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Wall insulation effect on building energy efficiency with the intermittent and compartmental energy consuming method

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Abstract. Based on the intermittent and compartmental energy consuming method of residential buildings in Hot Summer and Cold Winter Zone, a two-dimensional heat transfer model of one household flat is built for a transient study of the wall insulation effect on building energy efficiency. With the mode of compartmental energy consuming, the energy consumption of interior walls accounts for nearly 45% of the total amount, thus insulation for interior walls should be taken into more consideration as well as for exterior walls. With the intermittent energy consuming mode, exterior wall external insulation can decrease air-conditioner heating load. However, when cooling in summer nights, the temperature of wall is higher than both indoor and outdoor. External insulation hinders heat in walls from dissipating to outside, and thus there is an “anti-insulation” effect existing here. Interior insulation can effectively decrease both heating and cooling loads of air-conditioner.

Introduction

Hot summer and cold winter zone locates at the south center of China. The average temperatures of the hottest month and coldest month are 25–30 °C and 2–7 °C respectively, which are about 2 °C higher and 8 °C lower than the same latitude all over the world [1]. With the rapid development of economy and improvement of living standard, the requirements of indoor thermal environment went higher. Cooling and heating with air-conditioner has become the main means of improving indoor thermal comfort. The contradiction between the increasing amount of building energy consumption, especially the residential building energy consumption and increasingly serious energy shortage condition is followed and largely block the development of society. Building envelope energy saving is one of the most effective way to achieve building energy efficiency [2, 3]. The existing basic research of building energy efficiency in hot summer and cold winter zone mostly overlooked the characteristics of intermittent and compartmental energy consuming method. Until now, the energy saving measures here was, to a large extent, copied from the northern cold area where energy consumed by full time or part time in the whole building. Therefore, buildings in hot summer and cold winter zone generally adapt exterior wall external insulation system. However, the effect is not ideal after the system being generalized and the energy saving rate is far below expectation [4].

According to existing research results, exterior wall external insulation can decrease the heating load of buildings, but not always decrease the cooling load. Masoso and Grobler [5] used EnergyPlus software to analyze the annual air conditioning load of an office building in Botswana with six different set temperatures. The set air-conditioner operating time was from 6 a.m. to 6 p.m. which indicated a typical intermittent energy consuming mode. They found out that enhancing exterior wall external insulation can reduce annual heating load, but not always cooling load. There existed a critical air conditioning set temperature. When the set temperature was lower than it, energy could be saved, whereas the energy consumption would increase when the set temperature is higher. Tummu group [6] conducted experiment to study the intermittent air-condition cooling load with different window-wall ratios and different kinds of building envelope. Results showed that if there were no windows, both external insulation and internal insulation could decrease building energy consumption. As the window size increased, internal thermal insulation could still save energy, but external thermal insulation would turn up the anti-insulation behavior and increase energy consumption instead.

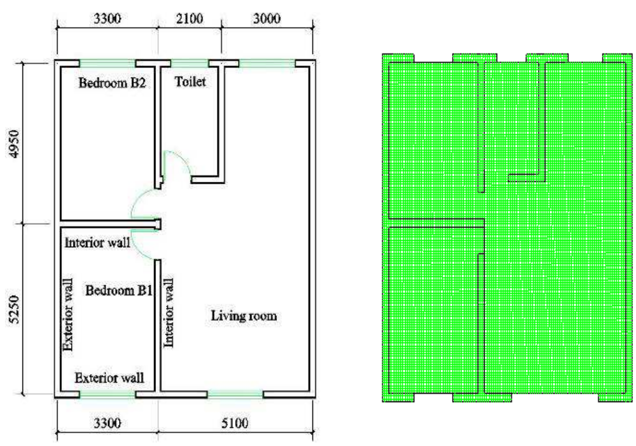
There widely exists intermittent and compartmental energy consuming method for buildings in hot summer and cold winter zone. It is worthy of further study that whether there is anti-insulation behavior existing in wall insulation, especially in exterior wall external insulation, and consequently could influence on cooling load and total load. Results above are based on the building energy consumption analysis software like DOE - 2.1E and EnergyPlus to calculate annual cooling load and heating load, the root cause for anti-insulation behavior still unclear. As some other parameters like wall surface temperature and heat flux, which are process amounts were failed to output precisely. Therefore, Using 2-D CFD model to replace widely used building thermal simulation software to analysis intermittent and compartmental energy consumption of cooling/heating by air-conditioners for residential buildings in hot summer and cold winter zone in China is necessary.

