Technical and Economic Analysis of External Wall Thermal Insulation for Nearly Zero Energy Buildings Based on Life Cycle Cost

Wei Liu, Zhen Yu*, Huai Li, Caifeng Gao and Guanqun Wang
China Academy of Building Research, No.30, North 3rd Ring East Road, Chaoyang District, Beijing, China
Email: yuzhen@chinaibee.com; 1066021808@qq.com

Abstract. The outer protective structure of nearly zero Energy building generally has better thermal insulation performance. With the increase of the thickness of the external wall insulation, the energy conservation gains decrease. This paper studies the economics of the life cycle cost of the external wall insulation of nearly zero energy buildings in different climate zones. Considering solar radiation and nocturnal radiation, an explicit one-dimensional unsteady heat conduction model is established by using the finite difference method, and the temperature of each point inside the wall at various times within 8760 hours of the year is calculated, thereby calculating the annual heat transfer amount per unit wall area. Considering the construction cost, annual operating cost, and discount rate, calculate the cost of the life cycle of the insulation material under different thicknesses in each climate zone. The best economic thickness of each insulation material in each climate zone is obtained.

Keywords. Nearly zero energy building; life cycle cost; one-dimensional unsteady; economic thickness.

1. Introduction
The development of nearly zero energy buildings in China has been inspired and influenced by the German passive housing technology system. “Technical Standards for Nearly Zero Energy Buildings” GB/T 51350-2019 (table 1) [1] emphasizes the application of better protective structure, high-performance doors and windows, high-efficiency heat recovery new wind system, high air tightness and heat-free bridge design of the building, with little primary energy to achieve good indoor environment.

Table 1. Nearly Zero Energy Buildings external wall heat transfer coefficient and indoor environment index.

| Heat transfer coefficient (W/ (m²·K)) | Climate zone | Severe cold | Cold | Hot summer and cold winter | Hot summer and warm winter | Moderate | Indoor environmental parameters | Winter | Summer |
|--------------------------------------|--------------|-------------|------|---------------------------|---------------------------|----------|--------------------------------|-------|--------|
| Residential building                 | 0.10-        | 0.15-       | 0.15-| 0.30-                     | 0.20-                     |          | Temperature ≥20 ≤26            |       |        |
| Public building                      | 0.15         | 0.20        | 0.40 | 0.80                      | 0.80                      |          | Relative humidity ≥30 ≤60      |       |        |
Due to the loss of energy consumption accounted for 23-34% [2] caused by the thermal transfer of external walls, conventional buildings use better insulation system to effectively reduce the loss of building heat, thus the corresponding cost will also increase. This research, from the life cycle cost perspective, studies the nearly zero energy buildings external wall insulation's technical and economic benefits.

There have been scholars analyzing the external wall insulation performance and economic perspectives. Mohammed [3] et al. carried out the optimization analysis of insulation thickness in Palestine, taking 8 provinces into account, considering weather data, energy prices, heat and cold source efficiency, etc. They studied two kinds of materials, using the number of days to calculate the hot and cold load, finding that the optimal thickness was between 0.4-9 cm, and the annual savings of 4 to 8 US dollars/m² were achieved at 18 °C, while the investment recovery period was between 0.9 to 1.6 years. Fohagui [4] et al. employed the same method to steadily calculate that the optimal insulation thickness of the research material for the building energy loss caused by annual thermal transfer of Cameroon external walls was between 8.2 cm-32 cm, the energy saving range 58%-86%, and the recycle period was 0.66-2.39 years. Bedri [5] et al. established a steady-state thermal transfer model, calculating the heat consumption of the wall by using the number of days of heating degrees, conducting comparative analysis of different climates, and finally determining the optimal thickness of insulation materials. Unsal [6] et al. studied the indoor environment of the building and used the fitting formula to estimate the optimal insulation thickness. Zhu [7] et al. used the degree-hour method to calculate the annual hot and cold load of each climate zone in China, whereupon they calculate the total life cycle cost and concluded that the SEPS in Urumqi, Beijing, Shanghai, Guangzhou and Kunming had an optimal thickness of 175 mm, 216 mm, 205 mm, 116 mm and 163 mm. Huang [8] used the number of days of heating degrees to establish a mathematical model of economic optimization of the thickness the external wall insulation layer, which minimizes the energy consumption cost and the insulation cost caused by the external wall during the life cycle of the insulation layer. Wang [9] used the number of days of heating and air conditioning degrees to calculate the thermal transfer and combined with the method of present value coefficient, which obtains the economic thickness value of different wall insulation materials in Chongqing area. The above articles use steady state calculate wall thermal transfer, without considering the influence of solar radiation and the wall’s own heat storage, thus the result is uncertain.

Xu [10, 11] et al. established a one-dimensional wall thermal and wet coupling transfer model, with the time-by-time meteorological parameters of a typical meteorological year in Nanjing as the outdoor boundary condition, to calculate the indoor, const temperature, constant humidity, the three kinds of insulation walls’ heat and humidity transmission, so as to calculate the economic advantages, but the study did not consider the impact of different indoor environments in winter and summer. Zhao [12] et al. used COMSOL heat and humidity transfer equation to conduct the discrete solution, and obtained the optimal insulation thickness of different orientations in the four cities in hot summer and cold winter, and thus came up with the conclusion that in the hot summer and cold winter areas, the insulation thickness of the building’s exterior walls do not need to consider orientations. Ozel [13] et al. used the finite differential method to solve the model of multi-layer walls with periodic boundaries, and used the lag time and the decay size of the hot flow wave as the basis for measuring the energy-saving performance of the insulation material, so as to optimize the position of the insulation material in the wall, but did not consider the economic benefits.

