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Technical Suitability of Energy Saving Scheme for Optimizing the Thermal Insulation Layer Thickness of Residential Building Exterior Wall

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ABSTRACT

From the perspective of technical suitability, this paper comparatively analyzed the economical thickness and suitable thickness of exterior wall thermal insulation material with the highest energy saving rate of building envelop, and attained the relationship, curves, and model of the economical thickness and suitable thickness of the insulation material. The purpose of this paper is to provide useful evidences for the energy saving of residential buildings and the optimization of the design of exterior wall, so that architectural designers could be inspired to consider the energy-saving issue of buildings from multiple angles such as economy and environment, and the optimal design scheme that is most beneficial to the environment could be created. This paper lays a theoretical basis for making investment decisions of energy saving buildings and avoiding unwise investment.

1. INTRODUCTION

Thermal performance of building envelop is a major factor affecting the energy consumption of the building, and by improving the thermal performance of envelop structure, the energy consumption of the building could be reduced effectively. In the thermal insulation system of building envelop, exterior wall contributes the most, exterior wall insulation can effectively decrease the air-conditioning load caused by the heat transfer of exterior wall. The selection of thermal insulation material and its thickness can greatly affect the energy saving effect and economic benefit, so it is an important measure to achieve building energy conservation [1-4]. Generally speaking, with the increase of the thickness of the insulation layer, the thermal performance of the building envelop enhances, the load of the building declines, and the operating cost of air cooling and heating systems decreases, but in the meantime, the construction cost of the building increases. Therefore, speaking from the viewpoint of engineering, the thickness of insulation layer that can minimize the total cost of a building during its entire life (namely the sum of the investment on the insulation layer and the cost of air conditioning is the smallest) is the optimal thickness [5]. Today, energy and environmental issues are getting worse around the globe, so the selection of the thickness of insulation layer is a problem related to both energy saving and environmental issues. A thicker insulation layer could reduce thermal load, but it couldn't offset the negative impact on environment caused by the production, use, and scrapping of the insulation material in its life cycle, as a result, the ultimate goal of energy saving no longer exists. The "suitable thickness" proposed in this paper refers to the optimal solution based on the balance of three types of indicators: economic indicators, energy consumption indicators, and environmental indicators, attention should be paid to the environmental indicators since the green and sustainable development of buildings has been greatly advocated these days, and such solution would be more reasonable and meaningful [6-13].

2. RELATIONSHIP BETWEEN INSULATION LAYER THICKNESS OF EXTERIOR WALL AND THE ENERGY SAVING RATE OF THE BUILDING

The thickness of insulation material determined by calculating the annual operating cost containing annual depreciation and energy loss is called the "economical thickness", and it is the minimum value of annual operating cost. In terms of the economical thickness of exterior wall insulation layer, world field scholars drew on the theory of life cycle evaluation to build economics models of insulation layer thickness for different types of buildings under different climatic conditions, they conducted research from different design angels and proposed methods for determining the economical thickness of insulation layer [14-25], and it's found that the regional climate features, building type, operating mode, and the differences in economic and technical levels can all affect the requirements of thermal insulation and energy conservation [26-37].

In this paper, the energy-saving and thermal insulation system of a 6-storey residential building in Wuhu City, Anhui Province, China was analyzed. Under the conditions that the exterior doors and windows of the building are made of heat-insulating aluminum alloy and hollow glass (2.50 $m^2 \cdot K$) and the roof is made of 30mm extruded polystyrene sheets (0.77 $m^2 \cdot K$), the relationships between the thickness of insulation layer, the energy saving rate of the building, and the energy consumption reduction rate were discussed, through the calculation of the Energy Saving System developed by Tangent Software, Table 1 was attained, as shown below:

Table 1. Calculation results of energy saving rate and energy consumption reduction rate of the residential building

Thickness of insulation layer (mm)	Heat transfer coefficient of exterior wall W/(m²·K)	Energy saving rate of the building	Energy consumption reduction rate
0	1.66	48.95%	
5	1.52	50.33%	2.82%
10	1.41	51.18%	1.69%
15	1.33	51.95%	1.50%
20	1.21	52.46%	0.98%
25	1.12	52.89%	0.82%
30	1.04	53.31%	0.79%
35	0.97	55.46%	4.03%
40	0.90	55.94%	0.87%
45	0.85	56.14%	0.36%
50	0.80	56.42%	0.50%
55	0.76	56.71%	0.51%
60	0.72	56.87%	0.28%
65	0.69	57.06%	0.33%
70	0.65	57.25%	0.33%
75	0.62	57.35%	0.17%
80	0.60	57.53%	0.31%
85	0.57	57.72%	0.33%
90	0.55	57.83%	0.19%
95	0.53	57.87%	0.07%
100	0.51	58.02%	0.26%

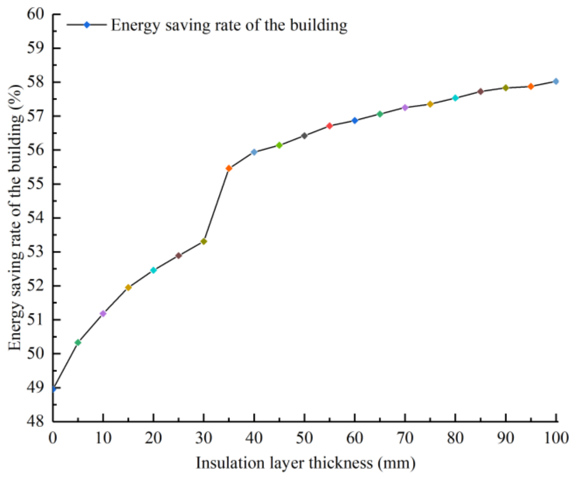

Figure 1. Relationship between insulation layer thickness and energy saving rate of the building

