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Experimental study on egress capacity of key facilities in pressurized oxygen-supplement compartments

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Pressurized buildings have emerged as a novel architectural solution to alleviate altitude illness in high-altitude regions. Unlike conventional buildings, evacuation from this kind of building has to experience a depressurization time, which results in air expansion and heat absorption, creating a dense fog and impairing sight within the buildings. Evacuation experiments were performed in a pressurized oxygen-supplement compartment to investigate the pedestrian motion properties. Based on the questionnaires, participants reported varying degrees of symptoms such as ear blockage, reduced environmental noise, and dizziness, which had a measurable impact on their mobility. We focus on the evacuation parameters through three basic building components: staircases, pressure transition cabins, and escape windows. As the visibility in the compartment decreases from high to low, the movement patterns of pedestrian shift from triangular to single-file with a significant decline in evacuation efficiency. It is found that there is a linear relationship between evacuation time and the number of evacuees through escape windows. The pressure transition cabin is a crucial evacuation route in emergencies, and evacuation time is recommended as the key metric for assessing its effectiveness. These findings offer valuable insights for emergency evacuation strategies in pressurized buildings.

Keywords: pressurized staircase, pressure transition cabin, escape window, pedestrian movement

PACS: 89.40.–a, 89.60.Ec, 01.50.Pa, 91.60.Gf

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1. Introduction

The Qinghai-Tibet Plateau, with an average altitude exceeding 4000 meters and encompassing approximately one-fourth of China's land area, is the largest plateau region in the world. In recent years, the plateau has experienced rapid development, with an increasing number of individuals traveling to the region for work, living, or leisure. Travelers who ascend to high altitudes without adequate acclimatization are prone to high-altitude illnesses, among which acute mountain sickness (AMS) is the most prevalent, primarily manifesting as headaches.[1] Exertion is a risk factor for AMS. When symptoms are mild, the best resolution method is to rest alone. If symptoms are severe enough, the patient must descend to a lower altitude.[1] However, due to rescue conditions, it is difficult to transport patients to the treatment area in time. In 1979, Becker in Germany designed the first portable hyperbaric chamber (PHC). It is designed specifically for treating altitude illness, which increases the inspiratory oxygen pressure and significantly increases the oxygen saturation of the arterial blood, effectively relieving the symptoms of AMS.[2] In addition, West[3] first proposed in 1995 that oxygen could be charged into a single room to reduce physiological altitude and perform oxygen conditioning.

In recent years, the pressurized buildings have emerged as a novel architectural solution for addressing high-altitude illness issues.[4] By oxygenating and regulating the internal environment, these structures substantially improve living and working conditions in high-altitude regions, demonstrating considerable value and development potential. It is well known that low pressure and low oxygen levels are characteristic of high-altitude environments. Unlike conventional buildings, pressurized buildings at high altitudes create a sealed environment, where oxygen is infused, and pressure is increased to simulate conditions found at lower altitudes. As a result, occupants within these buildings are exposed to pressures higher than those of the external environment, which presents unique challenges and requirements for safe evacuation during emergencies.

The impact of abnormal pressure conditions on pedestrian movement has been the focus of prior research, with particular attention given to low-pressure environments, such as those found at high altitudes. Studies have shown that these envi-

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ronments can adversely affect individuals both physiologically and psychologically, resulting in declines in various aspects such as sleep,[5,6] cognition,[7] language,[8] and memory.[9] It is found that the maximal oxygen uptake decreases with increasing altitude, decreasing by 6%–7% for every 1000 m ascent.[10] Additionally, maximal oxygen uptake does not recover with improved adaptability. Li *et al.*[11] further derived expressions for the escape velocity of different genders at different altitudes based on maximal oxygen uptake. Zhang *et al.*[12] conducted a simple simulation fire evacuation experiment in the Guanjiao Tunnel, revealing that pedestrians' walking speed was approximately 0.7 m/s. Besides, Zhang *et al.*[13] organized a field experiment with 20 participants in a high-altitude tunnel, examining response time, route selection, speed variation, and reactions to safety warning devices during long-distance tunnel evacuation. They observed that females exhibited a faster rate of speed decay compared to males. Nevertheless, there remains a significant gap in the study of pedestrian dynamics within pressurized buildings, with a notable lack of experimental research focused on pedestrian movement capabilities under specific conditions.

Unlike conventional buildings, the evacuation characteristics of pressurized buildings are distinct: during emergencies such as fires, the building must first undergo complete depressurization, allowing the internal and external pressures to equalize before evacuation exits can be opened.[14,15] During the depressurization process, the expanding air rapidly absorbs heat, and when the indoor temperature reaches the dew point, dense fog forms inside the building, significantly reducing visibility. There has been a lot of research on crowd dynamics in typical structures of conventional buildings.[16–19] However, for pressurized buildings, staircases are particularly susceptible to changes in visibility. Such changes can significantly alter pedestrian mobility and evacuation behavior, complicating safe evacuation efforts. Therefore, it is essential to conduct research on staircases, which represent a key structural element in these buildings.

