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Analysis of Energy Saving Design of Indoor-heating and Wall-insulation Used in Green Buildings

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Abstract: Indoor heating and wall insulation systems are vital parts in building energy saving designs. Based on the analysis of impact factors related to the energy saving design of indoor heating and wall insulation systems, this study adapted the variation of room temperature as the performance index of energy saving design. A calculation model of energy saving design was established based on heat balance theory. Using the proposed model, the variation curves of room temperature with time and the sensitivity of room temperature on various technical factors were analysed incorporating different insulating materials, thicknesses of insulation layer as well as different temperature and flow rate of hot water in the boilers. Finally, it is proposed that the design solution of energy saving system should consider and assess the technical, economic and environmental factors from the perspective of project life cycle. Results from the study showed that the simulation of the proposed model was clear and easily adaptable. The proposed model is capable of providing abundant simulated data for design personnel to predict the performance of the design and optimise the parameters. The findings in the study provided theoretical background and routine for the determination of parameters and design for indoor heating and wall insulation systems for developing and designing companies.

Key words: Green buildings, indoor heating, wall insulation, energy saving design

INTRODUCTION

To preserve energy and pursue sustainable development, energy efficiency has been widely adapted by many countries as an important index to evaluate green buildings. Take the LEED standard in the US for example, the weight of energy and atmospheric environment increased from 25% in LEED2.2 (2005) to 32% in LEED3.0 (2009) overall. The upcoming Green Buildings Assessment Standard consists of seven categories of indexes including: land saving and outdoor environment, energy saving and utilisation, water saving and utilisation, material saving and resources utilisation, quality of indoor environment, construction management as well as operation management, in which the "energy saving and utilisation" section weights 30% in residential buildings and 35% in community buildings (China, 201). It is clear that energy efficiency is a vital part of green buildings.

The term 'energy saving' is referred by the Green Buildings Assessment Standard generally as energy saving of space enclosing structures and energy consuming facilities. According to research, the total energy loss in space enclosing structures took as much as 70% of total energy lost. The space enclosing structures worked as a major approach of heat exchange between the internal and external space of the structure, with the energy loss of windows and walls took almost 50% of the total energy loss (Jiang, 2005). Evidently, improving the thermal performance of the materials in space enclosing structures and reducing the thermal loss and fluctuation of room temperature are efficient approach to improve the energy efficiency and thermal comfort of the structures.

The study titled 'Investigation of financial cost and profit in green buildings' which was funded by the Workgroup of Sustainable Construction in California, US showed that an extra 2% of capital invested in green building design provided 20% of saving in total cost of the building during the life cycle, which was 10 times of the initial investment. Studies in China also showed that there was lack of systematic research in the design of insulation in space enclosing structures and heating devices. The current designs normally take account of the ease of construction and level of construction cost instead of cost associated during building operation, causing significant waste of energy to the country (Liu and Liu, 2009). Therefore, it is fundamental for the development of green buildings and cultivation of energy

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efficiency to analysis systematically the design of indoor heating and wall insulation system in green buildings from the perspective of project life cycle to choose the most adaptable and economically viable projects.

KEY FACTORS IN THE DESIGN PHRASE OF INDOOR HEATING AND WALL INSULATION SYSTEMS

Types of wall insulation techniques: The selection of wall insulation techniques is the first step in the energy saving design of the wall insulation. With the development of green building in China, various types of wall insulation techniques advanced in a fast pace. The majority of the techniques include exterior insulation system, internal insulation system, self-insulation system and hybrid insulation system. The exterior insulation system is advantageous in superior thermal performance which eliminates the thermal bridge, protects the core structure and extends the serviceability of the buildings. The exterior insulation system does not take too much space within the structure and is easy to construct. Therefore, it has been widely used in various green buildings and is the most popular insulation technique used in the northern part of China due to its high cost efficiency (Liu, 2012; Shi *et al*., 2013). The exterior insulation system is also called the exterior insulation finishing system (EIFS). It provides superior energy efficiency, flexibility and creativity. It is a type of non-loadbearing spacing enclosing wall system combined with energy saving, thermal insulation, noise isolation and decoration (Sun, 2010). Therefore, this study explored in details the exterior insulation system.

Materials and thickness of the wall insulation

Materials of the wall insulation: The thermal performance of the wall insulation material is fundamental towards the efficiency of energy saving of the wall. Common wall insulation materials used in China can be categorised into three types: insulating mortar (powder), insulating boards and in-situ foaming insulating materials (Ma, 2008). Exterior insulating materials satisfying the Green Buildings Assessment Standard in northern part of China include: ETIRS insulating mortar, polyurethane foam plastic boards, extruded polystyrene slabs (XPS) and rock wool boards. Table 1 compares the major performance of the common insulating materials.