Feng [14] et al. used EnergyPlus to optimize the parameters of nearly zero energy buildings, protective structures in the cold region, taking the external cost of electricity prices into account, calculated the impact of different schemes on building energy consumption and LCC, and obtained the optimal thickness of SEPS exterior walls as 320 mm, the optimal insulation thickness of XPS roofing as 260 mm. Jie [15] et al. used energy-consumption software DeST for simulation, and analyzed the effect of roof insulation and exterior wall insulation on building energy consumption. Because of the overload of computational conditions, they used polynomial building load for regression fitting, compared with various energy forms, using the NPV method to calculate costs, and analyzed the
sensitivity of roofs and exterior walls to the whole life cycle of the building. Zhang [16, 17] et al. used DeST to simulate the different thickness of the six insulation systems in Hohhot, corrected the simulation results by the measure, analyzed the insulation properties of different insulation materials, used Matlab to carry out fitting of a polynomial of NPV, and obtained SEPS, XPS, PUR, rock wool, mortar, foam concrete, the 6 kinds of insulation materials are 88.0, 73.1, 43.1, 98.2, 93.4, 73.2 mm. Deng [2] et al. used DeST software to simulate the load of a typical building in Zhengzhou, discussed the energy consumption of different insulation materials and different insulation thickness, and used the NPV method to calculate the optimal economic thickness under different materials of a typical building in Zhengzhou. Pan [18] took typical office buildings as examples to study the variation of the yearly hot and cold load in different orientations, insulation material thickness in Beijing, Shanghai and Guangzhou, the three climates. They used EnergyPlus for simulation, concluded that the exterior wall’s insulation material thickness in all orientations in Beijing area and Shanghai except the south has a large energy-saving space, and for exterior wall in all orientations in Guangzhou area and in south in Shanghai area, the use of insulation basically does not have energy-saving space. Zheng [19] established the energy consumption analysis model of residential buildings on the TRNSYS platform to analyze the economic benefits of rock wool slabs, glass microbeads insulation mortar, 4 climate zones, 8 different simulation schemes for the annual energy consumption and changes in its energy saving, and thus obtained the optimal economic thickness of each climate zone. The above literature uses energy consumption simulation software to calculate the energy consumption of typical buildings. The energy consumption results obtained in the studies are the energy consumption per unit of building area. When the structure epidermis and body shape coefficient change, the energy consumption will change accordingly, the conclusion is limited by the selection of the research object building type. Therefore, the conclusion of the article is not sufficient.

The whole life cycle technical and economic analysis of the insulated exterior wall requires the calculation and simulation of the thermal transfer of the insulated exterior wall. The existing research on thermal transfer on the insulation of exterior wall is mostly based on the use of energy consumption simulation software, or as a steady state for thermal transfer simulation calculation. The annual exterior wall thermal transfer process, accompanied by wall heat storage, while solar radiation also has an impact on this, is a non-stable process. Using the monthly average method to calculate the annual energy consumption will cause deviation of energy consumption calculation, producing an uncertain result. The analysis of building energy consumption obtained by using energy consumption simulation software is the energy consumption per unit of building area, because of the limitation of parameters such as receptor coefficient, only applicable to this building, so the generality is insufficient. There are also a few scholars conducting one-dimensional unsteady thermal transfer calculation to obtain the insulation economic perspective, but the study did not take the impact of the external cost of gas and electricity into account. There is some deviation between the economic cost of calculation and the actual market cost, and the technical economy optimization value in different climate zones is not studied.

This paper studies the technical economy of the whole life cycle of the insulation of the exterior walls of nearly zero energy buildings. Unlike previous research, the boundary conditions, indoor environment and other parameters of this study meet the technical specifications of nearly zero energy buildings. In the analysis of the full life cycle cost, nearly zero energy buildings seek a comprehensive balance of initial investment and operating costs and other external benefits. The scope of the study includes the current nearly zero energy buildings’ commonly used insulation materials, discussing China’s different climate zones of various conditions. The research carried on the market research on the price and construction cost of the nearly zero energy building, adopted the finite differential method, considered the solar radiation and night radiation in each direction, established a one-dimensional unsteady thermal transfer differenced equation. Solving equation system calculates the temperature change of the building wall in the whole year, and thus calculates the thermal transfer of the insulation wall of the unit area for the whole year. The study includes 5 kinds of commonly used insulation materials in 4 climate zones in China and calculates the annual energy consumption of the
unit wall area with different orientation and different insulation thickness. Considering the external cost of gas and electricity, the net present value method is used, and the whole life cycle of technical and economic analysis is used to obtain the economic thickness of different insulation materials in different climate zones.

2. External Wall Thermal Transfer Calculation Method

2.1. Building Heat Exchange Process

In figure 1, $t_{out}$ is outdoor temperature, $t_5$ is air temperature of the air conditioning, $L_{S3}$ is air volume of the air conditioning, $L_{O}$ is air volume of outdoor penetration, $t_{e}$ is adjacent room temperature, $t_{in}$ is indoor temperature, $I$ is direct solar radiation, $t_{S1}$ is the inside temperature of the inner wall, $t_{S2}$ is inside temperature of the exterior wall, $T_{S3}$ is inside temperature of the exterior window, $t_{S4}$ is roof temperature, $t_{S5}$ is ground temperature [20].

As can be seen from the figure, the building thermal transfer is divided into three processes, including the thermal transfer process through the external-disturbed panel wall protective structure, the internal-disturbed lighting equipment personnel during the thermal transfer process, ventilation penetration and air conditioning. The thermal transfer of the protective structure includes three parts: Peripheral protection structure, outer and outer doors, inner enclosure structure. Peripheral protective structure has heat storage characteristics. The exterior surface is affected by outdoor temperature, direct solar radiation, sky scattering radiation, which gradually reflect to the interior of the building, and then passed to the interior by heat exchange. Exterior wall thermal transfer is a basically independent thermal process, so the study of exterior wall thermal transfer does not need to consider other factors.