The Fluent software can solve the coupling problem of flow heat transfer, and accurately obtain the inside and outside surface temperature and heat flux of walls in seconds. A typical two-bedroom flat of a certain residential district in Hangzhou China is selected here as the computational fluid dynamics (Fluent 12.0) simulation model. The detailed energy dissipation way in the established two-dimensional heat transfer model could be obtained to analysis the wall thermal insulation properties.

Numerical analysis model

The layout of the selected typical two-bedroom flat for numerical analysis is shown in Fig.1 (a). It includes bedrooms (B1 and B2), bathroom (W) and living room (D). The window-wall ratio is 0.4 and total area is 90.2 m^2. Both bedroom B1 and bedroom B2 have two interior walls and two exterior walls. The grid distribution of the selected flat model can be seen from Fig.1 (b).

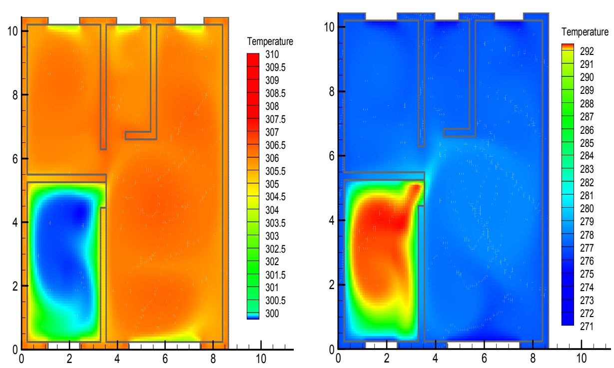
The difference between energy consumption of buildings with different wall material is investigated here. Three cases are studied: (1) all the walls without insulation, that is to say, wall material is only KP1 perforated brick without any thermal insulation material covered on the surface; (2) exterior walls with external insulation; (3) all the walls are internal insulated, there are 30 mm thick extruded polystyrene boards (XPS) being put on the indoor side of walls, and there is no insulation on the outdoor side. The detailed parameters of materials for building envelope in the model are presented in Table1.



（a）Layout of the selected residence unit

（b）Grid distribution of the selected residence unit

Fig.1 Physical model for numerical analysis



(a)Summer cooling

(b)Winter heating

Fig.2 Contours of indoor temperature at 2:00 after air-conditioner started

To simplify the model, take five reasonable assumptions as follows: (i) ignore the influence of thermal bridges such as columns and beams to set a two-dimensional heat conduction model and take no account of the heat transfer between the floors, because both upstairs room and downstairs room are assumed to air-conditioner operated and set the same temperature. The heat transfer capacity between the floors is negligible for simplification; (ii) the material of each layer is homogeneous and isotropic, and the physical thermal parameters do not change with temperature; (iii) insulation material closely contact with walls and the thermal contact resistance is not considered; (iv) rising typical daytime outdoor air temperature to replace the influence of solar radiation for simplification. In this simulation model, the daytime solar radiation did not directly affect the typical daily heating/cooling load， because the air condition operating during the night (22:00-6:00); (v) assuming that the room is empty and excluding the impact of the furniture thermal storage effect. Besides, thermal disturbance of people, lighting and electrical appliances is also not considered. Therefore, the process of heat transfer in walls can be regarded as a two-dimensional unsteady heat transfer without inner heat source, the thermal differential equation is:

$$\rho c \frac{\partial t}{\partial \tau} = \lambda\left(\frac{\partial^2 t}{\partial^2 x} + \frac{\partial^2 t}{\partial^2 y}\right) \tag{1}$$

Where ρ is density (kg•m^{-3}), c is specific heat (J•kg^{-1}•K^{-1}) and t is temperature (K) and τ is time (s).

Only convective heat transfer is considered between exterior surface and the outdoor environment. The exterior surface heat flow can be calculated from:

$$Q_{out} = h_{out} A(t - T_0) \tag{2}$$

Where hout is the coefficient of convective heat transfer for exterior wall external surface, and it can be specified as 19 W•m^{-2}•K^{-1}[7], A is the area (m^2) of the outer wall, t is the wall temperature (K) and T_0 is outdoor air equivalent temperature (K).