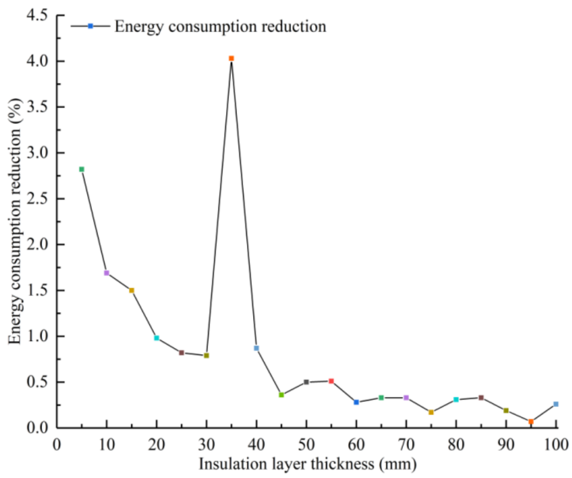

Figure 2. Relationship between insulation layer thickness and energy consumption reduction rate

By analyzing the data in the table, the relationship between insulation layer thickness and energy saving rate of the building was attained as shown in Figure 1, and the relationship between insulation layer thickness and energy consumption reduction rate was attained as shown in Figure 2.

By analyzing the trend of Curve 1, it's known that, when the thickness of insulation layer of the exterior wall is in the 0-40mm interval, the energy saving rate of the building keeps a certain increase trend, the increment grows gradually, and a leap appears in the 35-40 mm interval; starting from a thickness of 40mm, the increase trend of energy saving rate slows down, and it changes little as the thickness reaches 90mm. By analyzing the trend of Curve 2, it's known that, when the thickness reaches 35mm, the energy consumption reduction rate shows a dramatic change; when the thickness is larger than 40mm, the energy consumption reduction rate changes slowly and stabilizes. It indicates that in the 35-40 mm interval, the heat transfer coefficient drops rapidly with the increase of thickness, when the thickness exceeds a certain value, the heat transfer coefficient no longer changes much, and increasing thickness will cause the construction cost to increase [38].

It can be inferred that under a certain criterion of energy saving rate, for the envelop structure of a same building, there must be a most economical thickness of exterior wall insulation layer that can give the most significant energy saving effect of the building.

3. FORMULA DERIVATION OF INSULATION LAYER THICKNESS OF BUILDING ENVELOP

3.1 Thermal performance indicators of the thermal insulation material

Common thermal performance indicators of thermal insulation material include:

(1) Heat transfer resistance of building envelop R_0, m²·K/W;

(2) Heat transfer coefficient of building envelop K, K=1/ R_0, unit: W/ m²·K;

(3) Thermal resistance of building envelop, $R=\delta/\lambda$, unit: m²·K/W.

where, δ represents the thickness of the material layer, unit is m; λ represents the coefficient of thermal conductivity, unit is W/m²·K.

(4) Thermal inertia indicator $D=R\cdot S$

where, R represents the thermal resistance of the material, unit is m²·K/W; S represents the heat storage coefficient of the material, unit is W/m²·K.

(5) Average heat transfer coefficient of the exterior wall:

$$K_m=\left(K_p\cdot F_p+K_{B1}\cdot F_{B1}+K_{B2}\cdot F_{B2}+K_{B3}\cdot F_{B3}\right)/\left(F_p+F_{B1}+F_{B2}+F_{B3}\right)$$

where, K_m represents the average heat transfer coefficient of the exterior wall, unit is W/m²·K; K_p represents the heat transfer coefficient of the main body of exterior wall, unit is W/m²·K; K_{B1}, K_{B2}, and K_{B3} respectively represent the heat transfer coefficient of the surrounding thermal bridges of the exterior wall (including structural beams, beams above doors and windows, concrete slabs, structural columns, and constructional columns); F_p represents the area of the main body of exterior wall, unit is m²; F_{B1}, F_{B2}, and F_{B3} are surfaces of the surrounding thermal bridges of the exterior wall, unit is m².

3.2 Formula derivation

(1) Heat consumption of the building is:

$$q_H = q_{H\cdot T} + q_{\mathrm{INF}} - q_{\mathrm{I\cdot H}} \tag{1}$$

where, q_{H} represents the heat consumption indicator of the building (W/m^2); $q_{\mathrm{H\cdot T}}$ represents the heat consumption of per unit building area through the heat transfer of building envelop (W/m^2); q_{INF} represents the heat consumption of per unit building area through air infiltration (W/m^2); $q_{\mathrm{I\cdot H}}$ represents the internal heat gain of per unit building area of the residential building (including cooking, lightening, household appliances, and heat dissipation of human body), its value takes 3.8 W/m^2.

(2) Heat consumption of per unit building area of the building through heat transfer of building envelop is:

$$q_{\mathrm{H\cdot T}} = (t_i - t_{\mathrm{e}})(\sum_{i=1}^{m} \varepsilon_i \cdot K_i \cdot F_i) / A_0 \tag{2}$$

where, t_i represents the average indoor temperature of all rooms in the building, for common residential buildings, its value takes 18°C; t_e represents the average outdoor temperature during heating season, unit is °C; ε_i represents the correction coefficient of the heat transfer coefficient of building envelop; K_i represents the heat transfer coefficient of building envelop, unit is W/m$^2\cdot$K, for exterior wall, its value takes the average heat transfer coefficient; F_i represents the area of building envelop, unit is m^2; A_0 represents the building area, unit is m^2.