The abovementioned insulation materials have their own advantages and disadvantages. Proper material should be chosen according to the climate condition in respective area and technical and economical requirements of the building. Polystyrene boards are advantageous with low bulk density, low thermal conductivity, low water absorption, high noise isolation performance, high mechanical strength as well as high degree of accuracy in size and homogeneous in structure. Therefore, they provide outstanding insulating performance and are most commonly used in exterior insulation. However, the cost of polystyrene boards is relatively high. In general, other abovementioned materials are also common in accredited green buildings in northern part of China.

Thickness of wall insulation layer: The thickness of wall insulation layer is a key technical parameter in the design of wall insulation system. Theoretical research showed that thermal requirement reduces with the increase of the thickness of insulation layer as well as the amount of indoor heat generation; energy efficiency increases with the increase of the thickness of insulation layer. The rate of increase in energy efficiency reduces and when the thickness of insulation layer reached a certain amount, there is an upper limit in energy efficiency (Zhou and Xiao, 2009). The optimum thickness of insulation layer is related to the user, cost, physical characteristics of the insulation layer as well as the life of the building and insulation layer (Izquierdo *et al*., 2005). Statistics showed that the average thickness of insulation layer for exterior insulation system in northern China was 60 to 100 mm and for internal wall insulation, 20 to 40 mm.

Water temperature and flow rate of indoor heating: The temperature and flow rate of hot water are key technical factors in the design and control of indoor heating system. With the development of economics in China, there is an ongoing intensive requirement in energy. With

Table 1: Performance comparison of common wall insulation materials used in northern China

Name of material	Thermal conductivity factor W/(m●K)	Density kg/m3	Strength	Durability	Sustainability	Construction cost
ETIRS	0.060	≤220	High, can bear a certain amount of impact force	Fine	non-toxic	Low
Polyurethane foam plastic boards	≤0.025	40~60	Low	Good	Reusable	Relatively high
extruded polystyrene slabs (XPS)	0.033	22~30	Medium, can only bear loads in front direction	Fine	Cannot directly in contact with bonding agent; uses recycled materials	High
Rock wool boards	0.036	100~120	Low	Good	Normal	Low

the increase in living standards, the requirement of comfort increased. Therefore, determining a suitable water temperature and flow rate in the heating system and increasing the thermal efficiency of the system is significant to satisfy the tenants' comfort requirement, save energy and reduce environmental pollutions.

Economy and environmental impact

Economy: The energy saving design of indoor heating and wall insulation system is affected by the economic level and consumer behaviour in the specific area within a period of time. Due to the fact that the operating and maintenance cost of the building during its life cycle can be determined during design phrase, reducing the operating cost would result in an increase in construction cost. Although in theory the decision should be based on minimum life cycle cost of the building, there is a conflict of interest between the developers and the users. Therefore, it is necessary to reach a balance of the system considering the construction and operation cost.

Environmental impact: Green building is a type of building which, in its life cycle, maximises the reduction of resources (energy, land, water, materials), protects the environment, reduces pollutions, provides healthy, adaptable and high efficient utilisation space for the tenants is harmonic with nature (CSUS, 2009). Therefore, environmental impact is necessarily an important factor when determining the key technical parameters of the indoor heating and wall insulation system.

DESIGN MODEL AND SIMULATION OF THE INDOOR HEATING AND WALL INSULATION SYSTEM

Fundamental principles and assumptions of the model

Fundamental principles: Variation of room temperature is a key indicator of thermal load and comfort for green buildings. The reasonable selection of the variation of room temperature is significant for the energy saving of the building and quality of indoor environment. Using the variation of room temperature as the technical evaluation criteria of indoor heating and wall insulation energy-saving system, this study analysed the variation of room temperature with time with different material and thickness of the insulation layer as well as different hot water temperature and flow rate. The influence of different technical parameters to the variation of room temperature was compared, the efficiency of the designs was predicted and optimisation of parameters was conducted. This study provides theoretical basis for the energy saving design of indoor heating and wall insulation system.

