Simulation study on the influence of different thermal insulation materials on the thermal environment of shallow underground space

Zhen Pan¹,², Zhaocai Jiang³, Haoxu Wang², Wenjie Zhang¹,³,⁴, Fengcheng Huang¹,³ and Yingbo Zhao¹,³

¹ State Key Laboratory of Building Safety and Built Environment, 100013 Beijing
² Jianke EET Co., Ltd., 100013 Beijing
³ School of Energy and Power Engineering, Nanjing University of Science and Technology, 210094 Nanjing
⁴ E-mail: zhangwenjie001@139.com

Abstract. In the shallow frozen soil in severe cold areas, the overall thermal performance of the structure is very important for the creation of the internal thermal environment. In this paper, CFD simulation calculation software is used to analyze the internal temperature field distribution of the shallow buried underground space with ordinary thermal insulation structure using only polyurethane and three improved thermal insulation structures with rock wool, polystyrene board and aerogel added. The results show that the three improved thermal insulation structures have an average increase of 9°C, 10.5°C and 12.5°C in indoor temperature compared with ordinary thermal insulation structures. Among them, thermal insulation materials in the form of polyurethane + air + aerogel have the most obvious improvement to the indoor environment.

1. Introduction

With the development of science and technology and the continuous improvement of people’s living standards, higher requirements are put forward for the indoor environment in various scenarios. Among them, how to improve the thermal performance of structures in shallow frozen soil in severe cold areas is an issue that cannot be ignored. Underground space is a building built in rock or soil. Its existence relieves land use contradictions, improves the living environment in some special areas, and opens up new areas of life for people [1-3].

Scholars at home and abroad have conducted a lot of research on the thermal performance of underground space buildings: Su Yang et al. [4] proposed an optimized design scheme based on the Euler-Bernoulli thermal insulation performance cost remainder theory for the thermal insulation problem of the underground space structure of multi-storey cluster buildings, using this model design can increase the indoor temperature by 14% at the same outdoor temperature; Zhang et al. [5] aimed at the thermal insulation engineering problem of the underground commercial space of the Olympic Park, proposed the use of polyurethane rigid foam waterproof and thermal insulation integrated materials, and detailed the advantages and disadvantages of the material and the problems in its engineering application; Li [6] studied the heat transfer characteristics of the underground envelope structure and the analysis of thermal insulation, the results show that whether in winter or summer, the wall heat flow gradually decreases with the increase of underground depth. The farther the underground
building is from the ground surface, the less energy consumption of the envelope structure is; Wei et al. [7] studied the energy-saving technology of underground building wall in Jiangsu Province. When no insulation measures are taken for basement exterior wall, the heat transfer coefficient of wall is 2.67 W/(m²·K), when the 35mm thick extruded polystyrene board (XPS) is used for insulation, the heat transfer coefficient of the composite wall is 0.76 W/(m²·K), which greatly reduces the energy loss caused by the heat transfer of the wall structure; Hu et al. [8] insulated the ceiling of the basement without heating and produced a steel wire mesh polystyrene insulation self-hanging board, when the expanded polystyrene board with a thickness of 80mm is used as the thermal insulation material, the heat transfer coefficient of the composite floor is 0.011 W/(m²·K) lower than the maximum limit in the “Design Standard for Energy Efficiency of Public Buildings”; Yu et al. [9] studied the temperature stress and thermal insulation design of the sunken roof of a large underground square, and the results showed that the temperature stress has a great influence on the internal force of the structural roof, it is recommended that the surface temperature of the top board should be 5°C as a reference to set up an insulation layer. When polyurethane foam board and aluminum silicate fiber board are used as protection measures for the top board structure, the thickness of the insulation layer should reach 5mm and 7mm respectively to achieve the effect of insulation and crack prevention.

In summary, the current research on the insulation of underground spaces is mostly concentrated on urban underground buildings, and there are few studies on the thermal performance of structures in shallow frozen soil in severe cold areas. As conventional thermal insulation materials are limited by material performance, they cannot meet the requirements of thermal insulation performance under extreme cold environment temperatures, therefore, it is proposed to propose an insulation measure for a shallow underground space, simulate and verify the improvement effect of the insulation layer on the indoor environment in lower or even extreme climates through CFD simulation software.