Staircases, as vertical evacuation facilities, tend to induce congestion and stampedes more easily during evacuation processes. Consequently, previous studies have extensively investigated the factors affecting pedestrian evacuation in staircase areas. Peacock *et al.*[20] found that the width of staircases significantly affects the pedestrian evacuation efficiency, with wider staircases facilitating faster evacuation, while narrow ones lead to congestion, hindering evacuation. Lei *et al.*[21] conducted pedestrian evacuation experiments in school dormitories and found that the width of the stairs significantly affects evacuation efficiency. Additionally, Yang *et al.*[22] conducted experiments on stairs with different structures. The results indicated that the height and depth of stair steps have an impact on pedestrian speed and the capacity of pedestrian passage on stairs. Graat *et al.*[23] conducted pedestrian evacuation experiments on stairs with different slopes, and the results showed that as the slope of the stairs increases, pedestrian speed decreases accordingly. Fujiyama *et al.*[24] conducted staircase evacuation experiments by grouping participants according to age and found a direct influence of stair slope on walking speed. Burghardt *et al.*[25] analyzed experimental data to summarize the fundamental diagram of descending stairs and discussed the influence of stair gradient on this diagram. Qu *et al.*[26] considered three influencing factors: the geometric shape of stairs, the dimensions of steps, and the speed of individuals, to refine the social force model, facilitating the description of the movement characteristics and evacuation status of individuals on stairs. Similarly, focusing on the geometric shape of stairs, Sano *et al.*[27] conducted an evacuation drill for high-rise buildings and densely populated areas. Through observation, they found that the geometric shape of stairs and the location of exits have a significant impact on experimental data. Zeng *et al.*[28] investigated the influence of stairway occupant distribution and visibility on pedestrian convergence and evacuation efficiency in high-rise buildings. By analyzing video data, they found that the convergence process was influenced by both visibility and the initial convergence ratio. In terms of visibility impact, Seike *et al.*[29] studied pedestrian walking speeds in a full-scale tunnel filled with smoke, revealing a significant constraint on pedestrian movement speed with a negative correlation between extinction coefficient and walking speed. Cao *et al.*[30] conducted individual evacuation experiments under varying visibility conditions to analyze the effects of limited visibility on pedestrian speed, step length, step width, and step frequency. However, existing research on the staircase and the impact of visibility has predominantly been conducted within conventional buildings under standard atmospheric conditions, with limited studies addressing pedestrian movement within standard-sized staircases in pressurized buildings.

Additionally, transition cabins and escape windows are another two evacuation facilities in pressurized buildings, serving as critical components for ensuring safe and effective evacuation during emergencies.[31,32] Pressure transition cabins serve as vital interfaces between the pressurized interior of the building and the external environment. During an emergency, it plays a crucial role by allowing occupants to adjust to the pressure differential safely before exiting the building. This controlled depressurization helps prevent potential physical harm caused by sudden pressure changes. It is noted that the inner and outer doors of the pressure transition cabin are designed to open inward. When pedestrians use it, the inner door must be fully closed before the outer door can be opened for evacuation.[33–35] This design results in the available space within the pressure transition cabin being smaller than its actual area. Therefore, there is also a need for further research into the capacity of the transition cabin. Escape window pro-

vides an alternative evacuation route and is particularly useful in situations where the main evacuation routes, such as transition cabin, are compromised or inaccessible. This is particularly important for occupants on higher floors, who may need a direct and immediate route to safety. Transition cabin and escape window are integral to the safety and functionality of pressurized buildings. However, there is currently a lack of research addressing these critical facilities, highlighting an urgent need for investigation.

In summary, current research has primarily focused on controlled experiments conducted in standard atmospheric or low-pressure environments, while studies on pedestrian evacuation in pressurized buildings remain in their infancy. Evacuation patterns derived from conventional buildings may not be directly applicable to pressurized buildings. There is a pressing need for scholars to investigate the characteristics of pedestrian movement within pressurized buildings. Based on the aforementioned considerations, pedestrian experiments through staircase, transition cabin and escape window were conducted to explore the impact of visibility on pedestrian movement within pressurized buildings. The findings from this analysis help to address the existing research gap in pedestrian evacuation within pressurized buildings and provide valuable guidance for safe stairway evacuation during emergencies.

This paper is organized as follows: Section 2 outlines the experimental methods and setup in this study. Section 3 presents the key findings from the experiments for pedestrians through a staircase, a transition cabin and an escape window, respectively. Finally, Section 4 offers a comprehensive summary of the study.

2. Methods

2.1. Experiment environments and setup

Pressurized buildings increase internal pressure and adjust the indoor living environment indicators to achieve the same experience as the plain. It is of great significance to alleviate altitude illness and improve the travel experience. To investigate the pedestrian evacuation properties within pressurized buildings, controlled experiments in a pressurized oxygen-supplement compartment were carried out on December 5, 2023, in Wuhan.

In this study, we mainly analyze the pedestrian movement characteristics including speed and time through a staircase, a transition cabin and an escape window. As mentioned in the previous literature review, the dense fog formed during depressurization in pressurized buildings significantly reduces visibility. Staircases, which inherently involve vertical movement and crowd evacuations, are particularly susceptible to these visibility changes, affecting pedestrian flow and complicating safe evacuation efforts. In contrast, the escape window and transition cabin connect directly to the outside and are less affected by visibility. The pressure transition cabin, designed to balance pressure between the pressurized compartment and the external environment, is identified as the primary and necessary evacuation route during emergencies. It is typically used for limited occupancy, focusing on equipment use and controlled entry and exit rather than group movement. Escape windows, on the other hand, offer a last-resort evacuation option, especially for evacuees who cannot use the transition cabin and mainly examines the impact of obstacle crossing on individual evacuation. These differences in evacuation dynamics led us to introduce environmental visibility as a variable specifically in the staircase experiments.