(3) Heat consumption of per unit building area of the building through the heat transfer of exterior wall is:

$$q_{\mathrm{w}} = (t_i - t_{\mathrm{e}}) \cdot (\varepsilon_i \cdot K_i \cdot F_i) / A_0 \tag{3}$$

The formula for calculating the average heat transfer coefficient of the exterior wall is substituted into Formula 3 to get:

$$q_{\mathrm{w}} = (t_i - t_{\mathrm{e}}) \cdot (\varepsilon_i \cdot \frac{K_{\mathrm{p}} \cdot F_{\mathrm{p}} + K_{\mathrm{B1}} \cdot F_{\mathrm{B1}} + K_{\mathrm{B2}} \cdot F_{\mathrm{B2}} + K_{\mathrm{B3}} \cdot F_{\mathrm{B3}}}{F_{\mathrm{p}} + F_{\mathrm{B1}} + F_{\mathrm{B2}} + F_{\mathrm{B3}}} \cdot F_i) / A_0 \tag{4}$$

According to the relationship between heat transfer coefficient K and thermal resistance R,K=1/ R_0, there is:

$$K_{\mathrm{p}} = 1/R_i + \sum R + R \tag{5}$$

where, R_{i} is the heat exchange resistance of internal surface, its value takes 0.11; R_{e} is the heat exchange resistance of external surface, its value takes 0.05.

For the exterior wall, the materials of each layer of the columns and beams of thermal bridges are consistent, so the K_{B1}, K_{B2}, and K_{B3} values are the same; assuming: except for the insulation layer, the sum of the thermal resistance of other layers is R_0, the thermal resistance of the insulation material is $R=\delta/\lambda$, by substituting them into the formula, we can get:

$$K_{\mathrm{p}} = 1/(0.15 + R_0 + \frac{\delta}{\lambda}),\ K_{\mathrm{B}} = 1/(0.15 + R_1 + \frac{\delta}{\lambda}) \tag{6}$$

By substituting Formula 6 into Formula 4, we have:

$$q_{\mathrm{w}} = (t_i - t_e) \cdot (\varepsilon_i \cdot \frac{F_{\mathrm{p}}/(0.15+R_0+\delta/\lambda) + (F_{\mathrm{B1}} + \mathrm{F_{B2}})/(0.15 + R_1 + \delta/\lambda)}{F_{\mathrm{p}} + F_{\mathrm{B1}} + F_{\mathrm{B2}}} \cdot Fi) / A \tag{7}$$

After simplification, there is:

$$q_{\mathrm{w}} = \frac{(\mathrm{ti}\text{-}\mathrm{te}) \cdot \varepsilon_i \cdot F_i}{A_0} \cdot \left[\frac{F_p}{(0.15+R_0+\delta/\lambda)(F_{\mathrm{p}} + F_{\mathrm{B1}} + \mathrm{F_{B2}})} + \frac{F_{\mathrm{B1}} + F_{\mathrm{B2}}}{(0.15+R+\delta/\lambda)(\mathrm{F_p} + \mathrm{F_{B1}} + \mathrm{F_{B2}})} \right] \tag{8}$$

The indicator of coal consumption used for heating can be calculated by the following formula:

$$q_{\mathrm{c}} = 24Z \cdot q_{\mathrm{w}} / H_{\mathrm{c}} \cdot \eta_1 \cdot \eta_2 \tag{9}$$

where, q_{c} represents the indicator of coal consumption for heating, in standard coal, unit is kg/m^2; Z represents the number of days during the heating season, unit is d; H_{c} represents the heat value of standard coal, its value takes 8.14×10^3 W·h/kg; η_1 represents the conveying efficiency of outdoor pipe network, before taking energy-saving measures, its value takes 0.85, after taking energy-saving measures, its value takes 0.90; η_2 represents the operating efficiency of boiler, before taking energy-saving measures, its value takes 0.55, after taking energy-saving measures, its value takes 0.68.

By substituting Formula 9 into Formula 8, we can get:

$$q_{\mathrm{c}} = \frac{24 \cdot Z(t_i - t_e) \cdot F_i}{A_0 \cdot H_{\mathrm{c}} \cdot \eta_1 \cdot \eta_2} \left[\frac{F_{\mathrm{p}}}{(0.15+Ro+\delta/\lambda)(\mathrm{F_p} + \mathrm{F_{B1}} + \mathrm{F_{B2}})} + \frac{F_{\mathrm{B1}} + F_{\mathrm{B2}}}{(0.15+R+\delta/\lambda)(\mathrm{F_p} + F_{\mathrm{B1}} + F_{\mathrm{B2}})} \right] \tag{10}$$

Assuming: the coal price is C_1, then the energy consumption cost of per unit building area through the exterior wall is $C_1 \cdot q_{\mathrm{c}}$, the design life of the insulation material is T, the cost of per unit volume of the insulation layer is C_{e}, then the cost of insulation layer for per unit building area is:

$$C_2 = \frac{\mathrm{C_e} \cdot \delta \cdot S}{A_0} \tag{11}$$

where, S is the surface area of the exterior wall and the columns and beams of thermal bridges.

