Dynamic Load Calculation of Solar Radiation Heat Gain for Energy-saving Buildings Envelope in Winter

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Abstract. The paper analyzes the influence of solar radiation load for energy-saving building in winter, considering the thermal inertia of building envelope, a mathematical model of unsteady heat transfer is established, and a program is compiled to calculate the dynamic solar radiation load of building envelope in winter, which is a very practical calculation of solar radiation dynamic load. It not only changes the current situation that the calculation of solar radiation load in winter for energy-saving buildings can only use the steady-state algorithm, but also provides scientific and reliable data support for thermal comfort and the dynamic analysis of heating energy consumption for energy-saving buildings.

1. Introduction
It was announced to be implemented that the standard¹ issued by the ministry of housing and urban rural development was implemented from August 1, 2019, the heating energy consumption calculation must comply with the following regulations: calculated by monthly average dynamic method; the heating load from the heat transfer of the enclosure (including the hot bridge), solar radiation heat gain, inner heat gain, and the heat loss caused by natural ventilation, shall be all calculated; the influence of building thermal inertia on load should be considered in calculation.

At present, according to article 5.2.6 of the code¹, steady state heat transfer method, and orientation correction based on basic heat consumption, is still used in the calculation of heating load in winter, which is too rough to meet the requirements of annual energy consumption analysis and thermal comfort of energy-saving buildings.

The solar radiation is an important external disturbance among all factors in the external environment of buildings, solar radiation transmits heat into the room in different ways through various enclosure structures. Through transparent enclosures, such as glass windows, the solar radiation injected into the room increases the energy consumption of the air conditioning system in summer. Similarly, in winter, through transparent enclosure, the solar radiation emitted into the room also causes cooling load in winter. However, the current national regulations generally do not include this load in winter, which cause the room temperature may have a very significant impact, and even cause indoor overheating in winter in the buildings with large window-wall ratio. Even in the transition season, the excessive solar radiation heat not included in the transition season also extends the air conditioning cooling time, resulting in the increase of building energy consumption throughout the year. For energy saving and comfort, the solar radiation emitted into the room should be calculated and included in the load, so as to offset a large part of the energy consumption of the heating system in winter. In addition, the energy consumption of the heating system is increased by the solar radiation entering the room through the non transparent enclosure in winter, in order to achieve the goal of...
energy saving and indoor comfort, the dynamic calculation of solar radiation entering the room through the heat transfer of non transparent enclosure structure should also be carried out in winter.

Therefore, for the load caused by solar radiation in the whole year, the load caused by solar radiation should be calculated according to the dynamic method in cold area, hot summer and cold winter area. In this paper, the influence of building thermal inertia on the load is considered, the mathematical model of unsteady heat transfer is established, and the program is compiled to calculate the dynamic load of solar radiation in winter of building envelope, which is a practical calculation method of solar radiation dynamic load of energy-saving building envelope in winter. It can not only provide accurate data support for the design of energy-saving buildings' heating process in winter, but also help to achieve the win-win goal of reducing energy consumption of energy-saving buildings' heating in winter and thermal comfort of the environment in winter.

2. Dynamic load calculation of non transparent envelope in winter

Comprehensive temperature from outdoor calculation of air conditioning on design day in winter according to article 5.2.6 of code[3], the calculation method of hourly comprehensive outdoor temperature for air conditioning in summer is as follows:

\[
t_{zs} = t_{sh} + \left( \frac{\rho J}{h_w} \right)
\]  

(1)

\( t_{zs} \) — hourly comprehensive temperature of outdoor air conditioning in summer (°C)

\( t_{sh} \) — hourly outdoor temperature of air conditioning in summer (°C)

\( \rho \) — absorption rate of exterior surface of enclosure for solar radiation, may be taken as 0.7;

\( J \) — total solar irradiance of envelope in different directions W/m²

\( h_w \) — heat-transfer coefficient of external surfaces of buildings (W/m².°C)

According to the above mathematical model of heat transfer, the above reaction coefficient method is used to program, input the above external disturbance parameters, load results can be calculated and expressed as cooling load temperature. That is to say, the hourly load in winter formed by the unsteady heat transfer from the non transparent enclosure is expressed in the form of cooling load temperature, which is the opposite number of winter heat load in essence.