Continuous processing is adopted for heat flow and temperature distribution at the wall internal surface and the interface of two kinds of material, as the following equation:

$$t_i\big|_s = t_j\big|_s,\quad \lambda_i \frac{\partial t_i}{\partial n}\Big|_s = -\lambda_j \frac{\partial t_j}{\partial n}\Big|_s \tag{3}$$

There are the following four main energy using characteristics for the residential building in hot summer and cold winter zone: (i) compartmental; (ii) intermittent; (iii) mainly using air-conditioners; (iv) cooling in summer is the mainly part. Therefore, the accordingly four settings can be made: (i) selecting bedroom B1 as the only air-conditioner serving room; (ii) selecting energy using time for everyday from 10 p.m. through the night until 6 a.m. in the next day as a typical case, according to the intermittent energy consuming method of urban residential building; (iii) heating and cooling by air-conditioner, whose rated power is 2500W and the cooling/heating COP is 2.3/1.9[8]. The set temperature is 26°C for cooling and 18°C for heating and assuming that there is an internal heat/cold source evenly dissipating to the energy using room; (iv) typical climates characteristics of the summer and winter in hot summer and cold winter zone are used for calculation respectively. 37.2 °C is chosen as the daily highest meteorological temperature (T_{max}), 27°C as the lowest (T_{min}) and 32.1°C as the mean temperature in Hangzhou summer; the daily highest temperature (T_{max}) in winter is 6.2°C, the lowest (T_{min}) is 1.2°C and the mean temperature is 3.7°C[9]. Assuming that outdoor temperature periodically change with time in sine form. Temperature reached the highest at 2 p.m. and lowest at 2 a.m. Assumptions above can be expressed by the following function:

$$T_0 = -\sin\left(\frac{2\pi(\tau + 7200)}{86400}\right)\left(\frac{T_{\max} - T_{\min}}{2}\right) + \left(\frac{T_{\max} + T_{\min}}{2}\right) \tag{4}$$

Where T_0 is the outdoor air temperature (K), τ is the local time (s).

Function above is written into User Defined Function(UDF), together with the air condition operation command. The temperature control method of inverter air-conditioner was chosen in this model. When the indoor air temperature exceeded the set temperature, air conditioning started cooling or heating. To achieve the effect of cooling or heating, the source term of energy equation in Fluent was modified in the model. Cooling/heating capacity evenly dissipated in the air-conditioner occupied room in the form of internal heat source.

Table 1 Thermal parameters of the building envelope

	Material	Thickness Δx/mm	Dry density ρ/[kg/m^3]	Specific heat c/[J/(kg·K)]	Thermal conductivity λ/[W/(m·K)]
Wall	KP1 porous brick	240	1400	1050	0.58
Insulation material	plastic benzoic board	30	28	1380	0.03
Window	glass	5	2500	966	0.7
Door	pine wood	50	527	2720	0.35

Table 2 Operating patterns for calculation

	Application	Room	Time	Set temperature	Daily mean temperature	Windows and door
Intermittent energy consuming	cooling	B1	22:00~06:00	26℃	32.1℃	closed
	heating	B1	22:00~06:00	18℃	3.7℃	closed

For the consideration of ventilation during the day, assuming that when air-condition is started, all the doors and windows are closed, only heat transfer is considered and leave out the influence of infiltration; when the air-condition is closed, according to the ventilation requirements, assuming all the doors and windows are open and outside air flow into indoor space slowly, both mass exchange and energy exchange exist at the same time. Regard the closed windows and doors as simply thin-wall thermal resistance because of the small thickness and periodically open and close characteristic. The thermal resistance equals to $\Delta x/\lambda$, where Δx stands for thickness (m). All the working conditions for calculation are shown in table 2. The windows and the door periodically opening and closing are written into a journal file where periodically changing the boundary conditions of doors and windows was written to achieve the effect.

Set the initial temperature close to the steady state solution as much as possible to make iteration results reached steady state earlier. Stop iterative calculation after the cyclically change of wall and indoor air temperature reached steady state. Then, the cooling/heating load together with the air conditioning working frequency and duration can be calculated according to the change of indoor air average temperature.

Results and analysis

Temperature distribution and dynamic change

The complexity of building energy consumption in hot summer and cold winter zone is mainly embodied in the intermittent and compartmental energy consuming method.