The total heating cost of the exterior wall is equal to the sum of the one-time construction cost of the insulation layer and the heating consumption cost of per unit building area during the heating season within the design life:

$$C = C_1 \cdot q_c \cdot T + \frac{C_{\mathrm{e}} \cdot \delta \cdot S}{\mathrm{A_0}} \tag{12}$$

By substituting Formula 10 into Formula 12, we have:

$$C = C_1 \cdot T \cdot \frac{24 \cdot Z(t_i - t_e) \cdot F_i}{\mathrm{A_0} \cdot (4981.68)} \cdot \left[\frac{F_{\mathrm{p}}}{(0.15+R_0+\delta/\lambda)(\mathrm{F_p} + \mathrm{F_B})} + \frac{F_{\mathrm{B1}} + F_{\mathrm{B2}}}{(0.15+R+\delta/\lambda)(\mathrm{F_p} + \mathrm{F_B})} \right] + \frac{\mathrm{Ce} \cdot \delta \cdot S}{\mathrm{A_0}} \tag{13}$$

In above formula, except that the thickness δ of the insulation material of the exterior wall is a variable, all other parameters are constant values. As can be seen from the formula, with the increase of δ, q_{w} decreases gradually, and the relationship between the two is not linear. As the thickness increases, the energy consumption of exterior wall decreases rapidly, but the decrement gets smaller, and the relationship between the cost of insulation material and the thickness of insulation layer is linear, that is, the greater the thickness, the higher the cost. Therefore, the thickness should be kept within a certain interval, in which the minimum cost and maximum energy saving effect could be attained.

3.3 Empirical analysis of economical thickness of insulation material

With an actual engineering project as the example, general conditions of the project are summarized in Table 2, floor plan is shown in Figure 3.

(1) If the insulation material of the exterior wall and the columns and beams of thermal bridges is made of polyphenyl granule slurry, the corrected thermal conductivity coefficient λ is 0.07, wherein t_i=18°C, t_e=5°C, in areas with hot summer and cold winter, the εi is not counted, and the value of T (heating season) takes 72 days. F_p=1297.72m^2, F_{B1}=336.12m^2, F_{B2}=347.20m^2, R_0=0.261, R=0.178.

By substituting the data into Formula 8 for calculation and simplification, we get:

$$q_w = \frac{(18\text{-}5)\times 1981}{3054} \times \left[\frac{1298}{(0.15+0.261+\delta/0.07)\times 1981} + \frac{683}{(0.15+0.178+\delta/0.07)\times 1981} \right]$$

Assuming: the thickness of the insulation layer made of polyphenyl particles is between 20-100mm, by substituting the values into the formula, Table 3 and Figure 4 could be attained.

As can be seen from Figure 4, during the heating process of the building, as the thickness of insulation material changes, the decrease of energy consumption indicator doesn't change linearly. When the thickness varies between 20-70 mm, with the increase of thickness, the energy consumption of per unit building area through the exterior wall decreases significantly; when the thickness exceeds 70 mm, decrement of energy consumption slows down; when the thickness exceeds 120 mm, the decrement of energy consumption is not obvious. However, as the thickness grows, the investment cost of insulation layer grows linearly, thus it is known that increasing thickness won't save cost significantly since more investment will be needed.

Then the economy of the insulation material was analyzed. The coal price is C1=0.5 yuan/kg, it's assumed that the service life of the insulation material is 25 years, the price of polystyrene particles is 1,000 yuan/m^3, the surface area of the columns and beams of the exterior wall and thermal bridges S is 1981m^2, the building area A_0 is 3054m^2, by substituting them into Formula 13, there is:

$$C = C1 \cdot T \cdot \frac{24 \cdot Z(ti\text{-}te) \cdot Fi}{Ao \cdot 4981.68} \cdot \left[\frac{1298}{(0.411+\delta/0.07)1981} + \frac{683}{(0.328+\delta/0.07)1981} \right] \cdot \frac{1000 \cdot \delta \cdot 1981}{3054}$$

The thickness of insulation layer was selected between 10-100mm, then Table 4 and Figure 5 were attained.

Table 2. General conditions of the project

Project name	**No.12 residential building in a community in Liu'an city of Anhui province**	**Project address**		**Liu'an city of Anhui province**	
Constructor	A real state developer company	Building area (A_0)		3053.85m^2	
Shape of the building	Bar-shaped building	The shape coefficient	0.27	Surface area of the building	2672.72m^2
Number of floors	5	Height of the building	15.50m	Volume of the building	9879.09m^3

Table 3. The change of exterior wall energy consumption of per unit building area with the thickness of insulation material

Δ(mm)	10	20	30	40	50	60	70	80	90	100	110	120
q_w (kg/m^2)	16.15	12.67	10.42	8.86	7.70	6.81	6.10	5.53	5.06	4.66	4.32	4.02
q_c	5.60	4.39	3.61	3.07	2.67	2.36	2.12	1.92	1.76	1.62	1.5	1.39

Table 4. Cost of energy consumption after applying the insulation material

δ(mm)	10	20	30	40	50	60	70	80	90	100
C_1(Yuan)	91.68	71.88	59.1	50.26	43.72	38.64	34.7	31.44	28.82	26.52
C_2(Yuan)	6.49	12.98	19.47	25.96	32.45	38.94	45.43	51.92	58.41	64.90
C (Yuan)	98.17	84.86	78.57	76.22	76.17	77.58	80.13	83.36	87.23	91.42

Note: C_1 is the cost of energy consumption of the exterior wall for per unit building area during the 25 service life; C_2 is the one-time investment cost of the insulation material; C is the sum of C_1 and C_2.