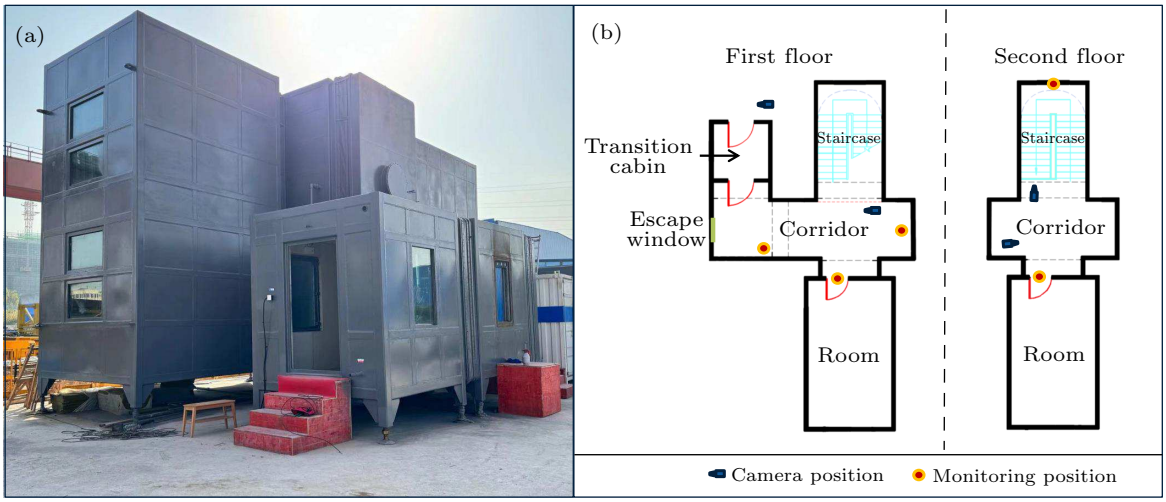


Fig. 1. Detail information of experimental setup: (a) external view of the pressurized compartment, (b) camera and monitoring positions.

The pressurized oxygen-supplement compartment for experiment is shown in Fig. 1(a). It is a full-size two-story compartment, and the internal structure is shown in Fig. 1(b). On the first floor, the standard cabin (3 m×6 m) that functions as a room is connected to the corridor and is opposite to the staircase. There is a pressure transition cabin at the exit connecting

the compartment to the outside environment. On the second floor, similarly, the staircase is opposite a standard cabin, and both are connected to the corridor. The pressurized compartment is fully enclosed during operation. Once an emergency occurs, pressure relief and evacuation are carried out simultaneously. There are two ways to evacuate to the outside: pressure transition cabin and escape window. The following describes their detailed use process.

A schematic diagram of the external appearance and structural dimensions of the pressure transition cabin is presented in Fig. 2. The usable internal area of the cabin is 2.1 m×2.1 m, with a door width of 0.9 m. The pressure transition cabin used in the experiment corresponds to the standard dimensions of cabins currently employed in pressurized buildings in high-altitude regions, providing a meaningful reference. Theoretically, the evacuation through a transition cabin involves several steps. First, individuals evacuate to the inner door of the transition cabin. If necessary, they activate the electric or manual control to open the transition valve (though this step is not required if the pressure inside the cabin is already equalized with the building). Once the pressure between the cabin and the interior of the building has equalized, they enter the pressure transition cabin. After this, they proceed to open the decompression valve between the cabin and the outside environment, either electrically or manually. Once the cabin has fully depressurized, individuals can open the outer door and then safely evacuate to the outside.

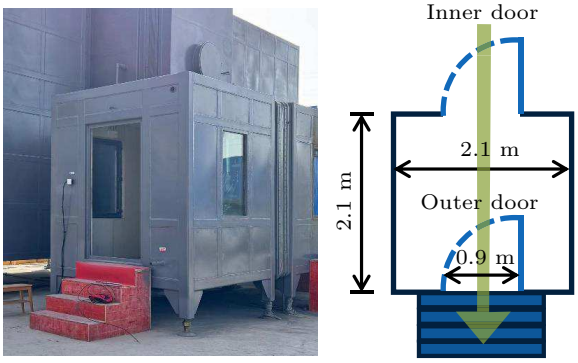


Fig. 2. The schematic diagram of the external appearance and structural dimensions of the pressure transition cabin.

When the pressure transition cabin is not possible or delayed in an emergency, the participants in the pressurized buildings can evacuate through the escape windows. The appearance and actual dimensions of the escape window are illustrated in Fig. 3. The escape window is located on the first floor of the pressurized compartment, positioned 0.8 m above the indoor floor and 1.6 m above the outdoor ground. The window measures 0.7 m in width and 1.0 m in height, allowing only one person to pass through. In operational pressurized buildings, the evacuation process via escape windows involves guiding evacuees to the window, where the designated impact point is shattered using a safety hammer, allowing them to escape by jumping through the window. For evacuees on the second floor, evacuation requires descending to the ground using a ladder after exiting the window.

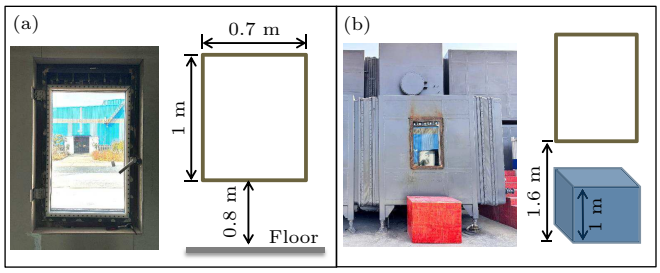


Fig. 3. The schematic and detailed dimensions of the escape window: (a) interior scene, (b) exterior scene.

To adjust the visibility, a membrane with a fixed light transmission (LT = 0.25%) was placed over the goggles to make visibility glasses (Fig. 4). Here the membrane is made of PET plastic. The light transmittance is determined based on the visual conditions in the dense fog state during pressure relief, that is, the pedestrians can only see the location of the light source and the outlines of other evacuees. Participants were asked to wear visibility glasses throughout the visibility-restricted experiments.