2. Model and calculation conditions

2.1. Physical model
The main body specification (length×width×height) of the shallow buried structure is 5m×2.2m×2.2m, one end of which is equipped with a channel with the same height as the main body, and the channel specification (length×width×height) is 1.5m×1.4m×2.2 m, an exhaust duct with an inner diameter of 0.2m is set on the opposite side of the channel.

When considering the number of personnel and equipment power, it is necessary to add personnel models and equipment models to the components. For shallow buried structures, in order to reflect the impact of personnel and equipment on the internal thermal environment of the structure, while simplifying the calculation process and improving the calculation accuracy, the persons in the shallow buried structure are abstracted into a cuboid with length, width and height of 0.45 m×0.20 m×1.75 m, and the equipment is abstracted as a cuboid with length, width and height of 1.00 m×0.60 m×0.70 m.

After putting 4 above-mentioned personnel models and 2 above-mentioned equipment models in the internal space of shallow buried structure, a perspective view of the geometrical model of the structure considering personnel and equipment is established as shown in Figure 1.

![Figure 1. Perspective view of shallow buried structure model.](image-url)
2.2. Calculation conditions

2.2.1. Boundary conditions and parameter settings for simulation. The most unfavorable meteorological and hydrological conditions in the winter in the past 10 years and the typical meteorological and hydrological conditions in the winter in the past 10 years in a certain area in northern my country are selected for simulation and analysis. The parameters are shown in the following Table 1:

| Working condition | Outdoor air temperature (°C) | Deep soil temperature (°C) | Outdoor mean wind speed (m/s) |
|-------------------|------------------------------|-----------------------------|-------------------------------|
| Working condition 1 | -36 (237K)                   | -5 (268K)                   | 3.1                           |
| Working condition 2 | -17 (256K)                   | -1 (272K)                   | 2.8                           |

The specific parameters of each layer of the insulation structure used are shown in the following Table 2:

| Material | Thickness (mm) |
|----------|----------------|
| Common insulation construction | Polyurethane 60 |
| Improved insulation structure 1 | Polyurethane 60, Air 30, Rock wool 10, Polyurethane 60 |
| Improved insulation structure 2 | Air 30, Polystyrene 10, Polyurethane 60 |
| Improved insulation structure 3 | Air 30, Aerogel 10 |

In this simulation, the lower boundary of the soil domain is set as a constant temperature wall surface to reflect the influence of the soil with a relatively stable deep layer on the heat transfer of the calculation area. For typical indoor working conditions, the heat flux to the human body and the surface of the equipment is used to reflect the heat dissipation of personnel and equipment, thereby simulating the impact of personnel and equipment on the internal working environment. The parameters selected for this simulation are: the heat flow of personnel heat dissipation is set to 30 W/m², and the heat flow of equipment heat dissipation is 10 W/m².

For the material settings in the calculation domain, the material properties required for the simulation in this part are shown in the following Table 3:

| Material | Density kg/m³ | Specific heat at constant pressure J/(kg·K) | Thermal Conductivity W/(m·K) | Viscosity kg/(m·s) |
|----------|---------------|---------------------------------------------|------------------------------|------------------|
| Air      | 1.225         | 1006.43                                    | 0.024                        | 1.7894×10⁻⁵      |
| Glass fiber reinforced plastic | 1540 | 1260 | 0.36 | \ |
| Soil     | 200           | 1010                                        | 1.16                         | \                |
| Polyurethane | 30  | 2475.2                                   | 0.024                        | \                |
| Rock wool | 120           | 840                                         | 0.046                        | \                |
| Polystyrene | 40      | 1500                                        | 0.040                        | \                |
| Aerogel  | 3             | 5490                                        | 0.018                        | \                |
2.2.2. **Computational domain setting and meshing.** The pre-processing software DesignModeler is used to set the calculation domain and mesh the main body of the simulation. In order to more realistically simulate the influence of outdoor low-temperature air and shallow soil depth on the internal temperature field of the shallow-buried assembled rectangular structure, set a cuboid soil calculation domain in the buried part and lower part of the model, and set an atmospheric calculation domain above it. Divide each different computing domain into a part, so that the boundary of each different computing domain in contact form an internal interface and couple them together. The schematic diagram of the computational domain is shown in Figure 2.