In this paper, the thermal properties of outdoor temperature, direct solar radiation, sky scattering radiation, and heat storage of the wall are considered. A one-dimensional unsteady thermal transfer model is established, and the temperature distribution in the wall at various moments is calculated, so as to calculate the annual thermal transfer of the exterior wall.

2.2. Simulation Method

Taking the different orientation of solar radiation throughout the year into account, the study calculated the annual solar radiation of each city for 8760 hours hour-by-hour solar radiation in the whole year. Using the finite differential method to establish an explicit one-dimensional unsteady thermal differential model, the forward differential is carried out from the outside, and the annual temperature of 8760 hours is discretely calculated according to the calculated time and step. The dynamic temperature of the inner parts of the wall at various times of the year is calculated, so as to calculate the energy consumption generated by thermal transfer per unit wall area in the whole year. The study takes the investment cost, construction cost, annual operating cost, discount rate into account to calculate the cost of the whole life cycle of exterior wall insulation. Using Matlab to write the program, the discrete differential equation of the exterior wall is solved, and the result is that the annual heat consumption and cooling consumption of the wall area are calculated, so as to get rid of the dependence on the traditional building energy consumption simulation software, not affected by the building type, body coefficient and other parameters.

2.3. Wall Thermal Transfer Calculation Model

A one-dimensional unsteady thermal transfer equation is established to separate time and space. As shown in figure 2, there are $m$ layers of material. By dividing the computing area of the $i$th layer material into $n_i-1$ equals, the $n_m$ number of discrete nodes are obtained, and the $n_m$ layer materials’ total number of discrete nodes are $N = 1 + \sum_{i=1}^{m}(n_i - 1)$. By discretizing the computed time of 8760 hours, $I$ number of time nodes can be obtained, and the time interval from one-time layer to the next is called the time step. $t_n^{(i)}$ represents the corresponding temperature for the $i$th moment of layer $n$. When calculating the thermal transfer of the wall, it is divided into three kinds of situations: exchange heat
between the surface of the wall and the external convection, the internal heat transfer of the same material wall, and the heat transfer between two materials contact surface.

![Figure 1. Heat exchange process in the room.](image)

![Figure 2. Spatial discrete schematic.](image)

2.3.1. Wall Surface and External Convective Heat Exchange Equation.

\[
\mu q + \lambda_1 \frac{t_2^{(i)} - t_1^{(i)}}{\Delta x} + h_{out} \left( t_{out} - t_1^{(i)} \right) = \rho_1 c_1 \frac{\Delta x}{2} \frac{t_1^{(i+1)} - t_1^{(i)}}{\Delta t} \tag{1}
\]

In the equation: \( q \) is radiation degree, W/m\(^2\); \( \mu \) is exterior wall solar radiation absorption coefficient; \( \rho_1 \) is density of material 1, kg/m\(^3\); \( c_1 \) is fixed pressure ratio heat of material 1, J/kg·K; \( h_{out} \)
is outdoor convection thermal exchange coefficient, W/m²·K; \( \lambda_1 \) is thermal conductivity of material 1, W/m·K; \( t_{\text{out}} \) is outdoor temperature, °C; \( \Delta x \) is differential thickness, m. \( a_1 = \frac{\lambda_1}{\rho_1 c_1} \) is heat diffusion rate, m²/s.

Transformation:

\[
t^{(i+1)}_1 = t^{(i)}_1 \left(1 - \frac{2h_{\text{out}} \Delta t}{\rho_1 c_1 \Delta x} - \frac{2a_1 \Delta t}{\Delta x^2}\right) + \frac{2a_1 \Delta t}{\Delta x^2} t^{(i)}_2 + \frac{2h_{\text{out}} \Delta t}{\rho_1 c_1 \Delta x} t_{\text{out}} + \frac{2\Delta t}{\rho_1 c_1 \Delta x} \mu q
\]  (2)

\( a_1 \frac{\Delta t}{\Delta x^2} \) is the Fourier number of \( F_{ot1} \) with a \( \Delta x \) feature length; \( \frac{h_{\text{out}} \Delta x}{\lambda_1} \) is the Boit number of \( B_{i1} \) with a \( \Delta x \) feature length.

\[
h_{\text{out}} \frac{\Delta t}{\rho_1 c_1 \Delta x} = \frac{\lambda_1}{\rho_1 c_1 \Delta x^2} = F_{ot1} \times B_{i1}
\]  (3)

Then

\[
t^{(i+1)}_1 = t^{(i)}_1 \left(1 - 2F_{ot1} B_{i1} - 2F_{ot1} t^{(i)}_2 + 2F_{ot1} B_{i1} t_{\text{out}} + 2 \frac{\Delta x}{\lambda_1} F_{ot1} \mu q \right)
\]  (4)

2.3.2. The Internal Thermal Transfer Equation of the Same Material Wall.

\[
\rho_1 c_1 \Delta x \left( t^{(i+1)}_n - t^{(i)}_n \right) = \lambda_1 \frac{t^{(i)}_{n+1} - t^{(i)}_{n-1} - t^{(i)}_n}{\Delta x}
\]  (5)

Ibid, get:

\[
t^{(i+1)}_n = F_{ot} \left(t^{(i)}_{n+1} + t^{(i)}_{n-1}\right) + (1 - 2F_{ot}) t^{(i)}_n
\]  (6)

2.3.3. Thermal Transfer Equations for Two Material Contact Surfaces. Due the small differential thickness, the temperature of the contact surface can be considered the same, but the materials on both sides are different in nature, so the following equation is established:

\[
\left(\rho_1 c_1 + \rho_2 c_2\right) \frac{\Delta x}{2} \frac{t^{(i+1)}_{n_1} - t^{(i)}_{n_1}}{\Delta t} = \lambda_1 \frac{t^{(i)}_{n_1-1} - t^{(i)}_{n_1} + t^{(i)}_{n_1+1} - t^{(i)}_{n_1}}{\Delta x}
\]  (7)

In the equation: \( \rho_2 \) is the density of material 2, kg/m³; \( c_2 \) is fixed pressure ratio heat of material 2, J/kg·K; \( \lambda_2 \) thermal conductivity of material 2, W/m·K.