The calculation method of hourly value of outdoor air comprehensive temperature in summer cannot be directly used in the calculation of hourly value of outdoor air comprehensive temperature in winter. The data of solar radiation and outdoor air temperature in winter are different from those in summer. In winter, the influence of outdoor air temperature and solar radiation on the load of non transparent enclosure is opposite, the load caused by the comprehensive temperature of outdoor air in winter may be heating load and cooling load. The clear method is to calculate separately for the convenience of load statistics. The specific process is as follows: firstly, the hourly air temperature calculated for the air conditioning in winter and the converted temperature caused by the hourly total solar radiation illuminance of the enclosure are taken as the input items to Substitute into the system of differential equations, the output load corresponding to these two parts of input is calculated by using the program compiled by the principle of reaction coefficient method, then the two parts of the load are algebraic added, the time-by-time dynamic load through the non transparent envelope will be obtained. Comprehensive outdoor air temperature in winter:

\[
t_{zs} = t_{sh} + \left( \frac{\rho J}{h_w} \right) = t_{sh} + t_r
\]  

(2)

\( t_r \) — The equivalent temperature caused by the hourly total solar radiation illuminance of the direction where the enclosure is located (°C)

\( \rho \) — absorption rate of outer surface of enclosure for solar radiation is 0.7.

\( J \) — total solar irradiance of envelope in different directions in winter, W/m², the example data can be obtained from the data set[2];
h<sub>w</sub> — heat-transfer coefficient of external surfaces of buildings (W/m<sup>2</sup>·℃)

<math> t_{sh} — hourly outdoor temperature of air conditioning in summer (℃) </math>

2.1. Mathematical model analysis of dynamic heat transfer

Heat transfer from of the wall makes a thermal system, which are partial differential equations and boundary conditions. Based on the heat exchange theory, when the thickness is far less than the length and width of wall, there is one-dimensional unsteady heat transfer in the wall<sup>[3]</sup>:

<math>
\frac{\partial t(x, \tau)}{\partial \tau} = \frac{\lambda}{\rho c} \frac{\partial^2 t(x, \tau)}{\partial x^2}

q(x, \tau) = -\lambda \frac{\partial t(x, \tau)}{\partial x}

\quad t(x, 0) = 0
</math>

The basis thought of thermal instantaneous response factors method<sup>[5]</sup> is three main steps, the process of which is: the disturbing quantity curve is dispersed in order of time of unit disturbing quantity; solve response factors that is the response of wall thermal system to unit disturbing; worked out the air conditioning cooling load temperature and the dynamic thermal basic data by superposing and integrating the response factors of wall.

For example, when calculate thermal instantaneous response factor \( Y(j) \), among which, \( -\alpha_j \) is the root of \( B(s) = 0 \), when \( -\alpha_j \) is not greater than \(-40\) , we can assure satisfactory precision.

<math>
Y(0) = K + \sum_{i=1}^{\infty} \frac{B_i}{\Delta \tau} (1 - e^{-\alpha_j \Delta \tau}), \quad j = 0
</math>

<math>
Y(j) = -\sum_{i=1}^{\infty} \frac{B_i}{\Delta \tau} (1 - e^{-\alpha_j \Delta \tau})^2 e^{-(j-1)\alpha_j \Delta \tau}, \quad j \geq 1
</math>

The disturbing quantity curve is dispersed in order of time of unit disturbing quantity, response of which active thenceforward over a long period of time. So we must work out the air conditioning cooling load temperature and the dynamic thermal basic data by superposing and integrating the response factors of wall. For instance, the formulas for calculating the air conditioning cooling load temperature \( t_i (n, k) \) is as follows:

<math>
\theta_x(n - j, k) \text{ is outdoor air synthetic temperature, } k \text{ is orientations of the wall, } n \text{ is a given time for calculating, discrete time is } \Delta \tau = 1h, \text{ at the suggestion of ASHRAE, } j \text{ is from 0 to 50.}
</math>

It is too difficult to calculate for the manual method, the paper develop software in VB, steps of which is: input the physical property parameter of material; calculate \( -\alpha_j \) the root of \( B(s) = 0 \), obtain the data of \( B_i \); calculate thermal instantaneous response factor \( Y(j) \); input outdoor air synthetic temperature; calculating and output the air conditioning cooling load temperature \( t_i (n, k) \).Walls in building are multilayer structure built up of different material, whose physical property parameter involve density \( \rho \), coefficient of thermal conductivity \( \lambda \) and specific heat \( c_p \), which derive from reference document. The reference value shall be taken according to can be obtained from the data set<sup>[2]</sup>.
2.2. *hourly load in winter caused by unsteady heat transfer of non transparent enclosure*

According to the above mathematical model of heat transfer, the above reaction coefficient method is used to program, input the above external disturbance parameters, load results can be calculated and expressed as cooling load temperature. That is to say, the hourly load in winter formed by the unsteady heat transfer from the non transparent enclosure is expressed in the form of cooling load temperature, which is the opposite number of winter heat load in essence.