![Schematic diagram of the overall computational domain](image1)

(a) Schematic diagram of the overall computational domain

![Details of the overall computational domain profile](image2)

(b) Details of the overall computational domain profile

**Figure 2.** Schematic diagram of computational domain.

The computational domain of the structure is meshed in the form of an unstructured grid. The maximum skewness value of the generated grid is 0.85789, which is lower than the required 0.9, and the grid quality meets the requirements. Finally, the number of grids in the entire computational domain is 13231262, and the overall grid generation is shown in Figure 3.

![Mesh division](image3)

**Figure 3.** Mesh division.

3. **Comparative analysis of simulation results**

Obtain the calculation and simulation results of the temperature field in the working area when the shallow buried structure adopts ordinary insulation structure and improved insulation structure through CFD simulation, Taking the non-insulation structure scheme as the control group, the simulation results of the temperature field in the working area of the structure under the above-mentioned several kinds of insulation structures were compared and analyzed.

3.1. **Comparative analysis of simulation results of ordinary thermal insulation structure and improved thermal insulation structure 3 (aerogel)**

   (1) Simulation results of the horizontal temperature field of ordinary thermal insulation structure and improved thermal insulation structure
In order to explore the temperature distribution of the plane where the cheeks are located in different situations such as sitting and standing. In this section, through the post-processing of the simulation results, we get the horizontal temperature field cloud diagrams of the ordinary thermal insulation structure and the improved thermal insulation structure with heights of 0.7m and 1.5m, as shown in Figure 4 and Figure 5.

![Cloud map of the temperature field at a height of 0.7m in the horizontal plane.](image)

**Figure 4.** Cloud map of the temperature field at a height of 0.7m in the horizontal plane.

![Cloud map of the temperature field at a height of 1.5m in the horizontal plane.](image)

**Figure 5.** Cloud map of the temperature field at a height of 1.5m in the horizontal plane.

(2) Simulation results of the vertical temperature field of ordinary thermal insulation structure and improved thermal insulation structure

In order to explore the temperature distribution in the vertical direction of the internal temperature field of the structure, this section uses post-processing of the simulation results to obtain the temperature distribution cloud diagrams of the side sections of the ordinary thermal insulation structure and the improved thermal insulation structure as shown in Figure 6.

![Cloud map of temperature field in side profile of personnel activity.](image)

**Figure 6.** Cloud map of temperature field in side profile of personnel activity.

From the diagram (a) of Figure 4 to Figure 6, it can be seen that when the shallow buried structure adopts the ordinary thermal insulation structure, the temperature of the main working area of the horizontal and vertical planes is between 270K and 272K; From Figure 4 to Figure 6(b), it can be seen that when the shallow buried structure adopts the improved thermal insulation structure, the temperature of the main working area on the horizontal and vertical planes is between 282K and 285K. It can be seen that when maintaining the horizontal and vertical temperature fields of the working area, compared with the ordinary thermal insulation structure, the temperature of the horizontal and vertical surfaces has a significant increase after the improved thermal insulation structure is adopted, indicating that the thermal insulation performance of the improved thermal insulation structure is very excellent.
3.2. Comparative analysis of simulation results of improved thermal insulation structure

(1) Simulation results of the horizontal temperature field of 3 types of improved thermal insulation structures

In order to investigate the temperature distribution of the cheek plane when people are sitting or standing, after the post-processing of the simulation results, the horizontal temperature field cloud diagrams of the three improved insulation structures with heights of 0.7m and 1.5m were obtained, as shown in Figure 7 and Figure 8.