Sorting out:

\[
t^{(i+1)}_{n_1} = \frac{a_{t_1} \Delta t}{\Delta x^2} t^{(i)}_{n_1-1} + \left(1 - \frac{a_{t_1} \Delta t}{\Delta x^2} - \frac{a_{t_2} \Delta t}{\Delta x^2}\right) t^{(i)}_{n_1} + \frac{a_{t_2} \Delta t}{\Delta x^2} t^{(i)}_{n_1+1}
\]  (8)

Assume \( a_{t_1} = \frac{2\lambda_1}{\rho_1 c_1 + \rho_2 c_2} \); \( a_{t_2} = \frac{2\lambda_2}{\rho_1 c_1 + \rho_2 c_2} \); \( a_{t_1} \frac{\Delta t}{\Delta x^2} \) is the Fourier number of \( F_{ot1} \) with a \( \Delta x \) feature length; \( a_{t_2} \frac{\Delta t}{\Delta x^2} \) is the Fourier number of \( F_{ot2} \) with a \( \Delta x \) feature length; the:

\[
t^{(i+1)}_{n_2} = F_{ot_1} t^{(i)}_{n_1-1} + (1 - F_{ot_1} - F_{ot_2}) t^{(i)}_{n_1} + F_{ot_2} t^{(i)}_{n_1+1}
\]  (9)

Using the above equations, the temperature of the indoor surface at all times of the year is calculated \( t^{(i)}_{N_1} \), and the energy consumption of the exterior wall is dissipated throughout the year.

\[
Q = \sum_{1}^{t} \Delta t \left|h_{in} (t^{(i)}_n - t_{in})\right|
\]  (10)

\[
E = \frac{Q}{\text{COP}}
\]  (11)
In the equation: \( h_{\text{in}} \) is indoor convection heat exchange coefficient, W/m\(^2\)·K; \( t_{N}^{(i)} \) is inside temperature of exterior wall, °C; \( Q \) is heat loss caused by wall thermal transfer in the whole year, kWh/m\(^2\)·a; \( E \) is the loss of energy consumption for the wall of the whole year, kWh/m\(^2\)·a; COP is energy efficiency ratio.

2.4. Radiation Calculation Model

The heat of the building’s peripheral protective structure is divided into two parts: outdoor convection heat exchange and solar radiation heat. Solar radiation is divided into direct solar radiation and scattering radiation, so it is necessary to calculate the building’s orientation of the annual solar radiation intensity. Direct solar radiation is related to the angle of solar exposure. The calculation of direct radiation requires calculation of the angle at which the sun irradiates each direction for the year of 8760 hours in each city.

The angle between the center of the Earth and the center of the sun and the equatorial plane of the Earth is called the argument of latitude. Day-by-day argument of latitude calculation formula [20]:

\[
\delta = 23.45 \sin \left( 360 \times \frac{284 + n}{365} \right)
\]  

In the formula: \( \delta \) is the argument of latitude; \( n \) is the date sequence number of the date of the calculated date in the year.

The angle of solar height \( h \) is the angle formed by the connection of a certain point on the earth’s surface and the connection of the sun to the earth plane, and the formula is calculated:

\[
\sin h = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega
\]  

In the formula: \( \varphi \) is the local latitude; \( \delta \) is the argument of latitude; \( \omega \) is the solar angle at the time.

The solar azimuth \( a \) is the angle between the projection of the sun to a given point on the ground and the southbound (local meridian) of the sun to a given point on the ground, calculated as:

\[
\sin a = \frac{\cos \delta \sin \omega}{\cos h}
\]  

The wall azimuth \( \gamma \) is included angle between the projection of the wall surface normal and the south, to the east is negative, to the west is positive, to the south is zero. The sun azimuth of the wall \( \varepsilon \) is the angle between the projection of a certain point on the wall and the sun on the horizontal surface and the projection of the wall surface normal on the horizontal surface, \( \varepsilon = a - \gamma \).

Each orientation’s direct radiation calculation:

\[
I_{DV} = I_{DN} \cos h \cos \varepsilon
\]  

In the formula: \( IDN \) is total direct radiation from the sun, W/m\(^2\); \( IDV \) is intensity of direct radiation received from each orientation on the surface of the wall, W/m\(^2\).

Each orientation’s scatter radiation calculation:

\[
I_{DS} = F_{S} \times I_{DH}
\]  

In the formula: \( IDH \) is the total scatter radiation from the sky, W/m\(^2\); \( IDS \) is intensity of scatter radiation received from each orientation on the surface of the wall, W/m\(^2\). Calculate the use of total direct radiation and total scatter radiation parameters for the DeST built-in city’s 8760 hours of hour-by-hour radiation parameters of the whole year [21].

Scatter radiation, W/m\(^2\), \( F_{S} \) is angle coefficient between each orientation and the surface and the sky, as in 0.5.

