The influence of thermal insulation position in building exterior walls on indoor thermal comfort and energy consumption of residential buildings in Chongqing

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Abstract. This paper focused on the influence of using position of thermal insulation materials in exterior walls on the indoor thermal comfort and building energy consumption of residential building in Chongqing. In this study, four (4) typical residential building models in Chongqing were established, which have different usage of thermal insulation layer position in exterior walls. Indoor thermal comfort hours, cooling and heating energy consumption of each model were obtained by using a simulation tool, Energyplus. Based on the simulation data, the influence of thermal insulation position on indoor thermal comfort and building energy consumption in each season was analyzed. The results showed that building with internal insulation had the highest indoor thermal comfort hours and least cooling and heating energy consumption in summer and winter. In transitional season, the highest indoor thermal comfort hours are obtained when thermal insulation is located on the exterior side.

1. Introduction

In 2014, China and the United States (US) signed a joint declaration on climate changing and cooperation of clean energy, and China formally indicated that its carbon emissions are expected to reach a peak in 2030 [1]. [2] pointed out that in 2013 China's total building energy consumption accounted for 19.5% of the total energy consumption, which showed an increasing trend every year. Thus, reducing building energy consumption is become an important part of the national goal of achieving energy conservation and emission reduction. To reduce energy consumption of buildings, the most critical way is to reduce the energy consumption resulted by improve indoor environment especially the thermal environment [3].

Chongqing is a typical city in hot summer and cold winter climate, located in the transitional zone between Qinghai Tibet Plateau and the Yangtze River Plain in China. Typical meteorological yearly data of Chongqing shows that the annual average temperature is 18.4 °C, the average temperature of the hottest month, July is 30.95 °C, the average temperature of the coldest month, January is 8.1 °C, and the annual average relative humidity is 80.6% [4]. It can be seen that Chongqing is hot in summer and cold in winter, as a result, residents have higher demands for cooling and heating. With the rapid increase of residents’ income, the residents’ demand to improve indoor environment is becoming an
urgent need [5]. However, the improvement of indoor thermal environment in Chongqing may result in a greater amount of energy consumption. Therefore, designers should simultaneously consider building energy consumption and thermal comfort when design buildings.

Adopting proper thermal insulation form is one of the effective ways to reduce building cooling and heating energy consumption [6]. [7] also pointed out that the design of building thermal insulation has to be considered a priority in the energy saving optimization. With the publication of energy saving design standards [8] and [9], building energy saving requirements will be more stringent and thermal insulation materials have been increasingly used in engineering.

Changing the position of the thermal insulation layer in the envelope will not only change thermal resistance, but it will have different effects on the heat transfer process between indoor and outdoor [10]. Many scholars have analyzed using position of thermal insulation materials in envelope:

In 2000, Bojic [11] studied the influence of different location of thermal insulation layer on the annual cooling load and the daily maximum cooling load in two high-rise residential buildings in Hong Kong by using HTB2 simulation software. The results showed that cooling load can be different when the insulation layer are placed in different locations in envelope, and the effect of increasing thermal insulation thickness on reducing cooling load becomes weak when the thickness of insulation material reaches a certain value. In 2001, Kossecka [12] designed six (6) typical external thermal insulation walls, with different thermal insulation layer placement. Six cooling and heating loads of the single residential with different walls were calculated using DOE-2.1E. It was concluded that the location of the insulation layer in the exterior wall significantly affects the energy demand of the building. In 2006, Ozel [13] set up twelve (12) different kinds of exterior wall through changing the position of thermal insulation layer in exterior wall, and analyzed the influence of each exterior wall on the time lag and decrement factor during typical summer and winter days. Analyzes of the results showed that the best distribution of insulation layer was in three equal parts at both sides and the middle section of the wall. In 2013, Tummu [14] studied the effects of different thermal insulation materials and thermal insulation layer location in the exterior wall on the heat transfer in the bedroom, living room and studio room in Thailand by using measurement and simulation methods. The data showed that insulation layer located in internal plane had better performance than the external one in all the rooms. In 2015, Ruan [15] studied the effects of external insulation and internal insulation in exterior wall, and pointed out that under the intermittent energy consuming mode, external insulation would increase cooling load in summer and the internal insulation could reduce the cooling load and heating load.