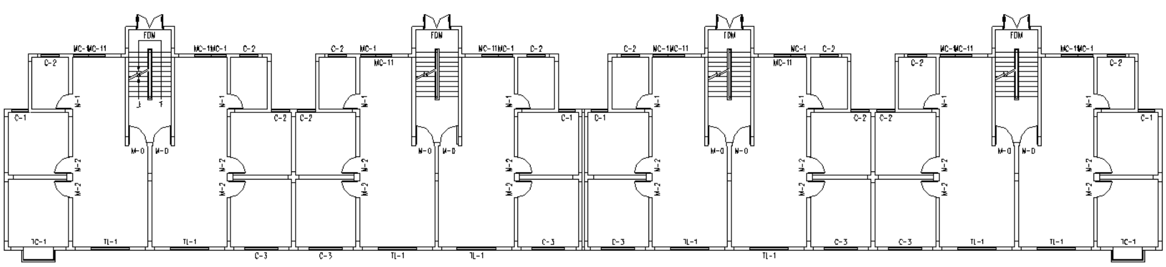

Figure 3. Floor plan of No. 8 residential building

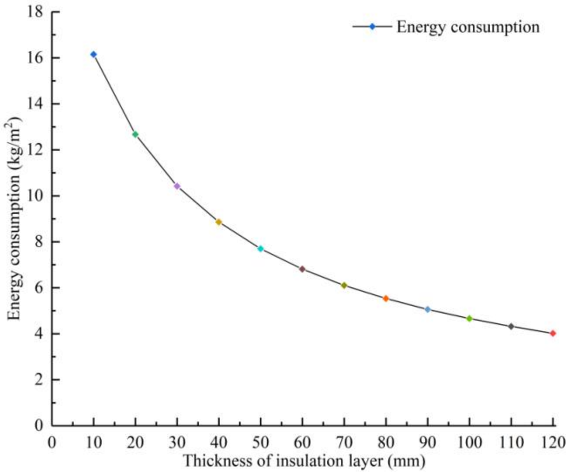

Figure 4. Relationship between insulation layer thickness and energy consumption

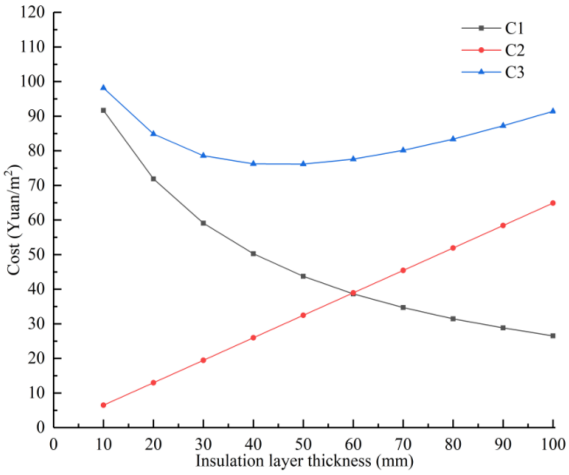

Figure 5. Relationship between insulation layer thickness and cost

According to the analysis results of above two examples, we can clearly see that in this project, with the increase of the thickness of insulation layer, the total cost of insulation layer during its service life is a parabola with a lowest point at 50mm. When the total cost approaches the lowest point, namely when the thickness varies between 40-60 mm, the curve changes gently, and the cost change rate is the lowest.

3.4 Conclusion about the economical thickness of building envelop

The economic benefit of the insulation layer is dynamically related to the one-time investment cost, but since it reduces the energy consumption of the residential building during its service life, with the passing of time, the use cost of the building will be lower than that of buildings that haven't applied the exterior wall insulation and energy saving techniques. As shown in Figure 6, the cost curve of insulation technique will intersect with the cost curse without applying the insulation technique at the N-th year, that is, starting from this year, the economic benefit of applying insulation technique to exterior wall will begin to show up, and it will last for quite a long time. The smaller the value of N, the higher the energy-saving efficiency of the applied technique, and the shorter the time it takes to achieve the economic benefit; the greater the value of N, the lower the efficiency, and the longer the time it takes to get economic benefit. In the mean time, it has also proved the necessity of applying insulation technique to the exterior wall of residential buildings. When a certain thickness of insulation layer is selected for the exterior wall, the point with the lowest value of the sum of initial investment and the cost of energy consumption of the building during operation is the most suitable input point.

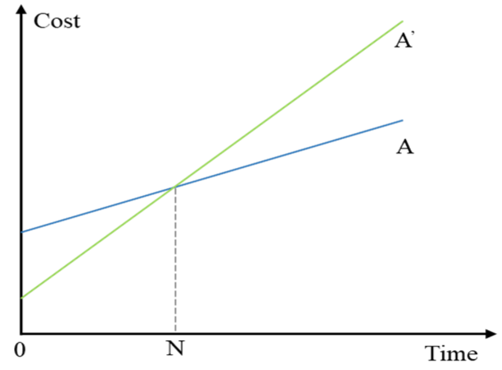

Figure 6. Relationship between cost of insulation layer and economic benefit

Assuming: after applying the insulation technique, the increment of production cost is Cm, the saved cost of energy consumption of the building is Cn, the value of Cm is determined by the investment cost of the energy saving technique itself, the higher the investment cost, the thicker the insulation layer. The value of Cn is determined by the energy saving level of the insulation technique, the more advanced the technique, the more the saved cost of energy consumption of the building during operation. With the increase of the insulation layer thickness of exterior wall, the energy saving efficiency increases accordingly, and the total cost declines; but when the thickness reaches a certain value, continue to increase the thickness of insulation layer will increase the total cost dramatically, therefore, the relationship between insulation layer thickness and cost is shown as Figure 7, we can clearly see that, as the thickness value grows, within the entire service life of the insulation layer, the total cost exhibits as a parabola with a lowest point. Thus, we can conclude the concept of economical thickness as follows:

