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ARTICLE

A Theory on Increasing the Heat Transfer Performance of Building Wall

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ABSTRACT

The target of traditional thermal conductivity of wall research is the spatial distribution form. In these studies, the change of thermal conductivity with temperature is neglected. Meanwhile, case studies are always used. This method needs large computation and it is hard to obtain the optimal result. In order to overcome the problems, a new approach has been put forward in this paper. Different from the traditional approach, the new approach solves an inverse problem under the concept of passive ideal energy-saving buildings to obtain the optimal distribution of heat ability with temperature on an external wall. The result for a typical summer day shows the heat ability distribution of a wall in summer is a staircase. It is similar to the heat pipe. It is also found that the optimal heat transfer property of the external wall is closer to the heat pipe when its heat capacity per square meter ($\rho c_p L$) is of extreme value. This study can provide guidance to researchers in building materials.

Keywords: Thermal conductivity; Building envelope; Passive room; Inverse problem; Nonlinear optimization

1. Introduction

Building energy accounts for 1/3 of the energy consumption of total social goods, increasing in these years. In China, the amount for the latter is about 15% and the ratio is increasing [1]. Meanwhile, carbon emission from buildings accounts for nearly half of that from the city [2]. Hence, it is really significant to put more emphasis on the energy-efficient building research. As the external wall separates the indoor and outdoor environment, proper thermal conductivity for it is important to achieve acceptable comfort for building occupants and reduced cooling and heating load.

Asan [3] studied the optimal location of insulation material which can achieve the maximum time lag and minimum decrement factor of outdoor temperature wave and found that placing half of the insula-

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tion in the mid-center plane of the wall and half of it in the outer surface of the wall gives very high time lags and low decrement factors (close to optimum values). Liu [4] studied the heat conduction problem for tightly compressed adjacent layers of plane plates with gradually varying heat conduction coefficients and obtained the effect of spatial distribution form of thermal conductivity on heat transfer property. Chen [5] considered thermal conductivity to vary with space coordinate according to a linear and an exponential law, based on this proposal six second order heat conduction differential equations were set up. The result showed these equations can't describe true variable-conductivity heat conductions problems. Mahlia et al. [6] analyzed the change between thermal conductivity and thickness of material, which obeys a non-linear polynomial function. Zhong and Zhang [7] investigated the transient heat transfer characteristics of building envelope that is made up of two kinds of three-layered structures. The results show that the position and arrangement of the insulation material are of important effect on the decrement factor and the time lag.

The target of traditional research is mainly on the spatial distribution form of thermal conductivity in order to obtain the optimal layout. In these studies, the way of overture is always used. This method has large computation and it is hard to obtain the optimal result.

Because humans can change clothes with the outdoor temperature, buildings are the same. That is to say, the ideal energy-saving building can properly change the thermal properties ($c_p(t), k(t)$) of external wall with its temperature. Based on this, the objectives of the present research are: (1) to put forward an approach for determining the optimal $k(t)$ of external wall (the $c_p(t)$ of external wall is assumed to be a constant in this study); (2) to demonstrate the application of the approach by using an illustrative example; (3) to provide guidance to researchers in building materials.

2. Problem description

The traditional process of space heating or cooling system design for a given building is shown in **Figure 1**. It can not determine the ideal thermal physical properties of building envelope material, the best natural ventilation strategy and the minimal additional energy consumption of the space heating in winter or air-conditioning in summer. In order to overcome these shortcomings, a new method based on the inverse problem is put forward by us, which is shown in **Figure 2**.