From the above research, we can see that the existing research mainly focused on the influence of thermal insulation material's location on the heat transfer and cooling and heating energy consumption of buildings. However, there is limited research on the influence of thermal insulation material's location on the indoor thermal comfort. In these previous energy saving optimization research, the indoor thermal comfort is somewhat not studied. Therefore, it necessary to explore whether the use of thermal insulation materials would affect the indoor thermal comfort when outdoor meteorological parameters are appropriate, and heating and cooling is not needed especially in the spring and autumn. In this study, an in-depth analysis of the influence of thermal insulation material's location in the exterior wall on the indoor thermal comfort is carried out. This study also investigated the influence of thermal insulation material's location in the exterior wall on residential building energy consumption in Chongqing area.

From the indoor thermal comfort and energy consumption perspective, this study established four (4) typical residential building models with different insulation layer location in the exterior wall in Chongqing. Heating and cooling energy consumption under air conditioning and indoor thermal comfort hours under natural ventilation were obtained by using the dynamic simulation software, Energyplus. Thorough analysis of the simulation results in different seasons, the influence of thermal insulation material's location in the exterior wall on indoor thermal comfort and energy consumption in Chongqing were obtained. This study provided a basis for designers to design the using position of thermal insulation materials and fills up the gaps in related research.
2. Methodology
This study established four typical residential building models with different insulation layer location in the exterior wall in Chongqing. Annual heating and cooling energy consumption under air conditioning and hourly indoor operating temperature and relative humidity under natural ventilation were obtained by using the dynamic simulation software, Energyplus. Based on the acceptable thermal comfort zone model and hourly indoor operating temperature and relative humidity, the annual indoor thermal comfort hours are obtained. Indoor thermal comfort hours and cooling and heating energy consumption of each building model are obtained and compared in every season, so the influence of thermal insulation material's location in the exterior wall on indoor thermal comfort and energy consumption is obtained. Then, through a comparison of indoor and outdoor meteorological parameters and statistical the standard deviation, maximum and minimum of operating temperature in each model, the influence of thermal insulation material's location in the exterior wall on indoor thermal comfort and energy consumption are explained.

2.1. Thermal insulation placement
The difference between the 4 models established in this study is that the exterior wall has different locations of thermal insulation layer, as shown in figure 1:

![Figure 1. Thermal insulation layers in the four exterior walls.](image)

The four walls are composed of outside to inside:

A. 10mm cement mortar + 30mm inorganic thermal insulation mortar + 200mm sintered shale porous brick + 10mm cement mortar
B. 10mm cement mortar + 20mm inorganic thermal insulation mortar + 200mm sintered shale porous brick + 10mm inorganic thermal insulation mortar + 10mm cement mortar
C. 10mm cement mortar + 10mm inorganic thermal insulation mortar + 200mm sintered shale porous brick + 20mm inorganic thermal insulation mortar + 10mm cement mortar
D. 10mm cement mortar + 200mm sintered shale porous brick + 30mm inorganic thermal insulation mortar + 10mm cement mortar

Model A is external insulation (thermal insulation layer is located on the external side). Model D is internal insulation (thermal insulation layer is located on the internal side). Model B and C are composed of different thickness of external and internal thermal insulation. The physical properties of the materials used for the four external walls are given in table 1.

| Table 1. Physical properties of external wall materials. |
|-----------------------------------------------|
| Material name                  | Thermal conductivity coefficient W/(m·K) | Density kg/m³ | Specific heat J/kg·K |
| Inorganic thermal insulation mortar | 0.07                                     | 280           | 1050                 |
| Sintered shale porous brick     | 0.58                                     | 1400          | 1050                 |
| Cement mortar                  | 0.93                                     | 1800          | 1050                 |
Inorganic insulation mortar is a common thermal insulation material which has the following advantages; low cost, convenient construction and so on. It has been widely used in the hot summer and cold winter area [16]. Based on the material thickness of the external wall and the physical properties of the material, the thermal performance parameters of the external wall are calculated as shown in table 2.

| Number | Total heat transfer coefficient W/(m • K) | Thermal inertia index |
|--------|------------------------------------------|-----------------------|
| 1      | 1.05                                     | 3.48                  |
| 2      | 1.05                                     | 3.48                  |
| 3      | 1.05                                     | 3.48                  |
| 4      | 1.05                                     | 3.48                  |

Owing to the same material and thickness, the exterior walls have the same thermal performance parameters. Meanwhile, the influence of the different thermal insulation location on thermal comfort and energy consumption are easier to analyse, when the thermal performance is same.

