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Thermal dynamic simulation of wall for building energy efficiency under varied climate environment

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Abstract: Aiming at different kind of walls in five cities of different zoning for thermal design, using thermal instantaneous response factors method, the author develops software to calculation air conditioning cooling load temperature, thermal response factors, and periodic response factors. On the basis of the data, the author gives the net work analysis about the influence of dynamic thermal of wall on air-conditioning load and thermal environment in building of different zoning for thermal design regional, and put forward the strategy how to design thermal insulation and heat preservation wall base on dynamic thermal characteristic of wall under different zoning for thermal design regional. And then provide the theory basis and the technical references for the further study on the heat preservation with the insulation are in the service of energy saving wall design.

All-year thermal dynamic load simulating and energy consumption analysis for new energy-saving building is very important in building environment. This software will provide the referable scientific foundation for all-year new thermal dynamic load simulation, energy consumption analysis, building environment systems control, carrying through farther research on thermal particularity and general particularity evaluation for new energy -saving walls building. Based on which, we will not only expediently design system of building energy, but also analyze building energy consumption and carry through scientific energy management. The study will provide the referable scientific foundation for carrying through farther research on thermal particularity and general particularity evaluation for new energy saving walls building.

1. Introduction

Building energy consumption account for about 30％of all primary consumption in China, and air conditioning energy consumption account for about of building energy consumption[1], air conditioning load of wall, especially in official building, is an important part of which, consequently, there will be remarkable energy-saving results under the optimal thermal design for the wall in official building.

Dynamic thermal characteristic of wall is not only scientific basis for design of architectural and environmental system, but also the theoretical basis for energy consumption analysis and energy manages. So the research of dynamic thermal characteristic of wall not only provide a technical basis for energy saving design for wall and architectural and environmental system, but also is becoming the key needs to be resolved to dynamic air conditioning load calculation and optimum control of air conditioning system operation.

China is a country with a vast territory, complicated land shape, and differs greatly in climate. In order to make building thermal design adapt to the regional climate features , and make indoor thermal environment adapt to thermal comfort of human body, there is 《code for thermal design of civil building》 (GB50176 - 1993) [2] published in China, in which five thermal design are zoned in China: extremely cold areas, cold areas, cold-in-winter-and-hot-in-summer areas, warm-in-winter-and-hot-in-summer areas, temperate areas.

At present, thermal design for energy saving of wall and the effect of which primarily are based on the control Index of thermal insulation and heat preservation and engineering practice. There are not dynamic thermal characteristic data and conclusion of wall based on based on dynamic heat transfer.

There is also not the dynamic heat transfer calculation analysis and data of wall amid at different kind of walls in different zoning for thermal design, which lead to no comprehension and the meaning of results popularize are not big.

Aiming at different kind of walls in seven cities of different zoning for thermal design, using thermal instantaneous response factors method, the author compiles software to calculation air conditioning cooling load temperature, thermal response factors, and periodic response factors. On the basis of the data, the author gives the net work analysis about the influence of dynamic thermal of wall on air-conditioning load and thermal environment in building of different zoning for thermal design regional, and put forward the strategy how to design thermal insulation and heat preservation wall base on dynamic thermal characteristic of wall under different zoning for thermal design regional. And then provide the theory basis and the technical references for the further study on the heat preservation with the insulation are in the service of energy saving wall design.

2. Mathematical Models for Heat Transfer of the Wall

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 [3][4].

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

$$q(x,\tau) = -\lambda \frac{\partial t(x,\tau)}{\partial x} \qquad (1)$$

$$t(x,0) = 0$$

λ —— thermal conductivity of wall layer, W/（m·K）;

c ——specific heat capacity of wall layer, J/（kg·K）;

ρ ——density of wall layer，kg/m3;

$t(x,0)$ ——temperature in initial time

The basis thought of thermal instantaneous response factors method[2] 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, $-\alpha_i$ is the root of $B(s)=0$, when $-\alpha_i$ is not greater than （—40）, we can assure satisfactory precision.