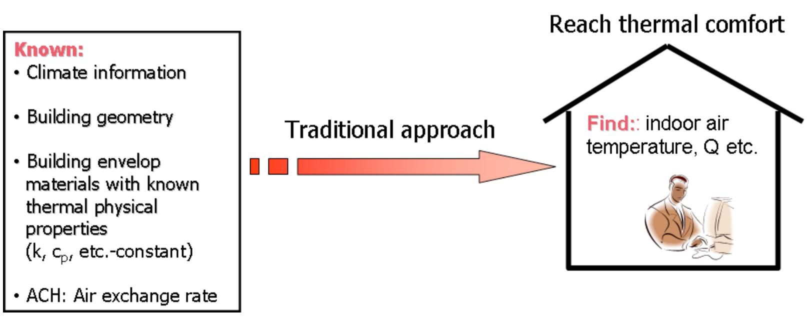


Figure 1. Schematic diagram of the traditional approach.

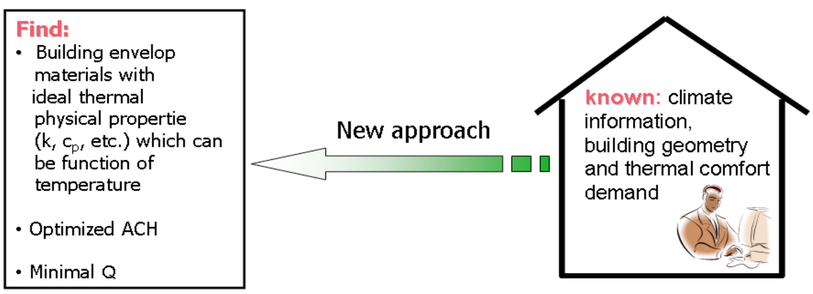


Figure 2. Schematic diagram of the new approach.

For a building that is located in a certain area, having indoor heat, heat ability, *ACH*, and heat ability of wall, the house temperature is the function of external wall heat ability.

$$t_o = f(k_{ew}(t)) \tag{1}$$

where,

$$t_o = \frac{h_r \bar{t}_r + h_c t_a}{h_r + h_c} \tag{2}$$

Integrated uncomfortable degree I [8] can be defined as follows:

$$I_{sum} = \int_{year} (t_o - t_H) d\tau \text{ When } t_o > t_H \tag{3}$$

$$I_{win} = \int_{year} (t_L - t_o) d\tau \text{ When } t_o < t_L \tag{4}$$

where, t_L = 16 °C ,t_H =28 °C.

Combining Equations (1)-(4), we have:

$$I_{sum} = f(k_{ew}(t)) \tag{5}$$

$$I_{win} = f(k_{ew}(t)) \tag{6}$$

As described before, the objective of the inverse analysis is to get the ideal $k_{ew}(t)$ by minimizing the I_{sum} and I_{win} values.

It is easily understood that the smaller $k_{ew}(t)$ is, the lower I_{win} is in winter. So we only study the optimal $k_{ew}(t)$ in summer.

3. Solution of the problem

3.1 Room model

Using the two-plate model in actual room [8]. The wall, floor, and ceiling are fixing into a plate. The radiations about wave in them are ignored. Another wall is the other plate. The error between simplification two plate model and house model is < 20%. Meanwhile, the heat ability of wall is not the sensitivity for error. So the model can be applied into the research of wall heat ability.

Then, the heat ability of external wall is evenly divided into any segments based on its self temperature in the paper and every segment has a heat ability value. two-plate with $k_{ew}(t)$ room model is developed. In order to validate the model, its calculated results and those directly calculated from Airpak model are compared and the maximum absolute deviation of indoor air temperature is 1 °C. It shows that the two-plate with $k_{ew}(t)$ room model can be used to determine the optimal $k_{ew}(t)$.

3.2 Nonlinear optimization method

Obtaining the optimization nonlinear model

Optimization goal: min I (k_1, k_2, k_3,...,k_N)

Restrictive condition: $k_{min} \le k_i \le k_{max}$ (i = 1,2,3,...,N)

As the known insulation materials used in wall, the thermal conductivity k_{min} is 0.02 W/(m·°C). According to analysis, on a typical summer day, it is found that, when the heat ability of the external wall is 35 W/(m·°C), the internal temperature values of the external wall are close to the same. Therefore, the 35 W/(m·°C) is large enough for the external wall thermal conductivity, and k_{max} is set to 35 W/(m·°C) of this paper.