Total radiation from each orientation [22]:

\[
q = I_{DV} + I_{DS}
\]  

In the formula: \( q \) is the total solar radiation of the orientation, W/m\(^2\).
During the night, the buildings protective structure will carry out long-wave radiation heat exchange to the surrounding environment. Long-wave radiation heat exchange is divided into radiation heat exchange for the sky and radiation to the ground heat exchange.

\[ q = q_{ra} = -C_b \varepsilon_{os} \varphi_{os} \left( \left( \frac{T_o}{100} \right)^4 - \left( \frac{T_s}{100} \right)^4 \right) + C_b \varepsilon_{og} \varphi_{og} \left( \left( \frac{T_o}{100} \right)^4 - \left( \frac{T_g}{100} \right)^4 \right) \]  

In the formula: \( C_b \) is black body radiation constant; \( T_o \) is outside surface temperature of exterior wall, K; \( T_s \) is equivalent temperature of the sky, K; \( T_g \) is the ground temperature, K; \( \varphi_{os} \), \( \varphi_{og} \) is the radiation angle coefficient of protective structure to the sky and the ground respectively. The exterior surface of the protective structure, the sky radiation surface and the ground constitute a closed system, \( \varphi_{os} + \varphi_{og} = 1; \) \( \varepsilon_{os} \) is the blackness of the radiation system between the exterior surface of the protective structure and the radiation surface of the sky, assuming \( \varepsilon_{os} = \varepsilon_o \), in which \( \varepsilon_o \) is the blackness of the exterior surface the protective structure; \( \varepsilon_{og} \) is the blackness of the radiation between the exterior surface of the protective structure and the ground, assuming \( \varepsilon_{og} = \varepsilon_o \varepsilon_g \), in which \( \varepsilon_g \) is ground blackness.

2.5. Whole Life Cycle Cost Calculation
The whole life cycle costs include the operation cost of the initial investment cost, which includes material costs and construction costs, and the calculation is shown as:

\[ LCC = TC_1 + TC_2 \]  

In the calculation: \( LCC \) is the economic costs of the nearly zero energy consumption building’s whole life cycle, yuan; \( TC_1 \) is the initial investment cost, yuan; \( TC_2 \) is the operation cost, yuan.

To calculate the whole life cycle cost, the operating cost should take the annual discount rate into account, the discount rate calculation:

\[ r = \frac{g - i}{1 + i} \]  

In the calculation: \( r \) is the discount rate, \%; \( g \) is the inflation rate, \%; \( i \) is the bank rates, \%.

\[ TC_2 = \sum_{j=1}^{j} E \times C_e \times (1 + r)^{-j} \]  

In the calculation: \( E \) is loss of energy consumption throughout the year due to the walls, kWh/m²·a; \( C_e \) is cost of electricity, yuan/kWh; \( j \) is jth year of building use.

3. Heat Transfer Calculation Results and Analysis

3.1. Boundary Conditions
This paper selects four typical cities in different climate regions of China (Harbin, Beijing, Shanghai, Guangzhou). Calculate the annual heat transfer of the unit wall area with different insulation materials, different orientations and different insulation thicknesses in different climatic zones. Analyze the effect of insulation materials on the heat transfer of external walls under the above conditions.

The research in this paper is mainly for concrete and external thermal insulation walls. Five kinds of thermal insulation materials were analyzed, which were graphite polystyrene board (SEPS), extruded polystyrene board (XPS), polyurethane, rock wool and vacuum insulation panel. The calculated thickness of the first four materials is 50 mm-400 mm, and the calculated thickness of the vacuum insulation panel is 20 mm-100 mm. Calculated as external thermal insulation wall, the wall is cement mortar, thermal insulation material, concrete, lime mortar, cement mortar from outside to inside. The set thickness of concrete and lime mortar is 30 mm, 300 mm and 30 mm respectively.
Calculate the indoor temperature: in summer, the indoor temperature is 26 °C, and in winter, the indoor temperature is 20 °C. The outdoor convective heat transfer coefficient $t_{\text{out}}$ is 19 W/m$^2$·K [23]; the near zero energy building in each climatic zone is much lower than the conventional energy-saving building due to its cold and heat load. The heat pump is usually used as the main cold and heat source to bear the load in the building. The heat pump is set for heating and cooling. The energy efficiency ratio of Harbin is 1.5 in winter and 2.5 in summer. The energy efficiency ratio of winter and summer in other cities is 2.5. Calculate the urban heating season and cooling season for each climate zone. Barbosa [24] has shown whether it is considered that the wet transfer of the wall will produce about 4% heat transfer error during the cooling season. Wall wet transfer has little impact on building energy consumption. This study does not consider the impact of wall wet transfer.

Calculated using the 8760 hourly weather parameters of the city built by DeST, DeST calculated and generated hourly meteorological parameters based on the measured data of 194 meteorological points provided by the National Meteorological Center for 50 years [21]. The Matlab program is used to iteratively solve the above equations (1) - (11). The iterative step size is 30 s and the differential thickness is 10 mm (the vacuum insulation panel has a differential thickness of 2 mm). The conditions for the existence of solutions of one-dimensional explicit unsteady state equations are [25]:

$$Fo \leq \frac{1}{2}$$

$$1 - FoBi - 2Fo \geq 0$$

The selected iterative step size and differential thickness are calculated to satisfy the condition. And 100 hours of iterative simulation calculation, the difference thickness from 2 mm to 10 mm, the difference in heat transfer is less than 0.1%.