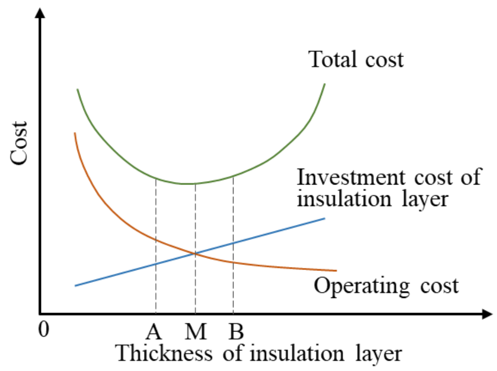

Figure 7. Optimal thickness and economical thickness of the insulation layer

(1) Point M in Figure 7 is the most economical thickness of exterior wall insulation layer, it is applicable to the energy saving and insulation system of a certain building or the

building envelop, at this time, the sum of the energy consumption cost of the building, the construction cost of the building, and the operating cost of the building is the lowest, and we can call it the most economical thickness of insulation layer that can minimize the total cost.

(2) There is a reasonable range for the economical thickness of exterior wall insulation layer. To ensure a reasonable economic benefit of the thickness of exterior wall insulation layer, it is not that the thicker, the better, actually, the closer to Point M in Figure 7 (the most economical thickness, in A-B interval), the better, and the thickness values closer to this interval are more economical.

(3) If the level of the energy saving and insulation technique of the exterior wall is much higher or lower than Point M, it will eventually lead to an increase in the total cost. If the thickness is much greater than Point M, it will lead to waste of the investment cost; if the thickness is less than Point M, then the thickness of the insulation layer should be increased; because the product cost is a one-time input, and the use cost grows over the years, so when it is lower than Point M, the thicker the insulation layer, the more obvious the economic benefit.

(4) For insulation techniques that are lower than Point M, although their economic benefit may not be the optimal, since the production cost is less, they might be applied in less developed areas with limited economic capability. If a too thick insulation layer is adopted, it might result in very high initial investment that exceeds the economic capability of the local.

4. THEORETICAL ANALYSIS OF SUITABLE THICKNESS OF INSULATION MATERIAL IN AREAS WITH HOT SUMMER AND COLD WINTER

The economical thickness of insulation layer is defined from the perspective of economics. Today, energy and environmental issues are getting worse around the globe, so the selection of the thickness of insulation layer is a problem related to a series of aspects including energy saving, environmental pollution, and human body health. To select the suitable type and dosage of insulation material, it's necessary to comprehensively consider the influence of the material and the product, namely the costs caused by its adverse impact on the ecological environment during the process of production, transportation, use and recovery. Therefore, this paper extends the concept of the economical thickness of insulation layer to the suitable thickness, which means to extend the scope of this concept to the impact of the material on environment so that it'll be economical in a more general sense. The calculation of the costs of the material's environmental impact involves the theory of the material's physical and chemical energy values, at present, there isn't a universal calculation result yet in the world academic circle, and it's difficult to get comprehensive, real, and uniform physical and chemical energy values. Thus, the suitable thickness of insulation layer proposed in this paper is also a relative concept, and this paper only descriptively analyzes its influencing factors and gives qualitative inference, but won't perform quantitative calculation or derivation. The aim is to enlighten designers to comprehensively consider the resource consumption of insulation material and the environment damage level so as to attain the suitable thickness to realize the optimal economic and environmental benefits.

This paper proposes the concept of suitable thickness of insulation material from two perspectives of economy and ecology to explore the possible intangible consumption of environment, ecology, and health caused during the production, processing, transportation and degradation of the material within the range of economical thickness, and figure out its dynamic relationship with the saved energy; the value intervals could be divided into high interval and low interval, and such value intervals are called the suitable thickness of insulation layer. This definition incorporates ecological factors and takes sustainable development as the strategic goal, it is a concept that balances economic development and environmental protection. Suitable thickness is a relative concept that can be used to balance two or several insulation materials, this paper extends this definition, employs the principle of equivalent factor to propose method for judging the suitable thickness, and takes two materials as examples to analyze the criterion indicators.

The impact potential of the insulation material on the ecological environment can be written as:

$$EP(j)=Q\cdot EF(j)$$

where, $j_1\rightarrow$ environment, environmental factor refers to the minimum pollution and damage of environment, it means to avoid causing damages to the natural environment, extract materials as little as possible, avoid using materials that can produce harmful chemicals, and not dump discarded materials casually but recycle them.

$j_2\rightarrow$ ecology, ecological factor refers to the reduction of energy and resource consumption, which means to use available materials according to local conditions, avoid using imported materials, use sustainable and low energy consumption materials, and use second-hand or recycled materials if possible.

$j_3\rightarrow$ health, health factor refers to avoid causing harm to the health of people, which means to use mold-proof materials or low volatile materials, prevent the fibers in insulation material from entering the atmosphere, keep good natural ventilation, reduce dust and allergic substances, and create a positive relationship between the indoor and surrounding environment.

The above three influencing factors were compared, for materials with greater impact potentials, the suitable thickness should be within the low value interval of economical thickness, namely the A-M interval in Figure 7, while for materials with less impact potentials, the suitable thickness should be within the high value interval of economical thickness, namely the M-B interval in Figure 7.