$$Y(0) = K + \sum_{i=1}^{\infty}\frac{B_i}{\Delta\tau}(1-e^{-\alpha_i\Delta\tau}), \qquad j=0$$

$$Y(j) = -\sum_{i=1}^{\infty}\frac{B_i}{\Delta\tau}(1-e^{-\alpha_i\Delta\tau})^2 e^{-(j-1)\alpha_i\Delta\tau}, \quad j\ge 1$$

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 worked out the air conditioning cooling load temperature and the dynamic thermal basic data by superposing and integrating the response factors of wall. For instance, Formulas for calculating the air conditioning cooling load temperature $t_l\ (n,k)$ is as follows:

$$t_l(n,k)=\sum_{j=1}^{50}Y(j)\theta_Z(n-j,k) \qquad (2)$$

$\theta_Z(n-j,k)$ is outdoor air synthetic temperature, k is orientations of the wall, n is a given time for calculating, discrete time is $\Delta\tau=1h$, at the suggestion of ASHRAE, j is from 0 to 50.

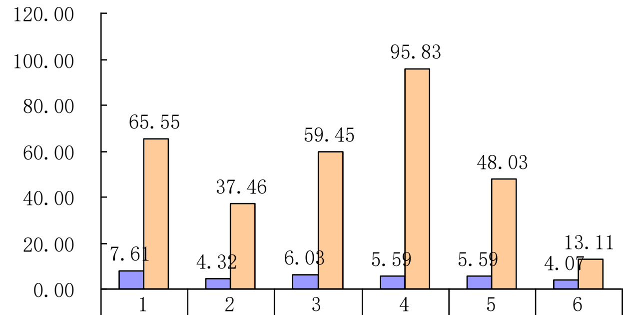
It is too difficult to calculate for the manual method, the paper develop software in VB, steps of which is: input the physical property parameter of material; calculate $-\alpha_i$ the root of $B(s)=0$, obtain the data of B_i; calculate thermal instantaneous response factor $Y(j)$; input outdoor air synthetic temperature; calculating and output the air conditioning cooling load temperature $t_l\ (n,k)$.

3. The Wall Model

Aiming at the south walls in table.1, by the software, this paper analyses and calculates the air conditioning cooling load temperature and the dynamic thermal basic data for the wall. According to reference document, the inner surface coefficient of convective heat transfer is 8.7 W/m^2°C, the inner surface coefficient of convective heat transfer is 19 W/m^2°C; the wall is a compound body made up of multi-layer structure with different material, the thermal resistance of multi-layer structure and the air blanketing is come from reference document [2], the results is shown as followed in table 1.

4. The Analysis on the Calculation Result

The heat transfer coefficient data and the maximal air conditioning cooling load temperature value for 6 kinds of south wall in summer in Nanjing as shown in the following figure1. We could tell that heat transfer coefficient of the wall No.1 and is No.4 respectively is 0.761 and 0.559, it indicated that heat preservation performance of the interior-insulation wall No.4 is superior to the No.1; and from which we could tell that the maximal air conditioning cooling load temperature value of the wall No.1 and is No.4 respectively is 65.55 and 95.83, which indicated that air conditioning cooling load increase instead of decreased though reduced in numbers of The heat transfer coefficient data, and the conclusion of No.3 and No.4 are the same. We also could tell both the heat transfer coefficient of the wall No.5 and that of wall No.4 are 0.559, but air conditioning cooling load of No.5 far fall behind those of No.4. By comprehensive comparison of the six walls data, we also could tell the wall No.6 achieve the best performance in heat preservation and the lowest value in air conditioning cooling load.



	1	2	3	4	5	6
The heat transfer coefficient ×10	7.61	4.32	6.03	5.59	5.59	4.07
the maximal air conditioning cooling load temperature×(-1)	65.55	37.46	59.45	95.83	48.03	13.11

figure1. The heat transfer coefficient data and the maximal air conditioning cooling load temperature value for 6 kinds of south wall in summer in Nanjing

The hourly value of the air conditioning cooling load temperature for five kinds of south wall in summer in Nanjing as shown in the following figure2.