The physical properties of thermal insulation materials are as follows in table 2.

| Material                      | Thermal conductivity $\lambda$ (W/m·K) | Constant pressure specific heat $c$ (J/kg·K) | Density $\rho$ (kg/m$^3$) |
|-------------------------------|----------------------------------------|---------------------------------------------|---------------------------|
| Graphite polystyrene board    | 0.033                                  | 1380                                        | 20                        |
| Extruded polystyrene board    | 0.029                                  | 1500                                        | 32                        |
| Polyurethane                  | 0.024                                  | 2475                                        | 30                        |
| Rock wool                     | 0.038                                  | 1340                                        | 120                       |
| Vacuum insulation panel       | 0.008                                  | 1280                                        | 400                       |

3.2. Calculation and Analysis of Annual Heat Consumption

3.2.1. Comparison of Annual Heat Transfer in Different Directions. Figure 3 is the total heat transfer of the graphite polystyrene board in each direction of Beijing, including the heat transfer in winter and summer (the total heat transfer amount shown below is the same). When the same material is used, the mean value of the four orientations of the graphite polystyrene board is 0.20, 0.49, 0.21, and 0.08, respectively. The difference between the maximum and minimum values of the four orientations at the same thickness is 5%. Because when a certain energy loss in summer is large, the energy loss in winter is small, which is the same and is consistent with the results of previous studies. It can be seen that the influence on the annual heat transfer amount is small, and the influence on other materials is consistent with this. The trends in Harbin, Shanghai and Guangzhou are consistent with those in Beijing, which are not listed here. Because the orientation has little effect on the insulation material, the following studies take the east direction as an example.
3.2.2. Comparison of Heat Transfer of Different Insulation Materials in Various Climate Zones.

Figure 4 shows the comparison of annual heat transfer of five kinds of thermal insulation materials under different thicknesses in Beijing. It can be seen from the figure that under the same thickness, the thermal conductivity of vacuum thermal insulation board is far less than that of other materials, and the annual heat transfer is far less than that of other materials. The other four materials’ heat preservation performance is from good to bad, in order are polyurethane, extruded polystyrene board, graphite polystyrene board, rock wool; with the increase of heat preservation thickness, the annual heat transfer decreases, but the decrease gradually decreases. When the insulation thickness of the vacuum insulation panel is increased from 20 mm to 100 mm, the heat transfer per unit area is reduced by 15.8 kWh/m²·a, which is reduced by 77.6%. The thickness of graphite polystyrene board, extruded polyphenylene polystyrene board, urethane ester and rock wool increased from 50 mm to 400 mm, and the heat transfer per unit area decreased by 25.9, 23.5, 20.3, 28.6 kWh/m²·a, which was reduced by 84.3% and 84.7%, 85.2%, 83.9%.

Figure 5 shows the comparison of annual heat transfer of 5 kinds of insulation materials under different thicknesses in Shanghai. It can be seen from the figure that the overall trend is consistent with that of Beijing. When the insulation thickness of vacuum insulation panels increases from 20mm to 100mm, the heat transfer per unit area is reduced by 11kWh/m²·a, which is reduced by 77.3%. The thickness of graphite polystyrene board, extruded polystyrene board, urethane and rock wool increased from 50mm to 400mm, and the heat transfer per unit area decreased by 18.0, 16.3, 14.1, 19.9kWh/m²·a, which decreased by 84.3% and 84.7%, 85.2%, 84.0%.

**Figure 3.** Annual total heat transfer of graphite polystyrene board in Beijing.

**Figure 4.** Annual heat transfer of different materials with different thicknesses in Beijing.

**Figure 5.** Annual heat transfer of different thicknesses of different materials in Shanghai.
Figure 6 shows the comparison of annual heat transfer of 5 kinds of insulation materials under different thickness in Harbin. It can be seen from the figure that the overall trend is consistent with that of Beijing. When the insulation thickness of vacuum insulation panels increases from 20 mm to 100 mm, the heat transfer per unit area is reduced by 31.9 kWh/m²·a, which is reduced by 77.2%. The thickness of graphite polystyrene board, extruded polyphenylene polystyrene board, urethane ester and rock wool increased from 50 mm to 400 mm, and the heat transfer per unit area decreased by 52.1, 47.4, 40.9, 57.7 kWh/m²·a, which was reduced by 84.3%, 84.7%, 85.2% and 83.9%.

Figure 7 shows the annual total heat transfer of five kinds of insulation materials under different thicknesses in Guangzhou. Guangzhou is a hot summer and warm winter area. The average temperature in winter is more than 10 ℃, and there is no need for heating in winter. It can be seen from the figure that the overall trend is consistent with that of Beijing. When the insulation thickness of vacuum insulation panels increases from 20 mm to 100 mm, the heat transfer per unit area is reduced by 4.5 kWh/m²·a, which is reduced by 77.2%. The thickness of graphite polystyrene board, extruded polyphenylene polystyrene board, urethane ester and rock wool increased from 50 mm to 400 mm, and the heat transfer per unit area decreased by 7.3, 6.6, 5.7, 8.1 kWh/m²·a, which was reduced by 84.3%, 84.7%, 85.2%, and 83.9%.

Under the same thickness in each climate zone, the insulation performance of five materials is from good to bad, followed by vacuum insulation panel, polyurethane, extruded polystyrene board, graphite polystyrene board, rock wool. With the increase of the thickness of the insulation, the annual total heat transfer in each climate zone decreased, but the reduction gradually decreased; the total heat transfer in Harbin decreased the most, and the least in Guangzhou. Insulation materials have the highest energy-saving potential in severe cold regions and cold regions, but the proportion of total heat transfer in the four climate zones is roughly the same.