Fig. 4. Visibility glasses.

To capture the movement process of pedestrians, cameras and monitoring systems were strategically installed to record the entire sequence. The specific locations of the cameras and monitoring equipment are illustrated in the diagram (Fig. 1(b)).

2.2. Participants

To ensure that our experimental conditions closely reflect those in actual high-altitude work environments, we specifically selected a gender ratio close to real-world scenarios in high-altitude industries. In settings such as the Sichuan–Tibet Line project department, the Muztagh Ata Observatory in Xinjiang, and the Lhasa Army Aviation Unit, where physically demanding tasks are primarily performed by males. This approach aligns the study conditions more closely with the operational contexts of these pressurized settings, making the findings offer more direct relevance to the specific demands and evacuation needs of pressurized environments in high-altitude regions.

The participants are all university students recruited online. A total of 46 volunteers including 41 males aged 18 to

26 years, with an average height of 176.02±5.69 cm and an average weight of 71.33±17.02 kg, and 5 females aged 18 to 28 years, with an average height of 160.60±3.29 cm and an average weight of 53.00±6.86 kg participated in the experiments. None of the participants had conditions like hand disabilities, heart diseases, or visual impairments. Each participant was compensated 180 RMB at the end of the experiment. The ethical approval of the research project was obtained from the Biomedical Ethics Committee at the University of Science and Technology of China.

Additionally, volunteers were thoroughly briefed before the experiment on the correct and safe usage of devices or components such as staircases, pressure transition cabins, and escape windows to ensure familiarity with the environment.

2.3. Experimental procedure

2.3.1. Pedestrian movement experiment on a staircase

The staircase used in the experiment had a lateral width of 1.30 m, with steps measuring 0.2 m in width and 0.16 m in height (Fig. 5). In the experiment, a constant pressure differential of 20 kPa between the pressurized compartment and the external environment was maintained. The number of participants (5, 10, 15, 25 individuals) and visibility (LT = 100% and LT = 0.25%) were adjusted during this experiment. LT = 100% indicates that the participants did not wear visibility glasses, allowing them to move with an unobstructed field of vision. In contrast, LT = 0.25% represents the condition where the participants wore visibility glasses with a specified light transmittance to simulate movement under low-visibility conditions during the depressurization process of the compartment.

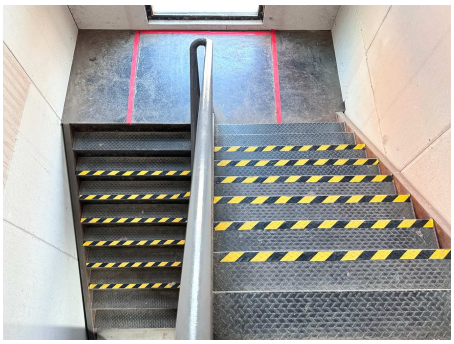


Fig. 5. Staircase inside the pressurized compartment.

At the beginning of the experiment, the participants of the experiment were randomly distributed within the enclosed room on the second floor. Upon the evacuation command is given, the door of the room was first fully opened and then the pedestrians started to evacuate via the staircase. When all the individuals arrived at the first floor, it indicated the completion of the staircase evacuation process. Participants were asked to imagine a high-risk emergency scenario (such as a fire or life-threatening event) to prompt a rapid evacuation. During the evacuation, participants could choose to use the stair handrails to assist their movement as needed and overtaking behavior was allowed. For low-visibility conditions, participants were required to wear visibility glasses continuously throughout the experiment and could not take them off until they received the completion command. Totally, eight experiments were performed as shown in Table 1, categorized by pedestrian quantity (4 groups) and visibility (2 groups).

Table 1. Detail information of staircase experiment.

Index	Number	Transmittance (%)
D-5-100	5	100
D-10-100	10	100
D-15-100	15	100
D-25-100	25	100
D-5-0.25	5	0.25
D-10-0.25	10	0.25
D-15-0.25	15	0.25
D-25-0.25	25	0.25

*The letter D represents descending stairs, the numerical value in the middle represents the number of individuals, and the number on the right indicates the transparency rate.

2.3.2. Pedestrian experiment through a transition cabin

The pressure transition cabin serves as one of the primary facilities on the evacuation routes in pressurized buildings during emergency situations. In this study, we solely investigated the capacity and transit efficiency of the pressure transition cabin, and the experiment was conducted under normal atmospheric pressure (the pressure difference with the outside is 0). The experimental procedure was as follows.



Fig. 6. The video snapshots captured during the transition cabin experiments.

Before the experiment, all the participants waited at the inner door of the transition cabin. Upon receiving the evacuation command, the inner door was opened and the pedestrian started to evacuate. After all individuals had entered the internal space of the pressure transition cabin, the last person entering the cabin closed the inner door. Then the outer door was opened for them to evacuate outside. The experimental variable in this experiment was the number of pedestrians, which gradually changed from 2 to 35. At higher densities, multiple experiments were conducted with small increments in the number of participants (T-24, T-26, T-28). Participants were

asked to evacuate as quickly as possible. Although the number of individuals waiting in front of the inner door was fixed for each experimental setup, participants could independently decide the number of people entering the compartment based on the available space within. Figure 6 presents video snapshots captured during the experiment.

A total of 9 experimental groups were conducted and the number of participants and corresponding density in the pressure transition cabin listed in Table 2.

Table 2. Detail information of pressure transition cabin experiment.

Index	Number	Density (m^{-2})
T-2	2	0.45
T-5	5	1.13
T-10	10	2.27
T-15	15	3.40
T-20	20	4.54
T-24	24	5.44
T-26	26	5.90
T-28	28	6.35
T-35	35	7.94

*The letter T represents pressure transition cabin, and the numerical value represents the number of individuals.