To view six kinds of south wall in summer in Nanjing, the hourly value of air conditioning cooling load temperature fluctuation and the greatest value are ranged from maximum to minimum: wall No.4, wall No.1, wall No.3, wall No.5, wall No.2, wall No.6, which indicated that fluctuation of indoor temperature of wall are ranged from maximum to minimum are the same sequence. In summer of cold-in-winter-and-hot-in-summer areas, the thermal insulation performance in summer is very important, the thermal insulation performance are ranged from superior to inferior are the same sequence. The greatest value and the fluctuation of the air conditioning cooling load temperature for No.6 drop off significantly. The lower the amplitude data of air conditioning cooling load temperature fluctuation is, the better thermal inertia result of the wall will be, and the better thermal stability result will be. All those come down to one point: the external-insulation wall No.6 is the best one in all six kinds of walls in energy-saving buildings.

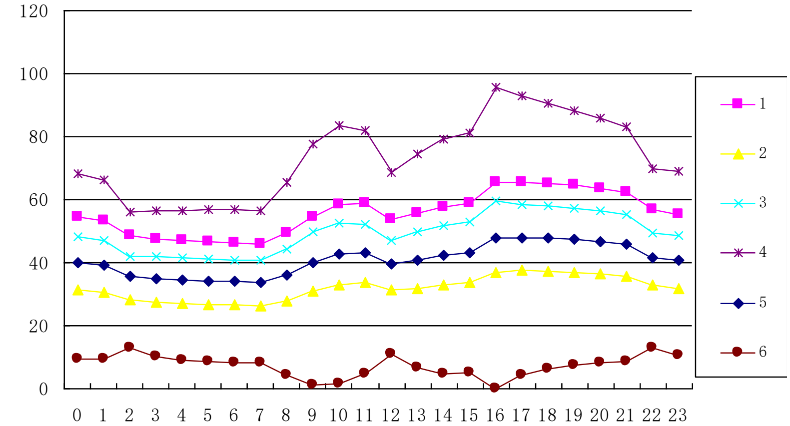


figure2. The hourly value of the air conditioning cooling load temperature for six kinds of south wall in summer in Nanjing

The hourly value of the air conditioning heating load temperature for six kinds of south wall in whiter in Haerbin as shown in the following figure3. We will arrive at similar conclusions to that of the figure2. But to view six kinds of south wall in summer in Nanjing, the hourly value of air conditioning cooling load temperature fluctuation and the greatest value are less than those in Nanjing. It indicated that wall in summer of cold-in-winter-and-hot-in-summer areas was influenced more by the dynamic thermal while wall in winter of extremely cold areas was influenced less by the dynamic thermal.

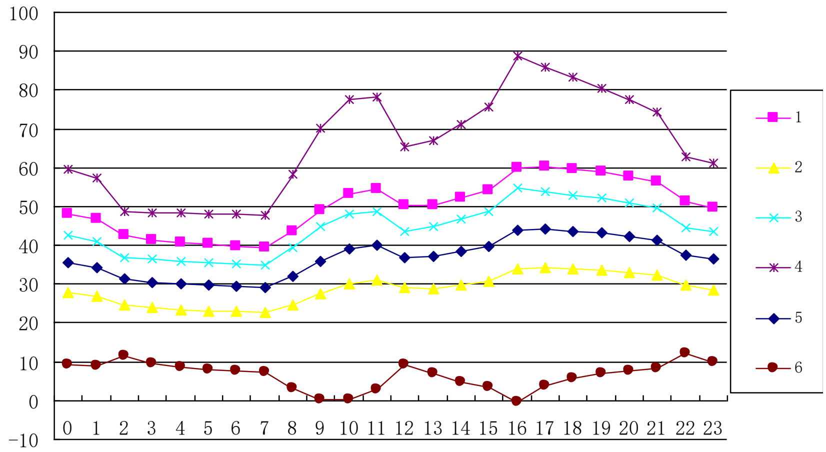
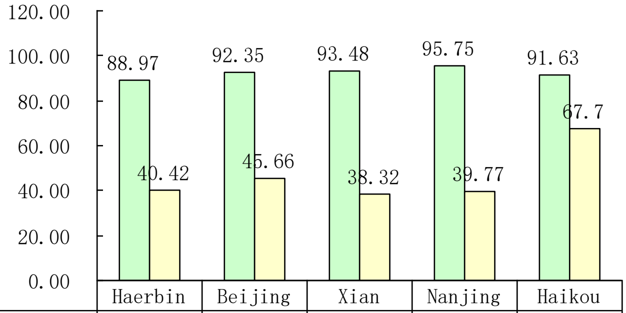