5. RELATIONSHIP BETWEEN ECONOMICAL THICKNESS AND ENERGY SAVING RATE UNDER DIFFERENT WINDOW-WALL RATIOS

In the energy-saving and insulation system of building envelop, compared with the energy saving of windows, the insulation measures of exterior wall can achieve more obvious energy saving effects. For a building, larger exterior wall area and smaller window area can get greater energy saving rate; but at the same time, windows can give natural ventilation and lighting conditions, they are a necessary condition for comfortable living and can save the energy consumption caused by artificial lightening and ventilation, therefore, controlling the window-wall ratio is an inevitable topic for attaining high-efficient and energy-saving houses.

Table 5. Relationship between insulation layer thickness and building energy-saving rate at low window-wall ratios

Insulation layer thickness	5mm	10mm	15mm	20mm	25mm	30mm	35mm	40mm	45mm	50mm
Building energy-saving rate	50.33%	51.18%	51.95%	52.46%	52.89%	53.31%	55.46%	55.94%	56.14%	56.42%
Insulation layer thickness	55mm	60mm	65mm	70mm	75mm	80mm	85mm	90mm	95mm	100mm
Building energy-saving rate	56.71%	56.87%	57.06%	57.25%	57.35%	57.53%	57.72%	57.83%	57.87%	58.02%

Table 6. Relationship between insulation layer thickness and building energy-saving rate at high window-wall ratios

Insulation layer thickness	5mm	10mm	15mm	20mm	25mm	30mm	35mm	40mm	45mm	50mm
Building energy-saving rate	49.78%	50.68%	51.49%	52.03%	52.48%	52.91%	53.39%	53.86%	54.09%	54.39%
Insulation layer thickness	55mm	60mm	65mm	70mm	75mm	80mm	85mm	90mm	95mm	100mm
Building energy-saving rate	54.62%	54.85%	55.05%	55.33%	55.42%	55.61%	57.53%	57.7%	57.75%	57.9%

In the past, due to the limitation of the structure of residential buildings and the economy, the area of windows in the living room and bed room is small, however, nowadays, as technical and economic levels are rising constantly, the area of windows of residential buildings is increasing , some buildings even open large windows toward east and west directions because of landscape considerations, and this is contrary to the energy saving of buildings since opening large windows is not conductive to energy conservation (especially in the east and west directions). Therefore, architects should take into account various aspects by adopting reasonable design schemes and suitable techniques based on the requirements of property developers and owners.

For the residential building example mentioned above, its energy saving rate under different window-wall ratios was analyzed. On the premise that the energy-saving and insulation system of the building envelop was fixed, by increasing the window-wall ratio, the energy saving rate of the building with an insulation layer thickness between 0-100mm was calculated, and the results are given in Table 5 and Table 6. Table 5 gives the energy saving rate at low window-wall ratios (east-west facing window-wall ratio is 0.09, south-facing window-wall ratio is 0.32, north-facing window-wall ratio is 0.25). Table 6 gives the energy saving rate at high window-wall ratios (east-west facing window-wall ratio is 0.09, south-facing window-wall ratio is 0.30, north-facing window-wall ratio is 0.25).

Figure 8 could be attained by comparing Tables 5 and 6.

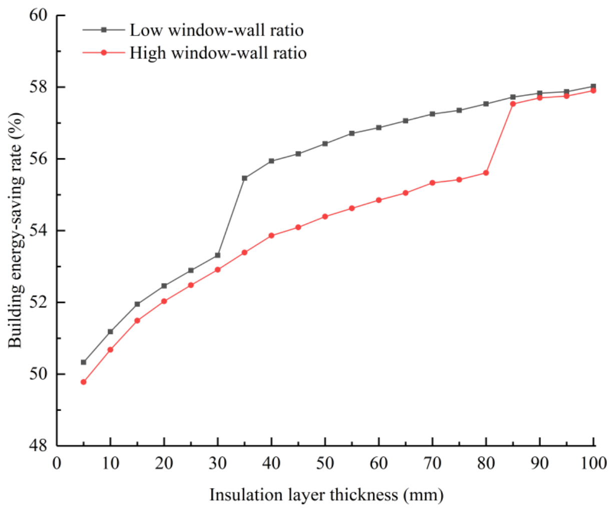

Figure 8. Relationship between insulation layer thickness and building energy saving rate under two kinds of window-wall ratios

Curves in Figure 8 indicate that, for a given energy saving rate, the required economical thickness of insulation layer is positively correlated with the window-wall ratio, that is, the higher the window-wall ratio, the greater the required thickness of insulation layer, and vice versa. At the same time, it also indicates that, when the wall area is larger, the energy-saving rate of the building is more sensitive to the variation of the thickness of insulation layer.

6. RELATIONSHIP BETWEEN INSULATION LAYER THICKNESS AND BUILDING ENERGY-SAVING RATE UNDER DIFFERENT HEAT TRANSFER COEFFICIENTS OF DOORS AND WINDOWS

Still, the energy-saving and insulation system of building envelop was fixed, the heat transfer coefficients of doors and windows were selected to be 2.3, 2.5, and 2.8, then the energy-saving rate and energy consumption reduction rate of the building under different thickness values of insulation layer were calculated, the results are given in Figure 7.

According to Table 7, curves were plotted and compared in Figure 9 and Figure 10.

According to Figures 9 and 10, with the change of the heat transfer coefficient of windows, the relationships between insulation layer thickness and energy-saving rate and energy consumption reduction rate of the building are basically not affected.