The compartmental energy consuming can be seen from the cloud pictures (Fig.2) of indoor temperature distribution at 2 a.m. (for example) when cooling and heating without insulation. In Fig.2 (a), the indoor temperature of bedroom B1 when cooling is obviously lower than that of rooms without cooling. Heat from the wall dissipating to bedroom B1 makes the air temperature near the wall surface higher than that of room center. In Fig.2 (b), the indoor temperature of bedroom B1 when heating is obviously higher than that of rooms without heating and the air temperature near the wall surface is lower than that of room center.

The intermittent energy consuming can be seen from Fig.3 where bedroom B1 indoor and environmental temperature dynamic change over time when cooling and heating without insulation. The shade in Fig.3 stands for air-conditioner serving time during which B1 indoor temperature fluctuates around the set temperature. When the air-conditioner in bedroom B1 is shut down and windows are open for ventilation, indoor temperature lags behind and gradually gets close to the environment temperature. The changing amplitude of indoor temperature is smaller than that of the environment temperature due to the existence of building enclosure. The temperature difference between indoor and outdoor when heating is larger than that of cooling and it conforms to the universal resident lifestyle in this region.

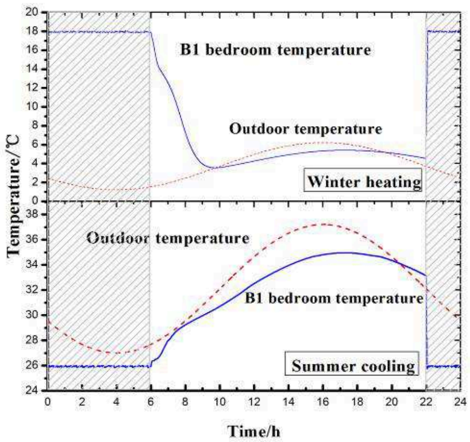


Fig.3 Variations of room B1 indoor temperature and ambient temperature

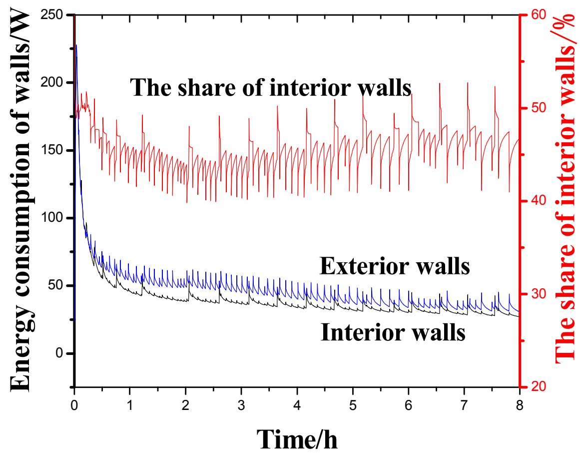


Fig.4 Energy consumption of walls without insulation when cooling

Energy saving effect of wall insulation

The difference of air conditioning daily cooling and heating load in Table 3 can reflect the energy saving effect of different insulation methods. Walls with internal insulation (case 3) could reduce cooling load by 20.5% and heating load by 48.2% compare with walls without insulation (case 1), while exterior wall external insulation (case2) could decrease heating load by 22.7% and increase cooling load by 21.4%. According to this, there exists anti-insulation behavior in exterior wall external insulation when cooling in summer. Results above are similar to those from Masoso and Tummu[6,7].

Table 3Air conditioning load with different wall insulation methods

	Average temperature difference	Case 1	Case 2	Case 3
	℃	MJ	MJ	MJ
Cooling load	2.44	5.6	6.8	4.45
Heating load	16.09	12.35	9.55	6.4

The influence of compartmental energy consuming method

If the air-conditioning system served all part of the building, there will be no heat transfer through interior wall since the air temperature is the same on both sides. The interior walls could be simplified as interior thermal storage mass in buildings. When the building are compartmentally air-condition served, the enclosures of energy consuming room can be divided into two kinds, exterior and interior wall as shown in Fig.1 (a). The boundary condition of convection heat transfer in exterior walls is different with that of interior walls, due to the outdoor and indoor temperature difference. Furthermore, the convective heat transfer coefficients are different between interior wall external surface and exterior wall external surface. Leave out the floor heat flux because both upstairs and downstairs are air condition served and set the same temperature. Therefore, the energy consumption of exterior and interior walls makes up the total enclosure structure energy consumption.