figure3. The hourly value of the air conditioning heating load temperature for six kinds of south wall in whiter in Haerbin

The hourly value of the air conditioning heating load temperature for six kinds of south wall in whiter in Haerbin as shown in the following figure4.In summer, the maximal fluctuation of air conditioning cooling load temperature on account of difference coefficient of heat transfer in six cities are ranged from 88.97 to 95.75, the variation scope is smaller, while the maximal fluctuation of air conditioning heating load temperature on account of difference coefficient of heat transfer in six cities are ranged from 38.32 to 67.7 ,there is a wide range in the variation scope in winter. Difference coefficient of heat transfer has much higher effect on air conditioning heating load than air conditioning cooling load.



	Haerbin	Beijing	Xian	Nanjing	Haikou
The maximal fluctuation of air conditioning cooling load	88.97	92.35	93.48	95.75	91.63
The maximal fluctuation of air conditioning heating load	40.42	45.66	38.32	39.77	67.7

figure4. The maximal fluctuation of air conditioning cooling and heating load temperature on account of difference coefficient of heat transfer in five cities.

5. An Example Result of Computing by the Software

Aiming at a series of new energy-saving walls in China building[6], for example, 8th wall, see table2, according to the above formula, the paper compiles VB programs to calculate, and work out air conditioning cooling load temperature for new energy saving walls, as follows table.3. Partial datasheet of 8th wall in table1 is given in the paper to fit an available space, the 4th layer is expanded polystyrene sheet [6], as follows table.2.

Table.1 walls data

wall number	thickness (mm)	structure sketch （outside-to-inside）	thermal conductivity W/（m·K）	specific heat capacity kJ/（kg·K）	density kg/m3
1	20	cement mortar;	0.93	1.05	1800
	30	XPS board;	0.03	1.38	35
	180	reinforced concrete;	1.74	0.92	2500
	20	cement mortar	0.93	1.05	1800
2	20	cement mortar;	0.93	1.05	1800
	60	XPS board;	0.03	1.38	35
	180	reinforced concrete;	1.74	0.92	2500
	20	cement mortar	0.93	1.05	1800
3	20	cement mortar;	0.93	1.05	1800
	40	XPS board;	0.03	1.38	35
	200	reinforced concrete;	1.74	0.92	2500
	20	cement mortar	0.93	1.05	1800
4	20	cement mortar;	0.93	1.05	1800

	180	reinforced concrete;	1.74	0.92	2500
	20	air blanketin;			
	40	XPS board;	0.03	1.38	35
	20	cement mortar	0.93	1.05	1800
5	20	cement mortar;	0.93	1.05	1800
	40	XPS board;	0.03	1.38	35
	20	air blanketin;			
	180	reinforced concrete;	1.74	0.92	2500
	20	cement mortar	0.93	1.05	1800
6	20	cement mortar;	0.93	1.05	1800
	60	XPS board;	0.03	1.38	35
	20	air blanketin;			
	180	reinforced concrete;	1.74	0.92	2500
	20	cement mortar	0.93	1.05	1800

Table.2 8th wall

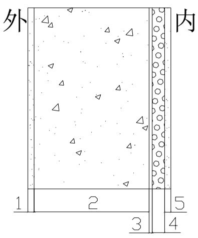
	thickness (mm)	structure sketch （outside-to-inside）
	20 mm	1. cement mortar;
	370 mm	2.reinforced concrete;
	10 mm	3. air blanketin;
	40 mm	4. EPS board
	20 mm	5. cement mortar