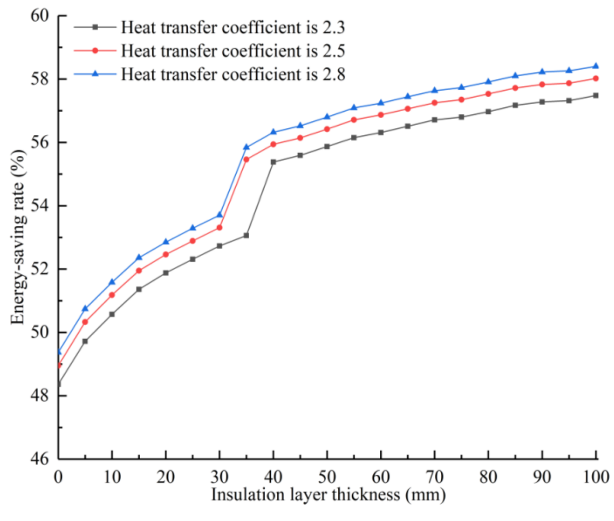

Figure 9. Variation of energy-saving rate of the building under different heat transfer coefficients of windows

Table 7. Calculation results of the energy-saving rate and energy consumption reduction rate of the building

Insulation layer thickness (mm)	Heat transfer coefficient of windows is 2.3m²·k		Heat transfer coefficient of windows is 2.5m²·k		Heat transfer coefficient of windows is 2.8m²·k	
	Energy-saving rate	Energy consumption reduction rate	Energy-saving rate	Energy consumption reduction rate	Energy-saving rate	Energy consumption reduction rate
0	48.36%		48.95%		49.37%	
5	49.72%	2.81%	50.33%	2.82%	50.74%	2.77%
10	50.57%	1.71%	51.18%	1.69%	51.58%	1.66%
15	51.36%	1.56%	51.95%	1.50%	52.36%	1.51%
20	51.88%	1.01%	52.46%	0.98%	52.85%	0.94%
25mm	52.31%	0.83%	52.89%	0.82%	53.29%	0.83%
30mm	52.73%	0.80%	53.31%	0.79%	53.70%	0.77%
35mm	53.06%	0.63%	55.46%	4.03%	55.84%	3.99%
40mm	55.38%	3.35%	55.94%	0.87%	56.32%	0.86%
45mm	55.59%	0.38%	56.14%	0.36%	56.52%	0.36%
50mm	55.87%	0.50%	56.42%	0.50%	56.80%	0.50%
55	56.15%	0.50%	56.71%	0.51%	57.09%	0.51%
60	56.31%	0.28%	56.87%	0.28%	57.24%	0.26%
65	56.51%	0.36%	57.06%	0.33%	57.44%	0.35%
70	56.71%	0.35%	57.25%	0.33%	57.63%	0.68%
75	56.80%	0.16%	57.35%	0.17%	57.73%	0.17%
80	56.97%	0.30%	57.53%	0.31%	57.91%	0.31%
85	57.17%	0.35%	57.72%	0.33%	58.10%	0.33%
90	57.28%	0.19%	57.83%	0.19%	58.22%	0.21%
95	57.32%	0.07%	57.87%	0.07%	58.26%	0.07%
100	57.48%	0.28%	58.02%	0.26%	58.40%	0.34%

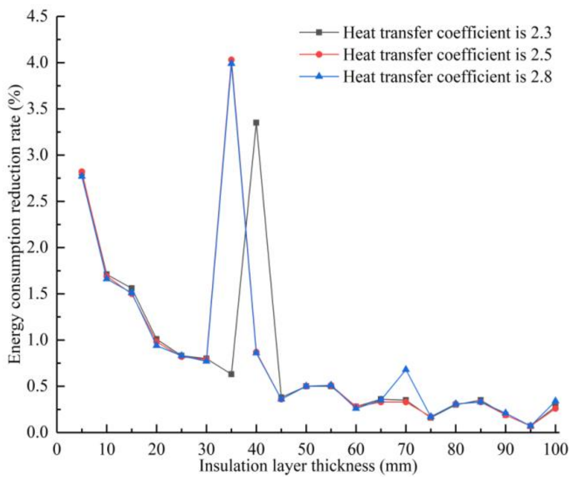

Figure 10. Variation of energy consumption reduction rate of the building under different heat transfer coefficients of windows

7. CONCLUSION

In this paper, the function of the economical thickness of insulation material was plotted through formula derivation and example calculation, and the economical thickness of the insulation layer of the example building was calculated and analyzed. Starting from the perspective of ecology, according to the dynamic relationship between the possible intangible consumption of environment, ecology, and health caused during the production, processing, transportation and degradation of the material and the saved energy, this paper defined the value intervals of suitable thickness of insulation layer within the range of economical thickness under different conditions, proposed the concept of the suitable thickness of insulation layer, and analyzed the relationship between economical thickness and suitable thickness. On this basis, this paper concluded that, for materials with greater impact potentials, the suitable thickness should be within the low value interval of economical thickness; while for materials with less impact potentials, the suitable thickness should be within the high value interval of economical thickness. China has a vast territory, there are large differences in the environment and climate of different regions, and the economic development level varies from place to place, so the development of energy-saving residential buildings must be adapted to local conditions, the buildings should be well planned and designed with practical purpose. Moreover, the buildings should be diversified and personalized, the constraints of construction projects should be analyzed based on actual conditions, the design schemes should be optimized based on comprehensive economic benefit, and the technological system that is most suitable for the local area should be selected to achieve the ultimate goals of improving living quality of residential buildings and reducing their costs.

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