The present wall insulation system in hot summer and cold winter zone was the exterior wall external insulation system which moved from the northern cold and severe cold area. As we can see from Fig.2 that the air temperature in rooms without air-conditioner served is close to the outdoor air temperature both in summer and winter. In extreme set cases, the energy consumption of interior walls accounts for about 70% of the total amount [4]. Therefore, there will be a little practical effect on reducing total energy consumption with the compartmental energy consuming method if only exterior walls are insulated.

The result of static analysis is established on the basis of steady condition and it is a little different with the actual situation. Dynamic analysis on energy consumption of external and interior walls based on the unsteady condition is conducted in this compute model. Dynamic variation of wall energy consumption when cooling in summer night with no insulation can be seen from Fig.4. The energy consumption of exterior and interior walls reached maximum within a few minutes after the air-conditioner are started, and then reduced gradually. It is because the indoor temperature reached the set temperature just within a few minutes and the energy consumption of walls gradually increases with the increasing of temperature difference between indoor air and the walls. After the air temperature reached a constant value, the wall temperature decreased, followed by the gradually reducing of energy consumption of walls. It is clear that the energy consumption of interior walls is a little lower than that of exterior walls, accounts for about 45% of the total energy consumption (Fig.4). There are two interior walls and two exterior walls for bedroom B1, while there is only one or no exterior wall for most of air-conditioner served rooms in actual residential buildings. Besides, there also exist energy consumption in the roof and floor [9], so the share of energy consumption of interior walls may increase and larger than that of exterior walls.

Therefore, only external walls are insulated could not effectively decrease the energy saving effect of buildings in hot summer and cold winter zone with the compartmental energy consuming method. Both exterior and interior walls should be insulated.

The influence of intermittent energy consuming method

The direction of heat flux in walls is unitary and unchanged if air-conditioner was serving all the time. When cooling in summer, heat flow from outside to inside (indoor temperature < wall temperature < outdoor temperature). When heating in winter, the heat flow from inside to outside (indoor temperature > wall temperature > outdoor temperature). In this situation, both external insulation and internal insulation can insulate part of the heat flow to achieve energy saving effect. However, with the intermittent energy consuming method, the direction of heat flow may not be one way and the energy saving effect for external insulation and internal insulation may be different.

Exterior wall temperature variations in different insulation methods when cooling are illustrated in Fig.5. The shaded part is energy consuming period, in which the wall temperature are higher than both the outdoor and indoor air temperature (the set temperature 26℃) no matter with which kind of insulation method. The wall heat flux direction is no longer single direction from outside to inside due to the heat storage of wall. The heat will both dissipate to indoor and outdoor from walls. The outdoor path of heat transfer will be cut off if external side was insulated and the proportion of heat dissipation from wall to indoor air will increase. Whereas, if the internal side of wall was insulated, the indoor path of heat transfer would be cut off. Accordingly, the energy consumption of walls in the three cases with different insulation methods when cooling is quantitatively analyzed (Fig.6).

In Fig.6, there is little difference for energy consumption of interior walls between case 1 (no insulation) and case 2 (exterior wall external insulation), and that of case 3 (all the walls with internal insulation) is relatively lower. The energy consumption of exterior wall is the lowest in case 3, while that in case 2 is the highest. It confirms the qualitative analysis discussed above, which states that there exist anti-insulation behavior in exterior wall external insulation system under this kind of energy consuming method. And the root causes of the anti-insulation behavior are as follows: with the intermittent energy consuming method, the heat storage of walls makes the wall temperature change lags behind outdoor temperature, so that the heat flow direction from walls is no longer single direction. Lower the specific heat of walls can suppress the anti-insulation behavior.

Similarly, exterior wall temperature variations in different insulation methods when heating are illustrated in Fig.7 and the energy consumption of walls are shown in Fig.8. The exterior wall temperature is higher than the outdoor air temperature and lower than indoor air temperature (the set temperature) when heating in winter, no matter with which kind of insulation method. The heat flux in walls is simply from inside to outside. Therefore, both internal insulation and external insulation can effectively resist part of heat flow to achieve energy saving effect. It can also be proved by the energy consumption of walls in the three cases with different insulation methods when heating in winter (Fig.8). The energy consumption of exterior wall in case 2 is much lower than that in case 1 and a slightly higher than that in case3. In the aspect of interior walls, the energy consumption in case 2 and case 1 is nearly the same, while it is the lowest in case 3.