Table.3 Air conditioning cooling load temperature ℃

time	orientations								
	S	SW	W	NW	N	NE	E	SE	H
0:30	18.4	18.4	18.5	18.4	19.1	18.3	18.3	18.3	18.4
1:30	17.6	17.7	17.7	17.7	17.9	17.6	17.6	17.6	17.6
2:30	17.0	17.0	17.0	17.0	17.1	17.0	17.0	17.0	17.0
3:30	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6
4:30	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4
5:30	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3
6:30	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4
7:30	18.1	18.1	18.1	18.1	19.6	25.1	26.6	22.9	21.0
8:30	19.8	19.8	19.8	19.8	20.5	30.3	34.0	29.3	26.8
9:30	23.3	21.5	21.5	21.5	21.8	32.0	37.9	34.2	32.8
10:30	27.3	23.0	23.0	23.0	23.8	30.9	38.4	36.9	38.4
11:30	31.2	24.3	24.3	24.3	24.7	28.2	36.6	37.8	43.2
12:30	34.2	28.2	25.5	25.5	25.7	27.2	32.8	36.8	46.8
13:30	35.9	32.9	28.3	26.4	26.5	27.1	29.6	34.0	48.7
14:30	36.0	37.2	33.3	27.3	27.0	27.3	28.4	30.3	48.8
15:30	34.6	39.9	38.2	30.6	27.1	27.2	27.7	28.5	47.1
16:30	32.1	41.1	42.0	34.4	26.9	27.0	27.2	27.6	45.7
17:30	28.6	39.9	43.3	37.0	26.3	26.3	26.4	26.6	40.2

18:30	26.3	36.2	41.3	36.9	26.7	25.3	25.3	25.4	34.2
19:30	23.6	28.0	30.2	28.3	23.8	23.2	23.2	23.2	27.1
20:30	22.1	24.0	25.0	24.2	22.2	21.9	21.9	21.9	23.7
21:30	21.0	21.9	22.3	21.9	21.0	20.9	20.9	20.9	21.7
22:30	20.0	20.4	20.6	20.5	20.1	20.0	20.0	20.0	20.4
23:30	19.2	19.4	19.4	19.4	19.2	19.2	19.2	19.2	19.3

We can also work out the dynamic thermal basic data for new energy saving walls. To fit an available space, the paper give just the partial datasheet of 8th wall as table.4 and the 4th layer is expanded polystyrene sheet [6], periodic response factors of which is as follows table.4，periodic response factors is drawn in figure 5.

Table.4 Periodic response factors

$X^*(i)$	$Y^*(i)$	$Z^*(i)$
3.2892308	-0.207824	1.4350401
-2.017977	0.5141028	-0.453814
-0.360442	0.2172091	-0.166803
-0.131130	9.29×10-2	-7.22×10^{-2}
-5.32×10^{-2}	4.01×10-2	-3.13×10^{-2}
-2.25×10^{-2}	1.73×10-2	-1.36×10^{-2}
-9.64×10^{-3}	7.50×10-3	-5.87×10^{-3}
-4.16×10^{-3}	3.25×10-3	-2.55×10^{-3}
-1.80×10^{-3}	1.41×10^{-3}	-1.10×10^{-3}
-7.80×10^{-4}	6.11×10^{-4}	-4.78×10^{-4}
-3.38×10^{-4}	2.65×10^{-4}	-2.07×10^{-4}
-1.46×10^{-4}	1.15×10^{-4}	-8.99×10^{-5}
-6.35×10^{-5}	4.97×10^{-5}	-3.90×10^{-5}
-2.75×10^{-5}	2.16×10^{-5}	-1.69×10^{-5}
-1.19×10^{-5}	9.34×10^{-6}	-7.32×10^{-6}
-5.17×10^{-6}	4.05×10^{-6}	-3.17×10^{-6}
-2.24×10^{-6}	1.76×10^{-6}	-1.38×10^{-6}
-9.71×10^{-7}	7.61×10^{-7}	-5.96×10^{-7}
-4.21×10^{-7}	3.30×10^{-7}	-2.58×10^{-7}
-1.82×10^{-7}	1.43×10^{-7}	-1.12×10^{-7}
-7.91×10^{-8}	6.20×10^{-8}	-4.85×10^{-8}
-3.43×10^{-8}	2.69×10^{-8}	-2.10×10^{-8}
-1.49×10^{-8}	1.16×10^{-8}	-9.12×10^{-9}
-6.44×10^{-9}	5.05×10^{-9}	-3.95×10^{-9}