To use the Sequential Quadratic Programming (SQP) method is used to the aforementioned non-linear problem.

4. Illustrative example: Results and discussion

4.1 The calculated conditions

An ordinary passive room in a multi-stories building in Beijing is analyzed. The dimensions of the simulated room are 5.7 m (depth) × 3.6 m (width) × 3.2 m (height). It has an external south-facing wall, and the thickness is 250 mm. The volume heat capacity of the external south-facing wall is 2.3 MJ/(m^3·°C) (180-mm-thick reinforced concrete and 70-mm-thick polystyrene board external wall are used as comparison case). A 1.7 m × 2.0 m double-glazing window is fixed in the exterior south wall. The overall heat transfer coefficient of the double-glazing window is about 3.1 W/(m^2·°C). The shading coefficient (*SC*) value of the window is 0.44 when the window is hung with curtain in summer. The thickness of three concrete hollow block internal walls, reinforced concrete floor and ceiling are all 200 mm.

The *ACH* is assumed to be 0.5 h^{-1} when the window is closed. However, the window is open to make full use of the summer night ventilation if the outdoor temperature is lower than 26 °C and higher than 20 °C then the *ACH* becomes 5.0 h^{-1}. The average indoor heat source from people, lights and equipment is about 10.8 W/m^2.

4.2 Results and discussion

The result of a typical summer day shows, the optimal thermal conductivity distribution of the external wall on a typical summer is a staircase function (see **Figure 3**).

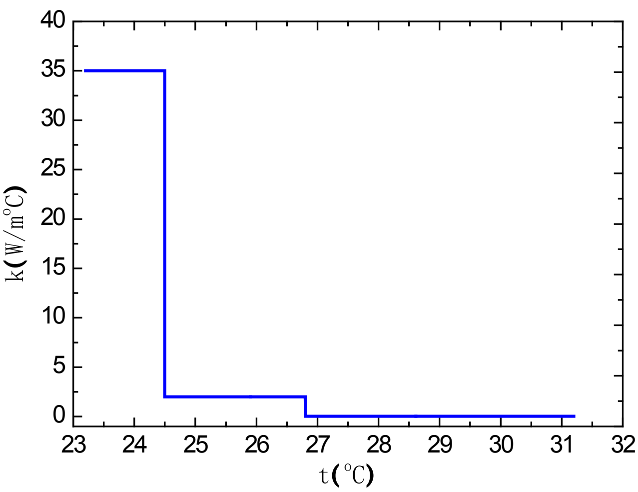


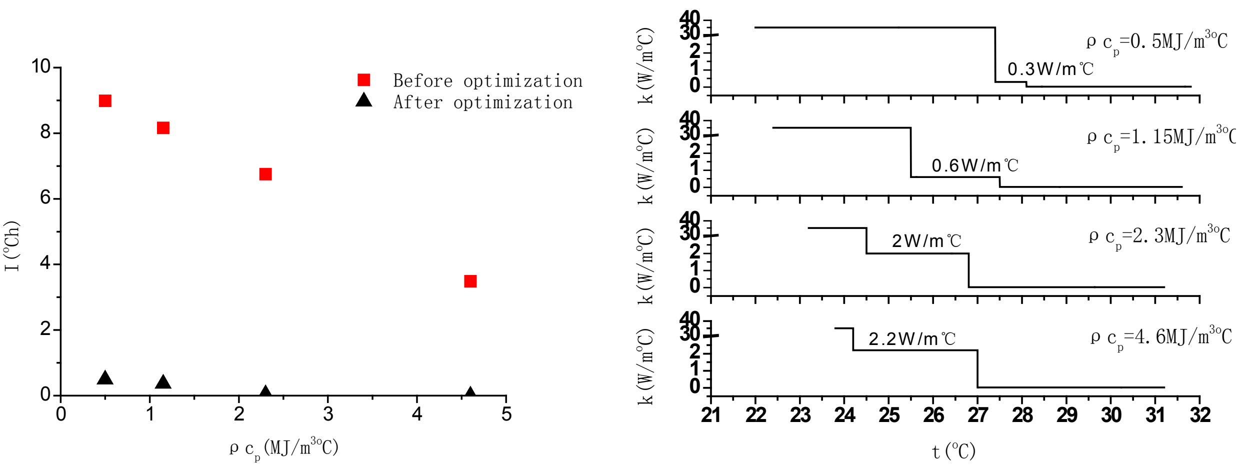
Figure 3. Optimal thermal conductivity distribution of external wall (Beijing, a typical summer day).