Table 2: Meanings of symbols in calculating equation of room temperature variation

Symbol	Meaning	Unit
Ma	Mass of air in the sealed room	kg
Ca	Specific heat of air	J kg^{-1} °C
Mo	Mass of other materials in the	
room	kg	
Co	Specific heat of other materials	J kg^{-1} °C
F	Flow rate of hot water	m3/sec
°C	Specific weight of water	Kg/m^{-3}
Cw	Specific heat of water	J kg^{-1} °C
Hr	Thermal conductivity factor	W/(°CK)
Ar	Surface area of the room	M2
°C	Conductivity factor	W/(m·K)
S	Thickness of wall	m
°C	Boltzmann constant	
s	Surface radiation factor	W/(m2K4)
Tri	Indoor temperature	°C
dt	Timeslice	S
Tin	Hot water temperature at the input of the exchanger	°C
Trv	Surface temperature of the room	°C
Tev	Outdoor environmental temperature	°C

The model was established based on boiler hot water supply which is common in northern China. The hot water flow rate in the exchanger is managed by valves which are controlled by a temperature controller so that a desire level of room temperature is maintained. The room exchanges heat with outside area by means of conduction, convection and radiation. According to thermal equilibrium:

- Variation of room temperature = Heat released by heat sources-indoor heat energy dissipation:

$$\begin{aligned}(M_a C_a + M_o C_0)\, dT_{ri}/dt = F\rho C_w (T_{in} - T_{ri}) - \\ H_r A_r (T_{ro} - T_{ev}) - A_r \lambda (T_{ri} - T_{ev})/S - \\ \varepsilon\sigma A_r (T_{rv}^4 - T_{ev}^4)\end{aligned} \quad (1)$$

The meanings of symbols in Eq. 1 are given in Table 2.

The left part of Eq. 1 is the transient variation of air and furniture temperature in the room. The first part on the right is the heat released by the exchanger; the second part is the thermal energy dissipation due to convection between the outer layer of the room and outside area; the third part is the thermal energy dissipation due to heat conduction from the walls to outside area; the fourth part is the thermal energy dissipation due to radiation of heat from outer layer of the room to outside area.

Model assumptions: In order to analyse the influence of key technical parameters to the variation of room temperature, factors of little effect on the results are neglected. The following assumptions were made during modelling:

- The walls of the room are made from materials of high thermal insulation. The difference of indoor and outdoor temperature is limited and therefore thermal energy dissipation due to convection and radiation is much smaller than that due to conduction through the walls, they can therefore be ignored
- Although window-wall ratio and the types of material of glass affect the indoor insulating performance, analysis incorporating multi materials is not conducted in order to study the insulating performance of the wall materials
- The influence of indoor furniture is ignored
- The walls and ceiling of the room are made from the same homogenous material
- The air in the room is able to flow evenly at all times
- The efficiency of the exchanger is high and the output water temperature is the same as the room temperature

Model establishment

Descriptive model for the variation of room temperature with time: Based on the above assumptions, Eq. 1 can be rearranged. The thermal energy dissipation due to conduction (the total dissipation) can be expressed as:

$$E = A_r \times \lambda(T_{ri} - T_{ev})/S \quad (2)$$

Substitute Eq. 2 into Eq.1 and eliminate the ignored parts yields:

$$M_a C_a dT_{ri}/dt = F\rho C_w(T_{in} - T_{ri}) - A_r \times \lambda(T_{ri} - T_{ev})/S \quad (3)$$

If the differential equation is solved to derive the conduction function of room temperature T_{ri} (the output) and the flow rate of hot water F(the input), the conduction function would be nonlinear as the input F and output T_{ri} are coupled. Furthermore, there is an independent constant term:

$$A_r \times \lambda T_{ev}/S$$

on the right hand side of the equation which adds difficulty to establish a conventional conduction function. Therefore, discrete method can be used to derive the difference equation (Xie, 1998; Edwards and Hamson, 1996):

$$M_a C_a[T_{ri}(n+1) - T_{ri}(n)] = F\rho C_w[T_{in} - T_{ri}(n+1)]\Delta T - A_r \times \lambda[T_{ri}(n+1) - T_{ev}]\Delta T/S \quad (4)$$

Let, $M_aC_a = A$, $pC_w = B$,, $A_\gamma \times \lambda/S = C$, $\Delta T = 1s_0$

Due to the fact that thermodynamic system is usually time-delayed, it is reasonable to set the sampling interval to 1 s or even longer. Substitute into the equation yields:

$$A[T_{ri}(n+1) - T_{ri}(n)] = FB[T_{in} - T_{ri}(n+1)] - C[T_{ri}(n+1) - T_{ev}] \quad (5)$$