![Cloud diagram of horizontal temperature field at height of 0.7m.](image)

(a) Improved insulation structure 1 (rockwool sliver)
(b) Improved insulation structure 2 (polystyrene board)
(c) Improved insulation structure 3 (aerogel)

Figure 7. Cloud diagram of horizontal temperature field at height of 0.7m.

![Cloud diagram of horizontal temperature field at height of 1.5m.](image)

(a) Improved insulation structure 1 (rockwool sliver)
(b) Improved insulation structure 2 (polystyrene board)
(c) Improved insulation structure 3 (aerogel)

Figure 8. Cloud diagram of horizontal temperature field at height of 1.5m.

(2) Simulation results of vertical temperature field of ordinary insulation structure and improved insulation structure

In order to explore the temperature distribution in the vertical direction of the internal temperature field of the structure, the temperature distribution cloud diagrams of personnel activities in the side profiles of the three improved insulation structures were obtained by post-processing the simulation results in this section, as shown in Figure 9.
It can be seen from Figure 7 to Figure 9(a) that when the shallow buried structure adopts the improved insulation structure 1(rockwool), the temperature of the main working area in the horizontal plane and vertical plane is between 279K and 281K. It can be seen from Figure 7 to Figure 9(b) that when the shallow buried structure adopts the improved insulation structure 2(polystyrene board), the temperature of the main working area in the horizontal plane and vertical plane is between 281K and 282K. It can be seen from Figure 7 to Figure 9(c) that when the shallow buried structure adopts the improved insulation structure 3(aerogel), the temperature of the main working area in the horizontal plane and vertical plane is between 282K and 285K. It can be seen that when maintaining the horizontal and vertical temperature fields in the working area, compared with the improved insulation structure 1(rockwool) and the improved insulation structure 2(polystyrene board), the temperature of horizontal plane and vertical plane increased obviously after adopting the improved insulation structure 3(aerogel), indicating that the improved insulation structure 3(aerogel) has excellent insulation performance.

3.3. Power simulation of auxiliary heating equipment

After adopting the improved thermal insulation structure, the mean space temperature of the shallow buried structure in the most adverse climate is 284.6K, that is, 11.6°C. In order to ensure the normal working of the staff at the ambient temperature of 15°C, it is necessary to add a certain power of auxiliary heating equipment to raise the temperature.

In order to simplify the simulation calculation, the equivalent conversion of heating equipment power was superimposed on the equipment power of the original calculation model. The heat dissipation power of the original model remained unchanged, and the simulation trial calculation was carried out by increasing heating power continuously.

Due to the small difference between the temperature and 15°C, the heating power will be set from 10W, and 5W will be added for each trial calculation. The trial calculation will be stopped when the average temperature of the monitored working area exceeds 15°C. The final trial calculation found that when the power of heating equipment reached 50W (indoor unit area power of 5.3W/m²), the temperature of the monitored working area reached 289.2K, that is, 16.2°C. When adopting the scheme of improved thermal insulation structure, only 50W auxiliary heating equipment is needed to make the average temperature of the working area reach the requirement of 15°C for the normal working environment of personnel.
4. Conclusions
In extreme climate, the internal temperature of ordinary thermal insulation structure is still at a low level, which is not suitable for personnel to work. After adopting the improved thermal insulation structure, the temperature of horizontal plane and vertical plane of shallow buried structure has a significant increase, which can effectively improve the working environment of shallow buried structure.

Improved insulation structure 3 (aerogel) has the best effect on raising the average indoor temperature, which is 3~4°C higher than the average indoor temperature of the other two improved insulation structures, and it has reached 7°C and 10°C, which can improve the comfort of personnel at work.

Due to the extreme climatic conditions outside, no matter whether the ordinary thermal insulation structure or the improved thermal insulation structure is adopted, it cannot reach the suitable temperature of 15°C for personnel work. Therefore, additional auxiliary heating is required. Among them, after adopting the improved thermal insulation structure 3 (aerogel), only 50W auxiliary heating equipment can be used to increase the temperature to above 15°C, which can achieve better energy-saving effects.

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