The integrated uncomfortable degree is reduced by 99% by optimization and the optimized highest indoor operative temperature is 1 °C lower.

The physical mechanism can be explained as follows: In summer, there are two heat transfer directions in the external wall. When the temperature of the external wall is lower, it plays a role in cooling indoor environment and heat transfer direction in it is from indoor side to outdoor side. At this moment, large thermal conductivity is helpful to reduce indoor temperature. When the temperature of external wall is higher, it plays a role in heating indoor environment and heat transfer direction in it is from outdoor side to indoor side. At this moment, small thermal conductivity is helpful to avoid exaltation of indoor temperature. So ideal $k_{ew}(t)$ is that large thermal conductivity lies in the low temperature region and small thermal conductivity lies in the high temperature region. Meanwhile, there exists an overlap region where thermal conductivity is a certain value which depends on the calculation case.

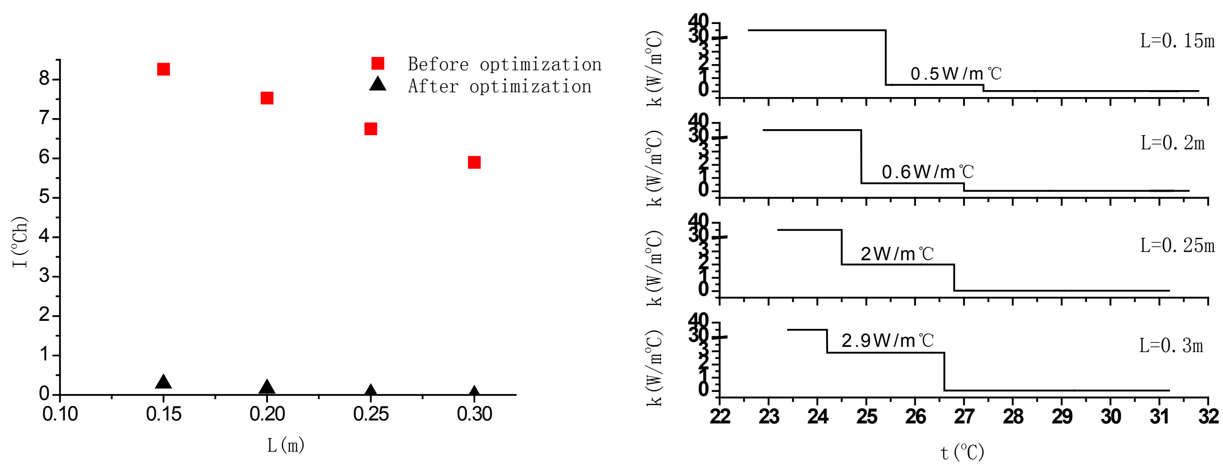
It is seen that the optimal heat transfer property of external wall is similar with the function of heat pipe from **Figure 1**. When the overlap temperature region is zero, they are the same. The reason is that when we see an external wall as a heat pipe with large thermal conductivity in the direction from indoor to outdoor and small thermal conductivity in the direction from outdoor to indoor, there are two heat transfer directions in the external wall. When the temperature of the external wall is low, the outdoor temperature is lower than the indoor temperature (because there is indoor heat source), so the temperature of inner surface of the external wall is higher than that of exterior surface of the external wall and the heat transfer direction in the external wall is from indoor to outdoor. At this time, the thermal conductivity of the external wall is large. On the contrary, when the temperature of the external wall is high, the outdoor temperature is higher than the indoor temperature (because the intensity of indoor heat source is not so large), so the temperature of exterior surface of the external wall is higher than that of inner surface of the external wall and the heat transfer direction in the external wall is from outdoor to indoor. At this time, the thermal conductivity of the external wall is small. This is the same with optimization result without overlap temperature region. As the overlap temperature region accounts for a less proportion in the actual optimization result, heat pipe can be considered to be applied in the design of optimal performance of the external wall.