2.3.3. Pedestrian experiment through an escape window

For safety during the experiment, a 1-meter-high platform was used to assist in the evacuation, serving as a buffer. Notably, the escape window used in the experiment conforms to the standard dimensions employed in pressurized buildings in high-altitude regions, making the findings relevant for such environments. Due to experimental constraints, the window-breaking step was omitted, and the study focused solely on the process of jumping through the window.

At the beginning of the experiment, participants waited in front of the closed escape window and were asked to evacuate as quickly as possible, ensuring their own safety when climbing or jumping. Upon receiving the evacuation command, the lead participant opened the window by turning the handle and the others followed by jumping through the window. Participants were grouped in combinations of 1 to 5 individuals, with multiple trials conducted for each group, and the entire evacuation process was recorded by cameras. Figure 7 presents snapshots of the evacuation process using the escape window. The transit efficiency of the escape window is aimed to study.



Fig. 7. The video snapshots captured during the escape window experiments.

3. Result

3.1. Physiological responses and behavior patterns

After the experiment, all the participants were asked to complete a questionnaire to collect their perceptions on the pressurization sensations and visibility sensations during the experiment in the pressurized compartment.

In the pressurization sensation questionnaire, the occurrence of symptoms such as tinnitus, ear blockage, ear pain, dizziness, headache, decrease in environmental noise, and weakened perception of surroundings among participants was recorded and presented in Table 3. It is found that the most pronounced effect on the subjects is ear blockage, reaching 86.96%, while 65.22% of the subjects also reported a decrease in ambient noise. These symptoms could lead to physical discomfort for pedestrians and may adversely affect their movement.

Table 3. Questionnaire content.

Symptoms	Proportion (%)	Symptoms	Proportion (%)
Tinnitus	36.96	headache	2.17
Ear blockage	86.96	decrease in environmental noise	65.22
Ear pain	23.91	weakened perception of surroundings	32.61
Dizziness	10.87		

Further, with the questionnaire the impact of pressurization and visibility on pedestrian mobility was asked to assess. The participants needed to rate their mobility on a scale of 1 to 5 under normal pressure conditions (ambient pressure) and after experiencing pressurization environment. Similarly, they rated their mobility under normal visibility conditions and by wearing visibility glasses. As depicted in Fig. 8, the statistical results indicate that 28.30% of pedestrians perceive a decrease in their mobility compared to a normal pressure environment. In comparison to normal visibility, 78.30% of pedestrians believe that wearing visibility glasses would decrease their mobility.

Combining the results of the questionnaires, it can be inferred that pressurization within buildings may create physical sensations that could impact pedestrians' balance, spatial awareness, and movement efficiency. This sensation is caused by the differences in air pressure between the inside and outside of the building, which can lead to discomfort. Compared to ordinary evacuation scenarios, where environmental factors such as smoke, fire alarms, or crowded spaces dominate, evac-

uations in pressurized environments are unique because this pressure-related discomfort can add another layer of complexity. When pedestrians are in poor physical condition, their ability to interact with the external environment will be weakened. Specifically, the cognitive load induced by pressurization sensations could affect individuals' decision-making and judgment capabilities. Some pedestrians noted "decrease in environmental noise" and "weakened perception of surroundings", which could delay their response to emergency evacuation signals, thereby increasing evacuation reaction time. On the other hand, the discomfort caused by pressure differences requires pedestrians to take more time to adjust, slowing their movement. In conditions of low visibility, the reduced movement speed and potential disorientation might contribute to congestion during evacuations, particularly in critical areas such as staircases where pedestrian flow is essential. Therefore, we subsequently analyze pedestrian movement capacity in pressurized environments under varying visibility conditions, focusing on spatial distribution, evacuation speed, and efficiency.

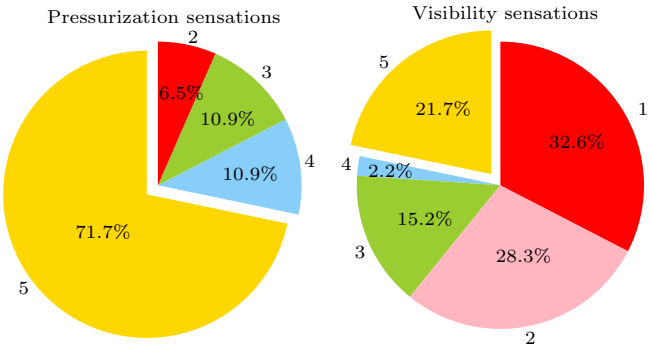


Fig. 8. Self-assessment of the pressurization and visibility on pedestrian mobility.

Some typical phenomena during pedestrian movement were observed from the video recordings. As shown in Fig. 9, while moving in situations of low visibility, pedestrians tended to use stair railings for support, maintaining closer spatial proximity to the stair railing, thus exhibiting single-file movement. However, in situations where visibility glasses were not worn, pedestrians did not consistently use railings throughout their movement, resulting in a more dispersed distribution on the stairs and presenting a triangular spatial pattern. This phenomenon is consistent with previous research findings,[36] indicating that reduced visibility affects pedestrian movement patterns. It emphasizes the need to consider this difference in relevant facility design and pedestrian management.