### 2.2. Simulation tool

This study used Energyplus V8.4.0 as the dynamic simulation tool for calculating the hourly indoor operating temperature, relative humidity and annual energy consumption. Energyplus is a building energy analysis tool developed in 2001 by the US Department of Energy, based on the most popular features and capabilities of BLAST and DOE-2 and has been widely used in throughout the world [17]. According to building model information from user's setting, Energyplus can calculate the annual energy consumption of the building as well as the hourly indoor thermal and humidity condition. Firstly, the building model is built without the air-conditioning system, and the operating temperature and relative humidity of the indoor in natural ventilation are calculated, which is the basic data for the evaluation of indoor thermal comfort. Thereafter, adding the air conditioning system, building cooling and heating energy consumption is obtained.

### 2.3. Indoor thermal comfort hours and acceptable humidity hours

Taking into account the people's psychological and behavioral adjustment, Yao [18] established the Adaptive Predicted Mean Vote (aPMV) based on automatic control theory, ‘black box’. The aPMV is a thermal comfort evaluation model for evaluating the thermal comfort of the human body in non-air-conditioned environment. According to the survey data, Wei [19] puts forward the acceptable thermal comfort zone (when \(-1 \leq aPMV \leq 1\)) of the residents in non-air-conditioned environment in Chongqing. As shown in figure 2, the vertical axis is the operating temperature, the horizontal axis is the moisture and the curve is relative humidity. The area surrounded by the dotted line is the acceptable thermal comfort zone. Based on the indoor air quality standard [20], the acceptable thermal comfort zone sets acceptable relative humidity range between 30%~80%.
This study made the following definitions:
Thermal comfort hours: indoor operating temperature and humidity points are in the range of acceptable thermal comfort zone in non-air-conditioned environment.
Acceptable humidity hours: indoor humidity points are in the range of acceptable relative humidity in non-air-conditioned environment.

2.4. Model specification
Figure 3 shows the layout of the building. The building has three (3) floors, with floor height of 2.8m, and there are two (2) residences in each floor. The house construction area is about 80m², which is the mainstream size of residence having three (3) people in Chongqing [21]. Figure 4 shows the drawing of the building.
The building envelope met the requirements of design standard for energy efficiency, 65% of residential building [8], as shown in table 3. The external wall was set in section 2.1 part of this paper.

Table 3. Setting parameters of envelope.

| Variable                                | Value   |
|-----------------------------------------|---------|
| Shape coefficient                       | 0.39    |
| Roof heat transfer coefficient W/(m·K)  | 0.69    |
| Roof thermal inertia index              | 2.55    |
| Exterior window heat transfer Coefficient W/(m·K) | 2.01 |
| North window wall ratio %               | 45      |
| South window wall ratio %               | 45      |
| East window wall ratio %                | 25      |
| West window wall ratio %                | 25      |

Based on the design standard for energy efficiency, 65% of residential building [8], cooling and heating periods were set. Cooling period (summer): June 1st - September 30th. Heating period (winter): December 1st to 30th and January 1st to February 28th. The heating setpoint was 18°C and cooling setpoint was 26°C. In the rest of the time (transitional season), the air-conditioning system was not operating. Due to the fact that the research object is the residential building, air conditioning system set to a split type air conditioner and the coefficient of performance was 3.5. If the outdoor temperature was in the range of 18-26°C, the indoor ventilation was 5 times/h, otherwise was 1 time/h. Occupancy was 25 m²/person and occupancy design load was 60 W/person (Seated, quiet). The lighting design load was 5 W/m², and the equipment design load was 4.3 W/m². Schedules for air conditioners, equipment and lighting used the template from EnergyPlus.