Then, dimensionless analysis is carried out for an external wall, and three natural physical parameters (ρc_p, L, $k(t)$), which are representative of the performance of wall, are obtained. **Figure 4** shows optimization results for thermal conductivity distribution of the external wall on a typical summer day with different ρc_p. It is seen that: (1) I_{sum} decreases after optimization and decreases with increasing ρc_p; (2) I_{sum} is almost zero when ρc_p is over 2.3 MJ/(m^3·°C). That is to say, for the case considered, 2.3 MJ/(m^3·°C) is the critical value of ρc_p for free-cooling building in Beijing; (3) The width and height of overlap temperature region increases and lower temperature is contained in the overlap temperature region with increasing ρc_p. It means that the optimal heat transfer property of the external wall is closer with heat pipe when its ρc_p is of the extreme value. The reasons for the above phenomena are as follows: The ability of the external wall increases increasing ρc_p, so its ability to adjust indoor temperature increases and I_{sum} will reduce. Meanwhile, with increase of ρc_p, the internal temperatures of the external wall raise less in summer. As a result, the overlap temperature region contains lower temperatures and internal temperatures of the external wall are more likely to simultaneously exist in heat transfer process in both directions of the external wall which causes the increasing width of overlap temperature region. Since the external wall has the function of giving out heat to the outdoor environment on a typical summer day, when ρc_p is infinity, the temperature of the external wall keeps unchanged and the temperature of inner surface is higher than that of exterior surface. Under this conduction, the ideal $k_{ew}(t)$ should also be infinity. So the height of overlap temperature region will increase until the maximum is obtained.



(a) (b)

Figure 4. Optimization results in a typical summer day with different ρc_p (L = 0.25 m).



(a) (b)

Figure 5. Optimization results in a typical summer day with different L (ρc_p =2.3 MJ/(m^3·°C)).

Figure 5 shows optimization results for heat ability of the external wall on a typical summer day with different L. It is seen that: (1) I_{sum} decreases after optimization and decreases with increasing L; (2) I_{sum} is almost zero when L is over 0.2 m. So for the case studied, $L > 0.2$ m can meet the requirements of free-cooling building in Beijing; (3) The width and height of overlap temperature region increases and lower temperature is contained in the overlap temperature region with increasing L. It means that the optimal heat transfer property of the external wall is closer to heat pipe when its L is of the extreme value. The reason for (1) is that the ability of heat insulation of the external wall increases with increasing L, so I_{sum} will reduce. The reasons for (2), (3) are the same as that mentioned above.

5. Conclusions

In this paper, a new approach for developing energy efficient buildings is put forward. An illustrative example of applying it is presented. The results show that:

● The optimal heat ability distribution of the external wall in a typical summer day is a staircase function.

● ρc_p and L has no effect on the form of optimal thermal conductivity distribution of the external wall, only existing certain stretching and offset.

● Heat pipe is more appropriate in the application of the design of optimal performance of the external wall when $\rho c_p L$ of the external wall is of the extreme value. It can provide guidance to researchers in building materials.

Author Contributions

Yu Zhang presented a solution to the problem known as the inverse problem method of the wall.

ShaoLei Sun established the room model and calculated the case.

Conflict of Interest

There is no conflict of interest.

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