4. The Whole Life Cycle Technical and Economic Analysis

4.1. Market Research
The market insulation materials prices, construction costs, and electricity prices were investigated. The results are as follows: Consider the external costs generated by electricity in the coal-fired power chain, and include the added value of electricity prices. From this, the external cost in China’s coal-electric chain is calculated to be 0.38 yuan/kWh. Extrusion polystyrene board is different from other materials in construction, and layering is required every 100 mm thick, so construction costs will increase. The average price per square meter of 25 mm thick vacuum insulation panel is 100 yuan, which is 4,000 yuan/m² after the equivalent (tables 3 and 4).
Table 3. Electricity price and economic interest rate.

| Electricity price (yuan/kWh) | External cost of coal power (yuan/kWh) | Inflation rate (%) | Benchmark interest rate (%) |
|-----------------------------|----------------------------------------|--------------------|-----------------------------|
| 0.53                        | 0.38                                   | 7.5                | 4.35                        |

Table 4. Insulation material price and construction cost.

| Insulation materials                  | Insulation material price (yuan/m³) | Construction price per unit area (yuan) |
|---------------------------------------|-------------------------------------|----------------------------------------|
| Graphite polystyrene board            | 650                                 |                                       |
| Extruded polystyrene board            | 800                                 |                                       |
| Polyurethane                          | 1000                                | 45                                    |
| Rock wool                             | 500                                 |                                       |
| Vacuum insulation panel               | 4000                                |                                       |

4.2. The Whole Life Cycle Costs of Different Materials in Each Climate Zone

\[ r = \frac{g - i}{1 + i} \]  

(20)

\( r \) is discount rate, \( \% \); \( g \) is inflation rate, \( \% \); \( i \) is bank rates, \( \% \), \( g=7.5\% \), \( i=4.35\% \). The calculation of the discount rate is 3.02\%, the whole life cycle of insulation materials is taken for 25 years.

Figures 8-11 are in four typical cities, 5 kinds of insulation materials’ whole life cycle cost under different insulation thickness (referred as LCC). It can be seen that when using rock wool, when the same thermal transfer coefficient is reached, \( LCC \) is generally lower than the rest of materials; When using XPS, due to the difference in construction costs, the insulation material is thicker, while its \( LCC \) is higher, so does the vacuum insulation plate; When SEPS and polyurethane are in the same heat transfer coefficient, the cost is basically the same. Assuming the difference of 3\% between the minimum \( LCC \) is the optimal economic range, so the optimal economic thickness of insulation in each city is as follows.

In Beijing, the optimal economic thickness of SEPS is 100-160 mm, the exterior wall thermal transfer coefficient is 0.28-0.19 W/m²·K, the operation cost ratio is 50-33\%; the optimal economic thickness of XPS is 80-100 mm, the exterior wall thermal transfer coefficient is 0.31-0.25 W/m²·K, the operation cost ratio is 52-44\%; the optimal economic thickness of polyurethane is 0.26-0.18 W/m²·K, the operation cost ratio is 46-31\%; the optimal economic thickness of rock wool is 110-210 mm, the exterior wall thermal transfer coefficient is 0.3-0.17 W/m²·K, the operation cost ratio is 53-30\%; the optimal economic thickness of vacuum insulation plate is 20-30mm, the exterior wall thermal transfer coefficient is 0.34-0.24 W/m²·K, the operation cost ratio is 51-36\%.

In Shanghai, the optimal economic thickness of SEPS is 80-140 mm, the exterior wall thermal transfer coefficient is 0.34-0.21 W/m²·K, the operation cost ratio is 49-29\%; the optimal economic thickness of XPS is 70-100 mm, the exterior wall thermal transfer coefficient is 0.34-0.25 W/m²·K, the operation cost ratio is 48-35\%; the optimal economic thickness of polyurethane is 0.33-0.21 W/m²·K, the operation cost ratio is 48-30\%; the optimal economic thickness of rock wool is 90-170 mm, the exterior wall thermal transfer coefficient is 0.35-0.20 W/m²·K, the operation cost ratio is 51-29\%; the optimal economic thickness of vacuum insulation plate is 20-25 mm, the exterior wall thermal transfer coefficient is 0.33-0.27 W/m²·K, the operation cost ratio is 41-33\%.

In Harbin, the optimal economic thickness of SEPS is 190-310 mm, the exterior wall thermal transfer coefficient is 0.16-0.1 W/m²·K, the operation cost ratio is 55-38\%; the optimal economic thickness of XPS 160-200 mm, the exterior wall thermal transfer coefficient is 0.17-0.13 W/m²·K, the operation cost ratio is 49-41\%; the optimal economic thickness of polyurethane is 140-220 mm, the
exterior wall thermal transfer coefficient is 0.16-0.1 W/m²·K, the operation cost ratio is 55-34%; the optimal economic thickness of rock wool is 230-390 mm, the exterior wall thermal transfer coefficient is 0.15-0.09 W/m²·K, the operation cost ratio is 55-33%; the optimal economic thickness of vacuum insulation plate 40-60 mm, the exterior wall thermal transfer coefficient is 0.18-0.12 W/m²·K, the operation cost ratio is 53-36%.

In Guangzhou, the optimal economic thickness of SEPS is 50-80 mm, the exterior wall thermal transfer coefficient is 0.5-0.34 W/m²·K, the operation cost ratio is 41-27%; the optimal economic thickness of XPS 50-70 mm, the exterior wall thermal transfer coefficient is 0.45-0.34 W/m²·K, the operation cost ratio is 36-27%; the optimal economic thickness of polyurethane is 50-60 mm, the exterior wall thermal transfer coefficient is 0.39-0.33 W/m²·K, the operation cost ratio is 32-37%; the optimal economic thickness of rock wool is 50-100 mm, the exterior wall thermal transfer coefficient is 0.56-0.29 W/m²·K, the operation cost ratio is 55-33%; the optimal economic thickness of vacuum insulation plate 20 mm, the exterior wall thermal transfer coefficient is 0.33 W/m²·K, the operation cost ratio is 22%.