The spatial distribution of pedestrians under various visibility conditions was quantified, as illustrated in Fig. 10. It can be seen that the visibility level significantly affects the spatial distribution of pedestrians on the stairs. Under low visibility conditions (0.25%), pedestrians are mainly distributed within a range of 0.6 m–1.0 m from the handrail. Combined with the video analysis, pedestrians relied on the stair handrail to move (Fig. 9(b)). As the number of pedestrians increases, some pedestrians chose to move closely against the wall. Under normal visibility conditions (100%), the position distribution of pedestrians is relatively dispersed (Fig. 9(a)). In addition, it is found that the position shows an uneven distribution phenomenon. This is because when pedestrians use the handrail to move, their bodies kept a certain distance from the handrail, while when moving against the wall, pedestrians walked close to the wall to seek a feeling of safety. In general, under low visibility conditions, pedestrians tend to use the stair handrail to assist evacuation first, and then choose to evacuate against the wall. In contrast, under normal visibility conditions, the position distribution is more scattered, and most pedestrians do not need auxiliary evacuation.

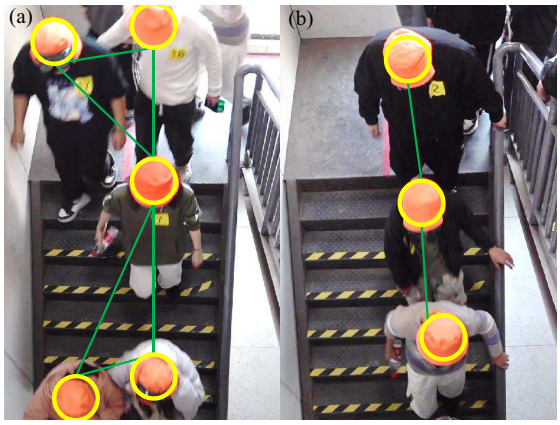


Fig. 9. Pedestrian movement patterns under different levels of visibility: (a) LT = 100%, (b) LT = 0.25%.

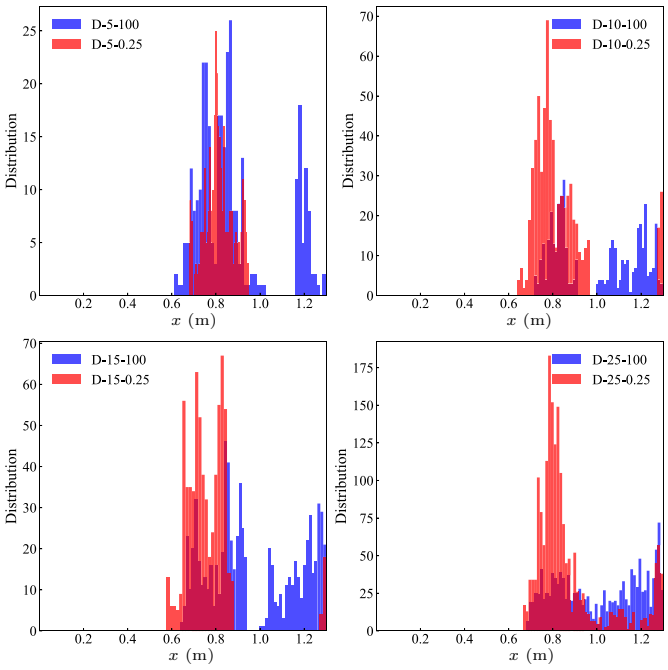


Fig. 10. Spatial distribution of pedestrians in the staircase under different visibility conditions. $x = 0$ m indicates the staircase handrail side and $x = 1.3$ m indicates the wall side.

3.2. Speed and evacuation time on the staircase

By analyzing the experimental video, pedestrian movement speeds on stairs were calculated as shown in Fig. 11. The speed was determined by dividing the projection distance of a pedestrian on the stairs by the time duration of their movement. The movement speeds of pedestrians under visibility conditions of 100% and 0.25% were 0.35±0.08 m/s and 0.20±0.07 m/s, respectively. They decreased with the increasing number of evacuees. These values are absolutely slower than that in conventional buildings. Further, it can be seen that pedestrian movement speeds under low visibility conditions were consistently lower than those under 100% visibility conditions regardless of the number of evacuees.

We summarized and compared the descent speeds of pedestrians on stairs across different building types in Table 4. It is indicated that, regardless of whether visibility is at 100% or low levels, the average descent speed within the pressurized compartments is significantly lower than the findings from other studies. This discrepancy may be attributed to several factors: (i) The stair tread width in the pressurized building is 0.20 m, which is narrower than other stair dimensions in conventional buildings. This reduced width can make it more challenging for pedestrians to maintain their balance while descending, prompting a more cautious approach to movement. (ii) According to questionnaire results, some individuals experience discomfort, such as ear blockage and headaches, due to the pressure environment within the building. This discomfort may increase the physical strain on evacuees, contributing to a slower evacuation speed.

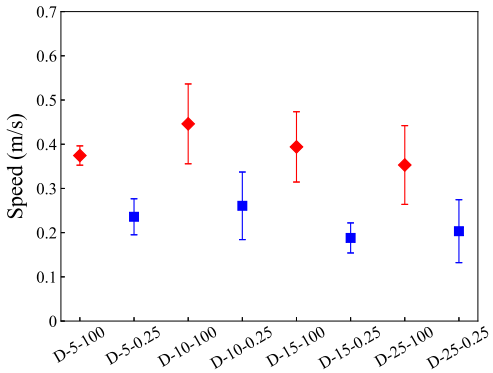


Fig. 11. Comparisons of speed under different visibility conditions.

Table 4. Comparisons of pedestrian descent speeds on stairs.