3. Results

Table 4. The annual results.

| Number | Annual energy consumption kWh/m² | Annual thermal comfort hours | Annual acceptable humidity hours |
|--------|---------------------------------|------------------------------|---------------------------------|
| 1      | 22.671                          | 3423                         | 8242                            |
| 2      | 22.643                          | 3425                         | 8233                            |
| 3      | 22.637                          | 3428                         | 8228                            |
| 4      | 22.631                          | 3435                         | 8225                            |

Table 4 shows the values of annual results of the four different building models. With the reduction of external insulation thickness and increase of internal insulation thickness, building energy consumption decreased from external insulation building 22.671 kWh/m² to internal insulation building 22.631 kWh/m². Meanwhile, thermal comfort hours increased from external insulation building 3423 to internal insulation building 3435. Annual thermal comfort hours and energy consumption showed an opposite trend. The internal insulation had the least acceptable humidity hours, which was 8225, accounting for 93.89% of the total hours of the year. All the four building models have good wet environment, so this study did not analyze the humidity. The following was a further analysis of the seasonal energy consumption, thermal comfort hours and operating temperature.

3.1. Summer

Table 5. Cooling energy consumption and thermal comfort hours in summer.

| Model   | Cooling energy consumption kWh/m² | Thermal comfort hours |
|---------|----------------------------------|-----------------------|

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Table 5 shows the cooling energy consumption and thermal comfort hours of different building models in summer. It can be seen that the external insulation building has the most cooling energy consumption which was 14.654 kWh/m$^2$. Model 2 and 3 had the same cooling energy consumption which was 14.634 kWh/m$^2$. The internal insulation building has the least cooling energy consumption which is 14.629 kWh/m$^2$. The external insulation building had the least thermal comfort hours, which were 241. With the reduction of external insulation thickness and increase of internal insulation thickness, thermal comfort hours gradually increased. The internal insulation building had the most thermal comfort hours, which were 260. Thermal comfort hours and cooling energy consumption showed opposite trend.

| Model | Average value of standard deviation of daily operating temperature $^\circ$C | Maximum operating temperature $^\circ$C | Minimum operating temperature $^\circ$C |
|-------|-------------------------------------------------|--------------------------------------|-------------------------------------|
| 1     | 0.525                                           | 38.012                               | 25.586                              |
| 2     | 0.532                                           | 38.052                               | 25.544                              |
| 3     | 0.536                                           | 38.072                               | 25.505                              |
| 4     | 0.539                                           | 38.079                               | 25.457                              |

**Figure 5.** Indoor operating temperature and humidity points in summer.  
**Figure 6.** Outdoor dry bulb temperature and humidity points in summer.

By taking internal insulation building as an example, the distribution of indoor operating temperature and humidity points in summer is shown in figure 5. It can be seen that the points were mainly distributed above the thermal comfort zone. Only some points below fell within the acceptable area. The operating temperature was basically distributed between 25 $^\circ$C and 38 $^\circ$C. Therefore, in order to improve the indoor thermal comfort, it is necessary to reduce the indoor operating temperature. Figure 6 shows the comparison of outdoor meteorological parameters [4], with acceptable thermal comfort zone in summer. Since there is no annual hourly outdoor operating temperature data in Chongqing, using the dry bulb temperature displayed the outdoor thermal environment in Chongqing. It can be seen that outdoor temperature was mainly distributed between 18 $^\circ$C and 38 $^\circ$C.

**Table 6.** Operating temperature distribution in summer.
Table 6 shows the operating temperature distribution in summer. It can be seen that the internal insulation building has the most average value of standard deviation of daily operating temperature which was 0.539 °C, the most maximum operating temperature was 38.079 °C and the least minimum operating temperature was 25.457 °C. This means that indoor temperature of internal insulation building had the largest fluctuation, mostly being affected by the outdoor weather and had the worst thermal stability. With the reduction of internal insulation thickness and increase of external insulation thickness, the average value of standard deviation of daily operating temperature and maximum operating temperature gradually decreased, and the minimum operating temperature gradually increased, which means the influence degree on indoor thermal environment of the outdoor gradually weakened. The external insulation building had the least average value of standard deviation of daily operating temperature was 0.525 °C, the least maximum operating temperature was 38.012 °C and the most minimum operating temperature was 25.586 °C. The thermal stability of the external insulation building was excellent, and it was not easily affected by the change of the outdoor environment.