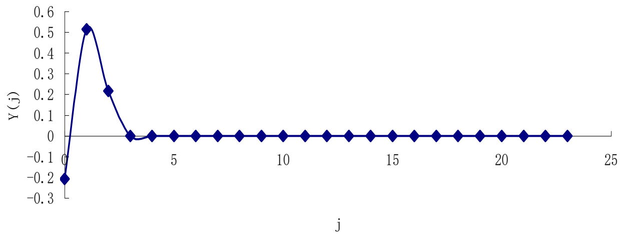


Figure 5. Periodic response factors Y*(j) curve.

6. Conclusions

6.1 In summer of cold-in-winter-and-hot-in-summer areas and warm-in-winter-and-hot-in-summer areas, the thermal insulation performance in summer is very important, the greatest value and the fluctuation of the air conditioning cooling load temperature for exterior-insulation wall No.6 with 60 mm XPS board and the air blanketing drop off significantly, the lower the amplitude data of air conditioning cooling load temperature fluctuation is, the better thermal inertia result of the wall will be, and the better thermal stability result will be. All those come down to one point: the exterior-insulation wall with insulating panel and the air blanketing is the best one in energy-saving buildings.
6.2 It is concluded that the heat preservation performance of the interior-insulation wall and the external-insulation wall is the same on account of difference coefficient of heat transfer, such as the wall No.5 No.4, but cold-in-winter-and-hot-in-summer areas, warm-in-winter-and-hot-in-summer areas, extremely cold areas and cold areas, the thermal insulation effect of the external-insulation wall is far superior to the interior-insulation wall in energy-saving buildings. The coefficient of heat transfer of wall is not dynamic thermal characteristic, the air conditioning cooling or heating load will increase when the coefficient of heat transfer of wall decreased, which break completely with the conventional ideas that the heat preservation performance increase when the coefficient of heat transfer decreased.
6.3 Difference coefficient of heat transfer has much higher effect on air conditioning heating load than air conditioning cooling load. We should select larger coefficient of heat transfer for wall in extremely cold areas and cold areas, which will be greatly reduced air conditioning heating load in winter, thereby increase building energy efficiency.
6.4 Compared with the air conditioning cooling load temperature for traditional walls, the air conditioning cooling load temperature for new energy saving walls drop off significantly, so that the air conditioning cooling load for new energy saving walls drop off significantly, and there are marked energy saving in building. The software will change the existing condition there is a lack of the data for new energy saving walls in air conditioning cooling load calculation, and apply the result of the reforms for new energy saving walls to air conditioning cooling load calculation.
6.5 The software will change the existing condition there is a lack of the data for new energy saving walls in the dynamic thermal basic data calculation. The data in the paper is on condition that the environmental parameters for air conditioning design are inputs. If you feed data of corresponding period such as all-year into the software, you can get the dynamic thermal basic data for corresponding period or all-year thermal dynamic load simulation, energy consumption forecasting and analysis. The software can be applied to the referable scientific foundation for all-year thermal dynamic load simulation, energy consumption forecasting and analysis.
6.6 The software provide functions of calculation the air conditioning cooling load temperature, heat transmission coefficient, thermal response factors, periodic response factors, and Z transfer function coefficient for new energy saving walls, which can also be used in designing of thermal engineering, carrying through farther research on thermal particularity and general particularity evaluation for new energy saving walls building.
6.7 It must be pointed out that the data in software is only for one city. If you feed data of the other area into the software, you can get the software for the other area.

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