	Our study	Peacock[20]	Huo[37]	Chen[38]	Zeng[36]
Type	controlled experiment	evacuation drill	controlled experiment	controlled experiment	controlled experiment
Environment	pressurized compartments	office building	office building	residential building	office building
Stair width (m)	1.30	1.22	1.26	1.16	1.30
Stair tread (m)	0.20	0.28	0.28	0.27	0.28
Stair riser (m)	0.16	0.18	0.15	0.16	0.15
Exit width (m)	1.0	0.91	1.26	1.16	1.30
Movement layer	2 to 1	10 to 1	9 to 1	20 to 1	9 to 3
Evacuees	5, 10, 15, 25	793	73	120	39
Speed* (m/s)	100% visibility: 0.35±0.08 0.25% visibility: 0.20±0.07	0.44±0.19	0.74–0.99	normal condition with light: 1.15±0.22 normal condition without light: 0.59±0.05 27% light transmittance: 0.55±0.08 16% light transmittance: 0.50±0.13	100% visibility: 1.25±0.28 12% visibility: 1.12±0.28 0% visibility: 0.5–0.14

* The data presented without additional explanation corresponds to normal visibility conditions.

Next, we will statistically measure the evacuation time to further analyze the impact of visibility on the movement characteristics of pedestrians on stairs in the pressurized compartment. The evacuation time is defined as the duration from the departure of the first pedestrian from the second floor to the arrival of the last pedestrian on the first floor. As illustrated in Fig. 12, under both conditions the evacuation time increases with the increasing number of evacuees. The evacuation time under low level of visibility is nearly twice of that under normal visibility and the increase rate of it is very small when the number of evacuees is less than 15. However, it shows a sharp rise and the evacuation time under low level of visibility is nearly three times of that under normal conditions when the number of evacuees reaches 25. This indicates that in the evacuation involving 25 individuals, the negative impact of low visibility on pedestrian movement becomes more pro-

nounced, thereby posing greater challenges to the evacuation. In general, pedestrian evacuation within pressurized compartments requires more time, emphasizing the need for increased attention to evacuation studies within pressurized building environments.

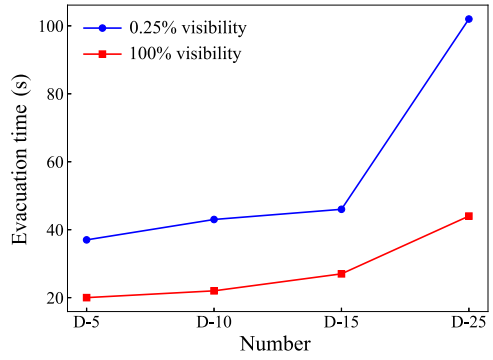


Fig. 12. Evacuation time under different visibilities.

In order to investigate the step-change variations in pedestrian evacuation time under conditions of 25 people, a graph depicting the relationship between pedestrian evacuation time and the number of evacuees (Fig. 13) was plotted. The calculation area represented the time for each pedestrian to reach the ground floor. The study revealed that, under 0.25% visibility conditions, each participant required more time to complete evacuation compared to 100% visibility. Significant congestion among pedestrians was observed under low visibility conditions.

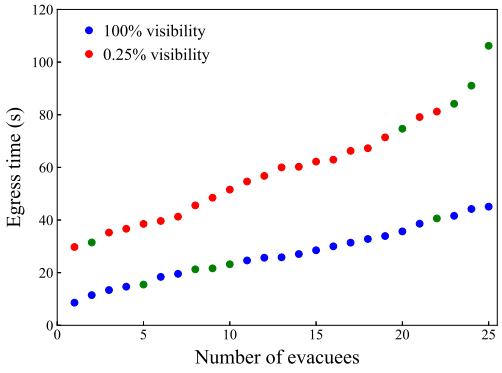


Fig. 13. Flow rate curve under conditions of 25 people. Green dots indicate female subjects within the condition.

3.3. Capacity of the transition cabin

The evacuation times for varying numbers of evacuees entering the cabin were quantified. The relationship between evacuation time and the number of pedestrians is depicted in Fig. 14. When fewer than 5 individuals were involved, evacuation time was primarily influenced by the duration required to open and close the cabin doors (stage 1). When the number of evacuees was between 5 and 20, the evacuation time exhibited a linear growth (stage 2), during which the density within the cabin remained below 5 m^{-2}, allowing for a smooth evacuation process with a relatively high level of spatial comfort. However, when the number of pedestrians reached 24 (stage 3), the evacuation time exceeded 60 seconds, surpassing the overall emergency depressurization time designed for the pressurized compartment, thereby diminishing the effectiveness of the transition cabin. In addition, in our experiment, the maximum number of people reached 35, corresponding to a density of 7.94 m^2, which significantly exceeded the operational capacity limit of the pressurized compartment. The experimental video showed that at this density, the cabin became severely overcrowded, requiring individuals to push against each other to open the outer door, resulting in a stepwise increase in evacuation time.

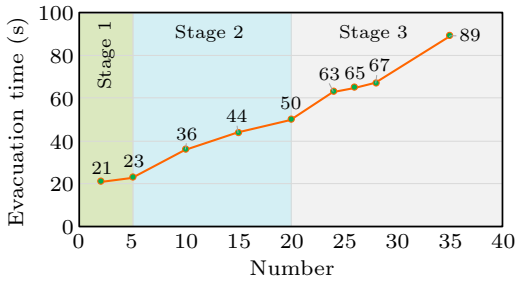


Fig. 14. The relationship between the transition cabin evacuation time and number of people.

Based on the experimental findings, it is recommended that future assessments of the evacuation capacity of transition cabin in pressurized buildings prioritize evacuation time as the key metric rather than spatial capacity. Considering the overall depressurization time and evacuation efficiency, it is advised that the number of individuals using the transition cabin should not exceed 20, and the density should be kept below 5 m^{-2}.