Rearrange Eq. 5 yields:

$$T_{ri}(n+1) = [A/(A+FB+C)] \times T_{ri}(n) + [FBT_{in} + CT_{ev}]/(A+FB+C)$$

Rearrange again yields the general expression:

$$T_{ri}(n) = [A/(A+FB+C)]^n \times [T_{ri}(0) - (FBT_{in} + CT_{ev})/(FB+C)] + [FBT_{in} + CT_{ev}]/(FB+C) \quad (6)$$

For a determined object, A, B and C are constants. The external temperature T_{ev} and the hot water temperature at the input of the exchanger can be treated as constant in a long period of time. The initial room temperature $T_{ri}(0)$ is known. If the flow rate of hot water F is stable, this equation can be viewed as an exponential function with the only variable n which is a discrete variable. The variation of n is sampled with an interval of 1 s. Even though the flow rate F, hot water temperature T_{in} and external temperature T_{ev} are functions of time, as long as they can be measured, the variation curve of room temperature with time can be describe by this model.

Sensitivity analysis of various technical parameters on room temperature: In order to discover the magnitude of influence of various technical parameters on the variation of room temperature, it is necessary to incorporate the possible range of value for each technical parameter considering the actual design objects, calculate the sensitivity factors for each technical parameter on the variation of room temperature and plot the sensitivity analysis diagram. The sensitivity of each technical parameter was then sorted to provide basis for reasonable selection and determination of each technical parameter. The sensitivity factor can be calculated as:

$$E_j = \triangleleft T_{rij}(n)/\triangleleft F_j \quad (7)$$

In Eq. 7: E_j is the variation of room temperature T_{rij} (n) sensitivity factor of technical parameter F_i $\triangleleft T_{rij}$ (n) is the variation rate (%) of variation of room temperature T_{rij} (n) when technical parameter F_j is changed by $\triangleleft F_j$ and $\triangleleft F_j$ is the variation rate (%) of technical parameter F_j.

Model simulation

Assumptions of basic data: It was assumed that a room had a dimension of $4\times5\times3$ m^3(L×W×H). The specific weight of hot water was ρ_w = 1000 kg m^{-3}, the specific heat of water was C_w= 4200 J kg^{-1} °C, the specific weight of air was C_a=1.29 kg m^{-3}, the specific heat of air was C_a = 1000 J kg^{-1}°C, the outdoor temperature was T_{ev} = 0°C, the initial room temperature was $T_{ri}(0)$ = 10°C and the general conductivity coefficient was 0.53. The influence of different insulating material, hot water temperature and flow rate as well as thickness of insulation on the variation of room temperature was analysed to provide basis of indoor heating and wall insulation design.

Comparison of different insulating materials: The hot water temperature at input was set as T_{in} = 80°C, the flow rate was F = 0.00001 m^3/sec and the thickness of material was 60mm. Selected materials include: XPS (λ_1 = 0.033 W/(m•K)), polyurethane foam plastic boards (λ_2 = 0.025 W/(m•K)), polyphenyl particles (λ_3 = 0.06 W/(m•K)). The influence of different insulating materials on the variation of room temperature was compared.

XPS: It can be calculated that:

- $A = M_aC_a = 60\times1.29\times1000 = 77400$
- $B = \rho C_w = 1000\times4200 = 4200000$
- $C = A_\gamma\times\lambda/S = (4\times3+4\times5+3\times5)\times2\times0.05/0.1 = 47$

Substitute these values into Eq. 6 yields:

$$T_{ri1}(n) = -25.86\times(0.999)^n+35.86$$

Polyurethane foam plastic boards: The time dependant equation of room temperature using the same method can be expressed as:

$$T_{ri2}(n) = -31.39\times(0.999)^n+41.39$$

Polyphenyl particles:

$$T_{ri3}(n) = -14.71\times(0.998)^n+24.71$$

Fig. 1 plots the functions.