Based on the analysis of indoor and outdoor meteorological parameters and thermal stability, it can be concluded that:

Thermal comfort: Due to poor thermal stability, the internal insulation building could change the indoor temperature more quickly than the other building models. When the outdoor temperature rose to a lower range, some points of the internal insulation building may be reduce to the acceptable thermal comfort zone. Due to the better thermal stability, external insulation was least affected by the outdoor environment. Although indoor temperature decreased, the indoor temperature couldn’t change rapidly. When the outdoor temperature increased to a lower range, the indoor temperature in external insulation building was higher than in the internal insulation building, and the temperature in external insulation building may not be reduced to the range of acceptable thermal comfort zone. So in the summer, the thermal comfort hours increases with the reduction in external insulation thickness and increase in internal insulation thickness.

Energy consumption: Due to the poor thermal stability, internal insulation was mostly affected by the outdoor environment. When the outdoor temperature increased to a higher range during daytime, the internal insulation building had the highest hourly operating temperature and the highest hourly cooling load. When the outdoor temperature decreased to a lower range during the night, the internal insulation building had the lowest hourly operating temperature and the lowest hourly cooling load. However, the internal insulation building had the lowest total cooling energy consumption in summer.

3.2. Winter

Table 7. Heating energy consumption and thermal comfort hours in winter.

| Model | Heating energy consumption kWh/m² | Thermal comfort hours |
|-------|-----------------------------------|----------------------|
| 1     | 8.017                             | 47                   |
| 2     | 8.009                             | 50                   |
| 3     | 8.003                             | 54                   |
| 4     | 8.003                             | 56                   |

Table 7 shows the heating energy consumption and thermal comfort hours of different building models in winter. It can be seen that the external insulation building has the most heating energy consumption was 8.017 kWh/m². Model 3 and internal insulation building had the least heating energy consumption, which was 8.003 kWh/m²/m². The external insulation building had the least thermal comfort hours, which was 47. With the reduction of external insulation thickness and increase of internal insulation thickness, thermal comfort hours gradually increased. The internal insulation building had the most thermal comfort hours, which was 56. Thermal comfort hours and heating energy consumption showed opposite trend.
By taking internal insulation building as an example, the distribution of indoor operating temperature and humidity points in winter is shown in figure 7. It can be seen that the points were mainly distributed below the thermal comfort zone. Only some points above fell within the acceptable area. The operating temperature was basically distributed between 9°C and 17°C. Therefore, in order to improve the indoor thermal comfort, it is necessary to improve the indoor operating temperature. Figure 8 shows the comparison of outdoor meteorological parameters [4], with acceptable thermal comfort zone in winter. It can be seen that the outdoor temperature was mainly distributed between 3°C and 15°C.

Table 8. Operating temperature distribution in winter.

| Model | Average value of standard deviation of daily operating temperature °C | Maximum operating temperature °C | Minimum operating temperature °C |
|-------|---------------------------------------------------------------|----------------------------------|----------------------------------|
| 1     | 0.297                                                         | 17.395                           | 9.354                            |
| 2     | 0.300                                                         | 17.491                           | 9.334                            |
| 3     | 0.302                                                         | 17.560                           | 9.316                            |
| 4     | 0.305                                                         | 17.618                           | 9.294                            |

Table 8 also shows operating temperature distribution in winter which was similar to summer. With the increase of external insulation thickness and reduction of internal insulation thickness, the thermal stability of the building gradually improved. The thermal stability of the external insulation building was the best and internal insulation building was the worst.

From the analysis of indoor and outdoor meteorological parameters and thermal stability, it can be concluded that:

Thermal comfort: Due to poor thermal stability, the internal insulation building could rapidly change indoor temperature than the other building models. When the outdoor temperature increased to a higher range, some points of the internal insulation building may increase to the acceptable thermal comfort zone. Due to the better thermal stability, external insulation was least affected by the outdoor environment. Although indoor temperature increased, the indoor temperature could change rapidly. When the outdoor temperature increased to a higher range, the indoor temperature in external insulation building was lower than in the internal insulation building, and the temperature in external insulation building may not increase to the acceptable range of thermal comfort zone. Consequently, in the winter, the thermal comfort hours increased with the reduction of external insulation thickness and increase of internal insulation thickness.
Energy consumption: Due to the poor thermal stability, internal insulation was mostly affected by the outdoor environment. When the outdoor temperature increased to a higher range during daytime, the internal insulation of building had the highest hourly operating temperature and the lowest hourly heating load. When the outdoor temperature decreased to a lower range during the night, the internal insulation building had the lowest hourly operating temperature and the highest hourly heating load. However, the internal insulation building had the lowest total heating energy consumption in winter.