5. Conclusion and Expectation
Nearly zero energy consumption building in each climate zones with the same thickness, 5 kinds of insulation material performance is rated from good to poor: vacuum insulation plate, polyurethane,
XPS, SEPS, rock wool; with the same insulation material and the same thickness, the orientation of the exterior wall of thermal transfer effect is little.

With the increase of insulation thickness, the total annual thermal transfer in each climate area decreases, while the decrease is gradually reduced. Harbin’s total thermal transfer is the highest, Guangzhou is the lowest, while the proportion of total thermal transfer in the four climate zones is about the same. The use of insulation materials in cold winter and hot summer areas has greater potential for energy conservation.

With the increase of insulation thickness, the whole life cycle cost of each climate zones shows the trend of decline first and then rise, so it is not recommended to blindly increase the thickness of insulation in the project.

When the exterior wall has the same heat transfer coefficient, the LCC of rock wool is lower than the rest of materials; the LCC of vacuum insulation plate is relatively high; using XPS, due to the difference in construction costs, when the insulation material is thicker, its LCC is higher; when SEPS and polyurethanes have the same heat transfer coefficients in the same exterior wall, the LCC is basically the same.

At present, this paper does not consider the impact of building’s internal disturbance and the effect of humidity transfer on the energy consumption of wall thermal transfer loss. In the next study, the author will further analyze these influencing factors and enhance the applicability of engineering application of the conclusion.

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References
[1] GB/T 51350-2019 Technical Standards for Nearly Zero Energy Buildings (China Architecture & Building Press).
[2] Zhu T, Song B and Deng Q 2015 Analysis of economical thickness of exterior insulation for high-performance wall Building Science (06) 75-79.
[3] Alsayed M F and Tayeh R A 2019 Life cycle cost analysis for determining optimal insulation thickness in Palestinian buildings Journal of Building Engineering 22 101-112.
[4] Cyrille Vincelas F F and Ghislain T 2017 The determination of the most economical combination between external wall and the optimum insulation material in Cameroonian’s buildings Journal of Building Engineering 9 155-163.
[5] Çomaklı K and Yüksel B 2003 Optimum insulation thickness of external walls for energy saving Applied Thermal Engineering 23 (4) 473-479.
[6] Söylemez M S and Ünsal M 1999 Optimum insulation thickness for refrigeration applications Energy Conversion and Management 40 (1) 13-21.
[7] Zhu P, Huckemann V and Fisch M N 2011 The optimum thickness and energy saving potential of external wall insulation in different climate zones of China Procedia Engineering 21 608-616.
[8] Huang C H and Ye Y J 2005 Economical optimum of insulation thickness on external wall of energy saving building Building Energy & Environment (06) 73-76.
[9] Wang H H and Wu W W 2008 Optimizing insulation thickness of external walls for residential buildings Journal of Chongqing University (08) 937-941.
[10] Xu C, Li S and Zou K 2019 Study of heat and moisture transfer in internal and external wall insulation configurations Journal of Building Engineering 24 100724.
[11] Xu C C and Li S H 2019 Analysis on optimum insulation thickness of external thermal insulation walls in Nanjing zone Journal of southeast university (Natural Science Edition) 49 (03) 558-564.
[12] Zhao Y J, Chen Y M and Liu X W 2017 Optimization of insulation thickness for building external walls in hot summer and cold winter zone Building Science 33 (04) 77-84.
[13] Ozel M and Pihtili K 2007 Optimum location and distribution of insulation layers on building walls with various orientations Building and Environment 42 (8) 3051-3059.
[14] Feng G.H, Xu X.L, Wang Y, et al. 2018 Sensitivity analysis of nearly zero energy buildings envelope design parameters based on energy consumption Journal of Shenyang Jianzhu University 34 (06) 1069-1077.
[15] Jie P, Zhang F, Fang Z, et al. 2018 Optimizing the insulation thickness of walls and roofs of existing buildings based on primary energy consumption, global cost and pollutant emissions Energy 159 1132-1147.
[16] Zhang T, Niu J G and Jin G H 2017 Study on energy-saving performance and economic thickness optimization of building insulation materials Building Science 33 (10) 149-156.
[17] Zhang T, Niu J G and Jin G H 2019 Study on economic thickness optimization of external thermal insulation system of buildings in severe cold area Architecture Technology 50 (01) 8-12.
[18] Pan D M and Lin D M 2008 Effect of building insulation on cooling and heating load in different climate areas HV&AC (08) 11-16.
[19] Zheng B 2012 Optimization Research of Insulation Layer Thickness on External Wall Residential (Anhui University of Technology).
[20] Yan Q S and Zhao Q Z 1986 Thermal Process of Building (China Architecture & Building Press).
[21] Zhu F T, Zhu Q F and Jiang Y 2004 Building environment design simulation software DeST(5): Generation of the values of the extraneous factors influencing building thermal processes HV&AC (11) 52-65.
[22] Wu J.C and Xu G 2003 Major Chinese cities’ solar radiant intensities in winter Journal of Harbin Institute of Technology (10) 1236-1239.
[23] Lu Y Q 2008 Design Manual of Practical Heating and Air Conditioning (Beijing: China Architecture & Building Press).
[24] Barbosa R M and Mendes N 2008 Combined simulation of central HVAC systems with a whole-building hygrothermal model Energy & Buildings 40 (3) 276-288.
[25] Yang S M and Tao W Q 2006 Heat Transfer (Beijing: Higher Education Press).