Comparison of different thicknesses of material: XPS was taken as an example. Selected thicknesses of material include: S_1 = 60 mm, S_2 = 80 mm, S_3 = 100 mm. Other conditions were the same as in Section 3.3.2:

- when S_1 = 60 mm
- $T_{ri1}(n) = -25.86\times(0.999)^n+35.86$
- when S_2 = 80 mm

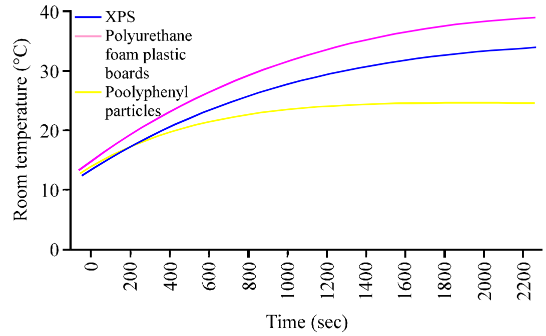

Fig. 1: Comparison of different materials

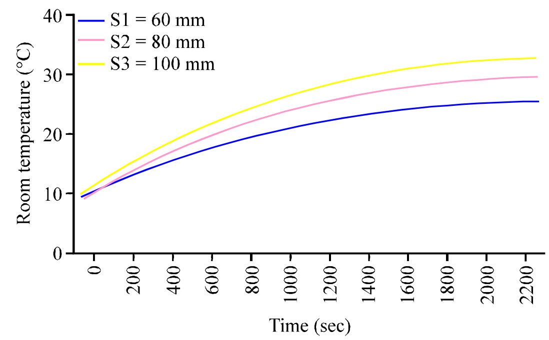

Fig. 2: Comparison of different thicknesses of material

- $T_{ri2}(n) = -31.60\times(0.999)^n+41.60$
- when S_3 = 100 mm
- $T_{ri3}(n) = -36.01\times(0.999)^n+46.01$

Figure 2 plots the functions.

Comparison of different hot water temperatures: XPS was taken as an example. Selected hot water temperatures include: T_{in1} = 60°C, T_{in2} = 80°C, T_{in3} = 100°C. Other conditions were the same as in Section 3.3.2:

- when T_{in1} = 60°C
- $T_{ri1}(n) = -16.89\times(0.999)^n+26.89$
- when T_{in2} = 80°C
- $T_{ri1}(n) = -25.86\times(0.999)^n+35.86$
- 30 when T_{in3} =100°C
- $T_{ri3}(n) = -34.82\times(0.999)^n+44.82$

Figure 3 plots the functions.

Comparison of different hot water flow rates: XPS was taken as an example. Selected hot water flow rates include: F_1 = 0.00001 m^3/sec, F_2 = 0.000015 m^3/sec, F_3 = 0.000005 m^3/sec. Other conditions were the same as in Section 3.3.2:

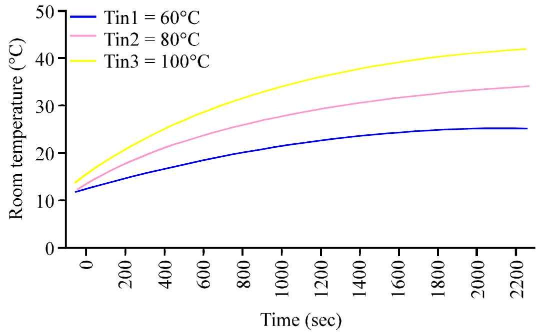

Fig. 3: Comparison of different hot water temperatures

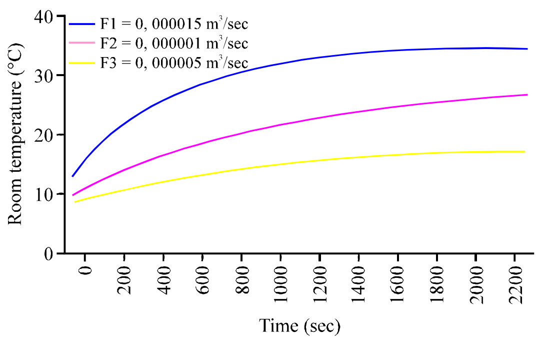

Fig. 4: Comparison of different hot water flow rates

- when $F_1 = 0.000015$ m^3/sec
- $T_{ri1}(n) = -33.94\times(0.998)^n+43.94$
- when $F_2 = 0.00001$ m^3/sec
- $T_{ri2}(n) = -25.86\times(0.999)^n+35.86$
- when $F_3 = 0.000005$ m^3/sec
- $T_{ri3}(n) = -13.11\times(0.999)^n+23.11$

Figure 4 plots the functions.

Sensitivity analysis: To further compare the magnitude of influence of different technical parameters on the variation of room temperature, a sensitivity analysis was conducted on each technical parameter using XPS as an example.