\[
CL_w = KF(t_{wl1} - t_n) = KF(t_{wl1} - t_n) + KF(t_{wl2} - t_n)
\] (7)

- $CL_w$ — hourly load caused by heat transfer of non-transparent envelope (W)
- $K$ — heat transfer coefficient of non-transparent envelope (W/m²·K)
- $F$ — heat transfer area of non-transparent envelope (m²)
- $t_{wl1}$ — the cooling load temperature of non-transparent envelope caused by the hourly temperature calculated outside for air conditioning in winter (°C)
- $t_{wl2}$ — the cooling load temperature of non-transparent envelope caused by the equivalent temperature from the total solar radiation illuminance of the direction (°C)
- $t_n$ — design temperature of air conditioning area in winter (°C)

3. *The example of cooling load in winter caused by unsteady heat transfer of wall*

For example, the wall in Table 1, according to the above formula, the paper compiles VB programs to calculate and work out air conditioning cooling load temperature for walls, as shown in Table 1.

### Table 1. The material composition of the wall

| Thickness (mm) | Structures sketch (outside-to-inside) |
|---------------|----------------------------------------|
| 20 mm         | 1. cement mortar;                     |
| 370 mm        | 2. reinforced concrete;               |
| 40 mm         | 3. EPS board                          |
| 20 mm         | 4. cement mortar                      |

Table 2. The cooling load temperature of non-transparent envelope caused by the equivalent temperature from the total solar radiation illuminance of the direction

| Time  | S     | W     | N     | E     | Time  | S     | W     | N     | E     |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0     | -17.52 | -17.52 | -17.52 | -17.52 | 12    | 10.54 | -7.23 | 2.81  | 1.17  |
| 1     | -17.52 | -17.52 | -17.52 | -17.52 | 13    | -7.23 | 2.81  | 1.17  | 1.17  |
| 2     | -17.52 | -17.52 | -17.52 | -17.52 | 14    | -7.23 | 2.81  | 1.17  | 1.17  |
| 3     | -17.52 | -17.52 | -17.52 | -17.52 | 15    | -7.23 | 2.81  | 1.17  | 1.17  |
| 4     | -17.52 | -17.52 | -17.52 | -17.52 | 16    | -7.23 | 2.81  | 1.17  | 1.17  |
| 5     | -17.52 | -17.52 | -17.52 | -17.52 | 17    | -7.23 | 2.81  | 1.17  | 1.17  |
| 6     | -17.52 | -17.52 | -17.52 | -17.52 | 18    | -7.23 | 2.81  | 1.17  | 1.17  |
| 7     | -17.52 | -17.52 | -17.52 | -17.52 | 19    | -7.23 | 2.81  | 1.17  | 1.17  |
| 8     | -17.52 | -17.52 | -17.52 | -17.52 | 20    | -7.23 | 2.81  | 1.17  | 1.17  |
| 9     | -17.52 | -17.52 | -17.52 | -17.52 | 21    | -7.23 | 2.81  | 1.17  | 1.17  |
| 10    | -17.52 | -17.52 | -17.52 | -17.52 | 22    | -7.23 | 2.81  | 1.17  | 1.17  |
| 11    | -17.52 | -17.52 | -17.52 | -17.52 | 23    | -7.23 | 2.81  | 1.17  | 1.17  |
Table 3. The heating load temperature of non-transparent envelope caused by the hourly temperature calculated outside for air conditioning in winter

| Time | 0   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| S    | 35.57 | 35.45 | 35.44 | 35.46 | 35.47 | 35.49 | 35.5 | 35.51 | 25.51 | 15.88 | 13.07 | 5.5 |
| W    | 35.57 | 35.45 | 35.44 | 35.46 | 35.47 | 35.49 | 35.5 | 35.51 | 35.11 | 34.76 | 34  | 33.95 |
| N    | 35.57 | 35.44 | 35.44 | 35.46 | 35.47 | 35.49 | 35.5 | 35.51 | 35.11 | 34.76 | 34  | 33.95 |
| E    | 35.57 | 35.45 | 35.44 | 35.46 | 35.47 | 35.49 | 35.5 | 35.51 | 20.79 | 15.02 | 19.4 | 23.74 |

4. Hourly cooling load formed by solar radiation entering through glass windows in winter

The calculation method of hourly cooling load formed by solar radiation entering through glass windows in winter is the same as summer. At present, the standard data only have the maximum value of the solar heat factor in summer, the solar altitude angle in winter is lower than that in summer. It is suggested that the monitoring organization should gradually improve the data of solar radiation heat gain factor in winter, and provide reliable data support for the calculation of solar radiation dynamic load of transparent enclosure in winter.

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