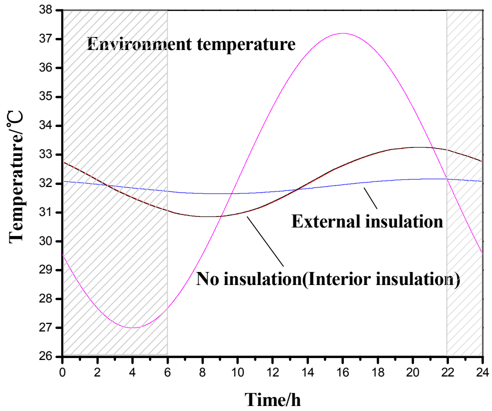


Fig.5 Exterior wall temperature variations in different insulation methods when cooling

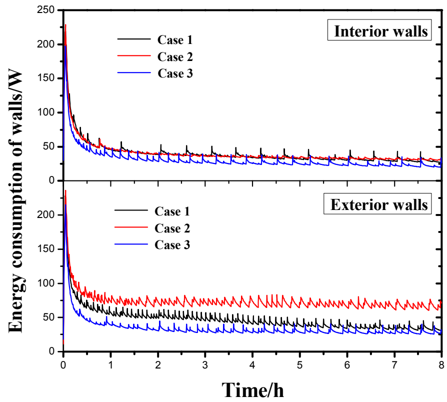


Fig.6 Energy consumption of walls in different wall insulation methods when cooling

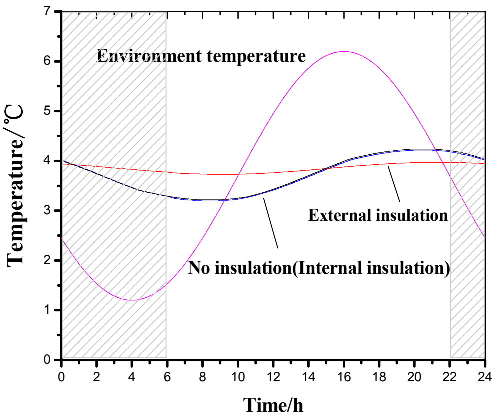


Fig.7 Exterior wall temperature variations in different insulation methods when heating

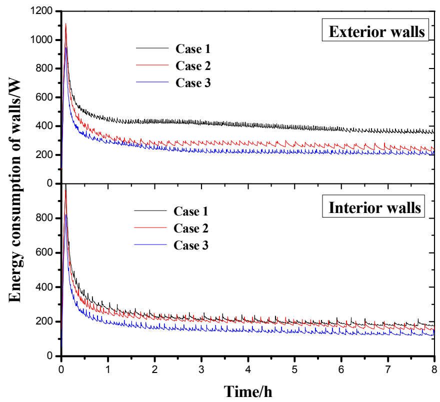


Fig.8 Energy consumption of walls in different insulation methods when heating

Conclusions

With the intermittent and compartmental energy consuming method, the energy consumption of the two interior walls is a little less than that of the two exterior walls, accounting for about 45% of the total energy consumption in one typical day. Both exterior wall insulation and interior wall insulation should be taken into consideration while propelling the building energy efficiency work in this region.

Compare with wall without insulation case, adding internal insulation to all the walls would be effective in reducing cooling load by 20.5% and heating load by 48.2%. Adding external insulation to exterior walls could reduce heating load by 22.7%, but will increase cooling load by 21.4%. There is anti-insulation behavior exist in exterior wall external insulation during summer cooling in hot summer and cold winter zone with the intermittent and compartmental energy consuming method.

With Fluent 12.0，annual cooling/heating load were unlikely to output for the large quantity of calculation. In previous studies, the results of anti-insulation behavior existing in wall insulation are deduced by annual cooling/heating load calculated from the software like DOE - 2.1E and Energy Plus while some other parameters like every second wall surface temperature and heat flux were unable to output. By choosing typical weather day of summer and winter in hot summer and cold winter zone for calculation respectively, the root cause for anti-insulation behavior existing in this climate region could be found.

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