Base condition: The insulating material was XPS boards with $\lambda_1 = 0.033$ W/(m•K) and a thickness of S = 60 mm; the hot water temperature was $T_{in} = 80°C$ and the flow rate was F = 0.00001 m^3/sec; the temperature of external environment was $T_{ev} = 0°C$ and the initial room temperature was $T_n(0) = 10°C$. Measurement was taken 20 min after the heating system was enabled. Varying the conductivity factor λ and thickness S of the insulating material as well as temperature T_{in} and flow rate of water F by the same proportion, the results are shown in Fig. 5.

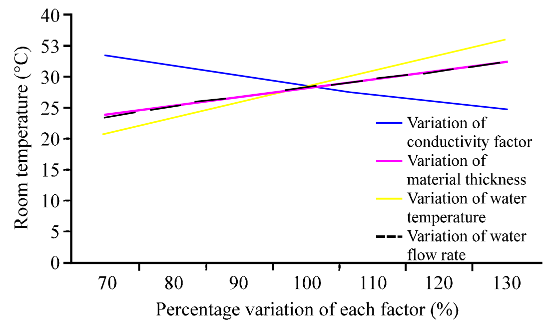

Fig. 5: Sensitivity analysis diagram of the variation of technical parameter

The sensitivity analysis of technical parameters showed that within reasonable and meaningful scope, the variation of hot water temperature had the most significant effect on the variation of room temperature, followed by the variation of conductivity factor; it can be proved that the room temperature would be the same with the magnitude of variation of hot water flow rate and the thickness of material. In other words, the sensitivity of the two factors on room temperature is the same.

COMPREHENSIVE ANALYSIS AND EVALUATION OF ENERGY SAVING DESIGN OF INDOOR HEATING AND WALL INSULATION SYSTEM

The final settlement of energy saving design of indoor heating and wall insulation system should not only consider technical factors but the economy and environmental impact of the project. At present, a certain level of advancement had been achieved in the assessment system and evaluation methods for energy saving designs: Hasan (1999) calculated the life cycle cost of exterior insulation system based on the concept of life cycle cost and estimated the payback period of asbestos insulating material and polystyrene boards; A comprehensive evaluation system for energy saving of buildings based on 19 factors is proposed (Cong *et al*., 2007); A comprehensive evaluation model based on fuzzy logic is proposed. The model was capable of not only reducing the influence of reliability of results by objective factors, but also improving the efficiency of data processing, decrease the intensity of calculation making the evaluation more operatable (Shi and Wei, 2009). However, the comprehensive evaluation of energy saving design is relatively complex with objective and subjective factors coexisted. It is therefore difficult to establish an evaluation system which is widely adaptable. In practise, comprehensive analysis, evaluation and selection should be carried out from the perspectives of technics, economy and environment, within the research scope of life cycle specified by the design object. For example, the sensitivity analysis in this study showed that the sensitivity of hot water temperature to the room temperature was greater than that of material. However, the cost of hot water is long-term but the cost of material is one-off and thus the discounted cost of material is lower than hot water. As a result, from the perspective of energy saving and economy, proper insulating material should be used to reduce the operation cost of hot water.

CONCLUSION

Due to the fact that the variation of room temperature affects significantly the energy efficiency of the building and indoor comfort, the study proposed an analytical model for the energy saving design of indoor heating and wall insulation system based on heat balance theory after the key factors which affect the variation of room temperature were analysed. Numerical simulation was then carried out to utilise the proposed model. The key conclusions were drawn as follows:

- The simulation curves clearly depicted the influence of key technical factors such as types and thicknesses of material as well as temperature and flow rate of hot water on the variation of room temperature. Therefore, the model provides abundant simulating data for design personnel to predict the performance of the design and optimise the parameters. Moreover, the model provides scientific basis for the energy saving design of indoor heating and wall insulation system
- The model incorporated key factors affecting the variation of room temperature but eliminated less significant factors. Different equation based on heat balance was proposed and the general expression of the numerical solution was established. The model is simple-structured and easy to calculate. Scenario prediction and calculation can be carried out using EXCEL. Furthermore, random disturbance can be incorporated in the model to study and examine the disturbance resistance of the system and discover relevant remedy procedure; additional impact factors can also be incorporated based on actual need such as the combined effect of different layers of materials of the wall and window-wall ratio, refining the model to be more comprehensive and complete
- There are numerous factors affecting the selection of energy saving design of indoor heating and wall insulation system for green buildings in northern China. In practise, the final selection of design should not only base on the variation of room temperature which is a significant technical factor, but should also base on the analysis and measurement of the comprehensive assessment system which is established by investigating and analysing the technical, economic, environmental and political conditions at the location where the design object resides

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