3.3. Transitional season

| Model | Thermal comfort hours |
|-------|-----------------------|
| 1     | 3135                  |
| 2     | 3133                  |
| 3     | 3128                  |
| 4     | 3119                  |

The transitional season does not belong to the cooling and heating period, as a result, this part only analyze thermal comfort hours. As it can be seen from table 9, thermal comfort hours of the four building models were all longer than 3000 hours. The lowest was internal insulation building, and thermal comfort hours was 3119, reaching 84.94% of the total hours of the transitional season. With the reduction of internal insulation thickness and increase of external insulation thickness, thermal comfort hours gradually increased. The external insulation building had the most thermal comfort hours, which were 3135, reaching 85.38% of the total hours of the transitional season.

![Figure 9. Indoor operating temperature and humidity points in transition season.](image1)

![Figure 10. Outdoor dry bulb temperature and humidity points in transition season.](image2)

When considering internal insulation building as an example, the distribution of indoor operating temperature and humidity points in transitional season is shown in figure 9. It can be seen that the points were mainly distributed in the acceptable thermal comfort zone, which means that there was good indoor thermal environment in transitional season. Figure 10 shows the comparison of outdoor meteorological parameters [4], with acceptable thermal comfort zone in transition season. It can be seen that the outdoor thermal environment of the transition season was clearly better than other seasons, and 61.37% hours met the requirements of the 5 ventilation times/h, which could help improve the indoor temperature.

| Model | Average value of standard deviation of daily operating | Maximum operating temperature °C | Minimum operating temperature °C |
|-------|--------------------------------------------------------|-----------------------------------|----------------------------------|
|       |                                                        |                                   |                                  |
Table 10 also shows operating temperature distribution in transition season which has the same law as summer. With the increase of external insulation thickness and reduction of internal insulation thickness, the thermal stability of the building was gradually improved. The thermal stability of the external insulation building was the best and internal insulation building is the worst.

Based on the analysis of indoor and outdoor meteorological parameters and thermal stability, it can be concluded that:

Thermal comfort: Due to poor thermal stability, the internal insulation building could quickly change the indoor temperature than the other building models. When the outdoor temperature increased to a higher range, some points of the internal insulation building may increase beyond the acceptable thermal comfort zone. Due to the better thermal stability, external insulation was least affected by the outdoor environment. Although indoor temperature increased, could not quickly change the indoor temperature. When the outdoor temperature increased to a higher range, the temperature was lower than in the internal insulation building, and the temperature in external insulation building may still be in the range of acceptable thermal comfort zone. At the same time, the internal insulation building could reduce the indoor temperature more quickly than the other building model. When the outdoor temperature reduced to a lower range, some points of the internal insulation building may be lower than the low limit of acceptable thermal comfort zone. Therefore, in the transitional season, the thermal comfort hours increased with the reduction of internal insulation thickness and increase of external insulation thickness.

Thus, the external insulation was the most appropriate thermal insulation form in the transitional season, which could increase the thermal comfort hours. However, all the four building models had a comfortable indoor environment in the transition seasons.

4. Conclusions
Based on the above analysis, the following conclusions were drawn:

- Under the condition of the same thermal insulation material thickness, the residential buildings in Chongqing with internal insulation had the most thermal comfort hours in summer and winter. On the contrary, in the transitional season, it was external insulation. From the perspective of the whole year, the thermal comfort hours of internal insulation building was the largest.
- In Chongqing, the residential buildings with internal insulation had the lowest cooling and heating energy consumption.
- The residential building with internal insulation had poor thermal stability and was more likely to be influenced by the outdoor temperature. In summer, building with internal insulation had the highest hourly operating temperature and hourly cooling load during daytime, and the lowest hourly operating temperature and hourly cooling load during the night. In winter, building with internal insulation had the highest hourly operating temperature and the lowest hourly heating load during daytime, and the lowest hourly operating temperature and the highest hourly heating load during the night. The internal insulation was suitable for the building which had personnel long stay in summer night and winter day. Contrary to internal insulation, the external insulation was suitable for the building which had personnel long stay in winter night and summer day.

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