3.4. Transit efficiency of the escape window

The evacuation time through the escape window was defined as the duration from the issuance of the evacuation command by the organizer to the moment when the last individual exited the escape window and landed on the ground. The average evacuation time for each group was calculated, and the relationship between evacuation time and the number of evacuees is shown in Fig. 15. The results indicated a linear relationship between evacuation time and the number of individuals using the escape window. This relationship was further quantified through linear regression

$$T = 1.71p + 2.75,$$

where T represents the evacuation time and p denotes the number of individuals.

Since the escape window remained open throughout the evacuation process, the interception of 2.75 seconds corresponds to the combined time required for reaction and window-opening during the experiment. This fitted equation can be used to estimate evacuation times for different numbers of individuals using the escape window.

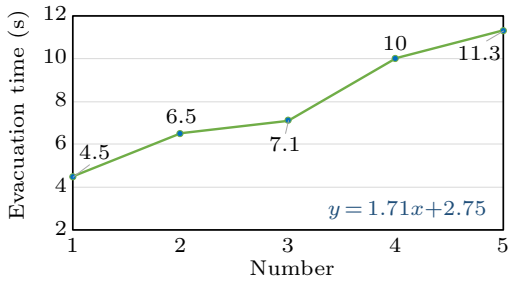


Fig. 15. The relationship between evacuation time and number of pedestrians using the escape window, including the fitting line.

4. Discussion and conclusion

This study offers valuable insights into pedestrian movement within key facilities of pressurized compartments. Evacuation experiments were conducted under a constant pressure differential of 20 kPa to evaluate the transit efficiency of staircase, pressure transition cabin, and escape window. These three components represent critical evacuation routes in pressurized building environments, each with unique challenges. Though the exact layout may vary across building types, escape windows and pressure transition cabins are essential components in pressurized buildings, while staircases are required in all pressurized buildings with two or more floors. Notably, the pressurized compartments used in this study were constructed using standard components. In other words, the staircases, transition cabins, and escape windows adhered to uniform standard dimensions. This standardization enhances the applicability and relevance of our results and conclusions, offering substantial reference value for other pressurized buildings built with similar standardized components. Besides, conclusions were drawn with consideration of potential gender imbalance, deliberately reflecting the real-world conditions observed in pressurized service industries, such as the Lhasa Army Aviation Unit.

Pressure is the most fundamental distinction between pressurized buildings and ordinary scenarios. Questionnaire results highlight the importance of considering sensory factors that may disrupt pedestrian coordination during pressurized environment evacuations. It revealed that ear blockage was the most reported effect during pressurization, with 86.96% of participants experiencing this symptom, and 65.22% noting a reduction in ambient noise. These symptoms can heighten challenges in high-density or emergency situations, potentially impacting mobility and overall evacuation effectiveness. 28.30% of participants reported difficulties in mobility under pressure conditions. Evacuating pedestrians from pressurized compartments present greater challenges compared to conventional evacuation scenarios. To address this, we recommend adaptive training for individuals expected to spend extended periods in pressurized environments, with attention given to monitoring their physiological responses.

Staircase evacuation experiments were conducted to assess factors such as the number of pedestrians and visibility. The analysis focused on variables including movement patterns, speed, and evacuation time. Pedestrian evacuation in the staircases of pressurized buildings exhibits movement patterns similar to those in ordinary scenarios, with the primary difference being in the speed of movement. Under low-visibility conditions, pedestrian speed was consistently slower and evacuation time longer compared to 100% visibility conditions, regardless of the number of evacuees. Observations from video and quantitative analysis of pedestrian spatial distribution revealed that under low-visibility conditions, pedestrians tended to form a single-file pattern, whereas in the absence of visibility glasses, they adopted a triangular spatial pattern. It was noted that pedestrians exhibited a preference for using the stair railing rather than the wall when evacuating. This preference should be considered when designing safety measures and evacuation plans. Clearer markings and guidance systems can be placed along the stair handrails in pressurized buildings to assist pedestrians in accurately locating the handrails, even in low-visibility conditions, thus enhancing movement flow. Additionally, attention should be given to ensuring appropriate handrail height for ease of use and safety.

The pressure transition cabin, serving as a critical facility between the pressurized compartment and the external environment, is identified as the primary evacuation route during emergencies. The study found that when 35 people entered the transition cabin, they had to push against each other to open the outer door, resulting in a significant stepwise increase in evacuation time. Moreover, this number far exceeded the maximum occupancy limit specified for pressurized compartments. Based on these findings, it is recommended that evacuation time, rather than spatial capacity, should be used as the key metric for assessing the evacuation capability of transition cabins in pressurized compartments. Considering the overall depressurization time and evacuation efficiency of the compartment, it is advised that no more than 20 people use the transition cabin at a time in an emergency, with the density kept below 5 m^{-2}.

Escape windows serve as an alternative evacuation route in situations where evacuees cannot use the transition cabin. Experiments were conducted to examine the evacuation rate through the escape windows. The linear relationship observed between evacuation time and the number of evacuees provides a practical guideline for estimating evacuation times, thereby supporting the development of more reasonable and effective evacuation strategies.

In conclusion, this study enhances our understanding of pedestrian behavior within pressurized compartments, laying a foundation for both research and practical applications in the safety management of these environments. Future research

could consider factors such as age group differences, gender distribution, and specific architectural features. For instance, examining the behavior of various age groups under pressure could help identify age-specific challenges and enable the development of tailored evacuation strategies. Incorporating scenarios such as corridors, bottlenecks, and even focusing on full-building evacuations in pressurized environments would provide more practical guidance for establishing comprehensive evacuation strategies in pressurized buildings.

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