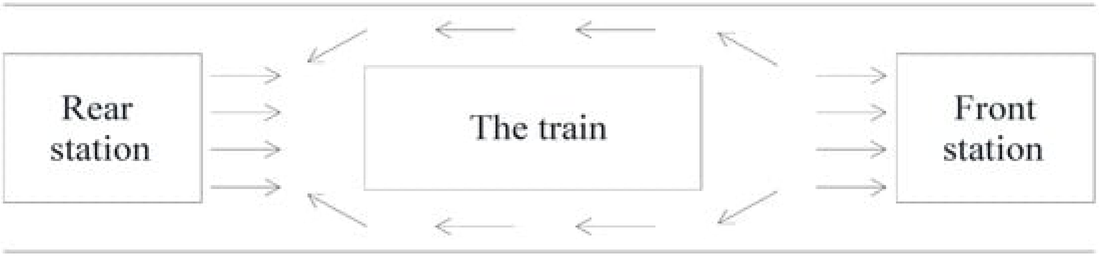

Figure 3. Formation mechanism of piston wind [63].

The piston effect allows tunnels and platforms to be ventilated, which saves energy. Wen et al. [65] discovered, however, that the piston effect may worsen indoor air quality in subway stations. They argue that reasonable space design can provide a foundation for effective ventilation and air pollution control in subway stations. To improve the complex environment of a subway station, architectural layout design must be combined with indoor ventilation design. Their research also found that the station design with an atrium improves ventilation and pollution control [66]. Hwang et al. [67] discovered that the bacterial concentration on the subway platform increased in the absence of a platform screen door (PSD). Particulate matter inflow can be reduced by combining a ventilation system and

PSD [68]. Dong [69] devised a novel system for outfitting the PSD with a programmable air vent. Physical methods are increasingly being used to remove organic pollutants, bacteria, and microbes from subway platforms. These methods, however, may produce other pollutants such as ozone and nitrogen oxides [66].

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