Analysis on the influence of solar radiation on heating load of existing residential buildings in Western Sichuan

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Abstract. The calculation of the solar radiation heat is important to the accuracy of heating load prediction, especially in area with sufficient solar radiation, e.g. western Sichuan in China. However, only a few researches are focused on the specific effects of solar radiation heat in this area. Therefore, based on a practical residential building in Western Sichuan and the survey data, the heating load during the day and night in a heating season under different working conditions are compared in this paper. The influence of solar radiation on the heating load of residential buildings in Western Sichuan is analyzed, and the correctness of the simulation software is verified by experiments. The results show that the solar radiation will greatly increase room base temperature in the daytime. In a heating season, the heating load of the building increases by 26.12% without considering solar radiation heat. During the day (9:00 to 18:00) and night (18:00 to 9:00), the heating load increases by 35.69% and 19.80%, respectively. Besides, solar radiation mainly affects the south exterior wall in a north-south residential building. The heating load of south rooms is 27.52% less than north rooms, with 35.92% less during the day and only 22.08% less during the night.

Keywords: residential building, solar radiation heat, heating season, heating load

1. Introduction
The Western Sichuan Plateau is part of the southeastern margin of the Qinghai Tibet Plateau and the Hengduan Mountains, about 2500~4500 meters above sea level. It is located in cold climate areas. The climate characteristics can be summarized as: cold climate, low humidity, low pressure, high wind speed and strong solar radiation.\cite{1} In the previous experiments, it was found that the room base temperature of some non-heating rooms could reach more than 15 °C in the daytime in winter. This demonstrates that the solar radiation has a great influence on the heating load in this area. So the effects of solar radiation on heat load have a high research value.

For a long time, many scholars have studied the influence of solar radiation and the application of solar heating system. A S El-Asfouri\cite{2}, R Levinson\cite{3}, G Oliveti\cite{4}, Chen B\cite{5} analyzed the influence of solar radiation on thermal performance of building envelope. Govind NK\cite{6}, Xingxing Zhang\cite{7}, Qi Qi\cite{8} made in-depth researches on different forms of solar heating system. In the study of solar radiation in high latitude and cold regions, there are many researches on solar energy applications. Hongmao Wang\cite{9} and Yongtao Ma\cite{10} studied the application of single solar system in these areas. Besides, Runliang Shi\cite{11}, Lei Wang\cite{12}, Zonghe Zheng\cite{13} and Jianguo Cheng\cite{14} studied the application of solar energy combined with other systems in high latitude and cold areas. And Wei Xiao\cite{15}, Xianhui Li et al\cite{16}, Hancheng Yu\cite{17} studied the application of solar house in these regions. However, there are few studies on the specific impact of solar radiation on heating load in high latitude and cold region.

Numerous researchers have studied the solar radiation and its application of the buildings, however, few studies have been done for the influence on solar radiation of buildings, especially in high altitude and cold regions. Therefore, in this paper, DeST software is used to simulate the hourly heating load of solar
radiation in heating season. And the effect of solar radiation on residential buildings in Western Sichuan is researched. It lays the foundation for the research on the application of the solar energy.

2. Theoretical calculation model

2.1. Room load calculation model
Room load includes sensible heat load and latent heat load. Because the room has no wet source and air conditioning fresh air, the heat load only consider sensible heat load in this paper. The calculation of sensible heat load is based on the theory of room air heat balance. According to Reference [18], the mathematical expression of the heat balance equation of room air is in Equation (1):

\[ \sum_{k=1}^{N} f_k \cdot h_{s,k} \left[ t_{n,k}(n) - t_r(n) \right] + [q_1(n) - q_2(n)] + \frac{t_{a(n)}q_1(n) + \psi_{a(n)}q_3(n)}{1 + \frac{t_{a(n)}q_1(n) + \psi_{a(n)}q_3(n)}{1} + q_3(n)} = V \cdot c_p, \rho_r \cdot t_{r}(n) - t_{r}(n-1) \]  

where \( N \) is the number of enclosure structures, \( f_k \) is the inside surface area of the enclosure structure, \( m^2 \). \( h_{s,k} \) is surface convective heat transfer coefficient between inside surface and indoor air, \( W/(m^2 \cdot ^\circ C) \). \( t_{n,k}(n) \) is the inside surface temperature of the enclosure structure at the moment \( n, ^\circ C \). \( t_r(n) \) is the indoor air temperature at the moment \( n, ^\circ C \). \( q_1(n) \) is the convection heat dissipation from lighting, sensible heat of the human body and explicit heat of equipment at the moment \( n, W \). \( q_2(n) \) is the room sensible heat consumed by water evaporation, \( W \). \( L_a(n) \) is the air infiltration at the moment \( n, m^3/h \). \( c_{p,a} \), \( c_{p,\tau} \) are the indoor and outdoor air specific heat capacity, respectively, \( kJ/(kg \cdot ^\circ C) \). \( \rho_r \), \( \rho_a \) are the indoor and outdoor air density, respectively, \( kg/m^3 \). \( t_a(n) \) is the outdoor air temperature at the moment \( n, ^\circ C \). \( q_3(n) \) is air conditioning system sensible heating energy, \( W \). \( V \) is the room volume, \( m^3 \). \( \Delta \tau \) is the time interval, \( s \).

2.2. Solar radiation calculation model
According to Equation (1), \( t_{n,k}(n) \) is the related item after considering the factors such as solar radiation. Moreover, the intensity of solar radiation in Western Sichuan is large, its influence on heating load in winter cannot be ignored. Therefore, the calculation of solar radiation heat is critical. There are many calculation models of solar radiation at present, and this paper uses the solar radiation calculation model in DeST to calculate.

For direct solar radiation, DeST use projection transformation method to calculate the shadow of each surface at first. And then the direct solar radiation of each surface is calculated by combining the direct radiation and the incidence angle at the present time.

For diffuse solar radiation, diffuse radiation from the sky, the ground and the surrounding building surface reflection radiation are considered in DeST. The total diffuse radiation is the sum of three radiations, and the calculation is in Equation (2).

\[ I_{d,t} = I_{d,s} + I_{d,g} + I_{d,b} = \varphi_s I_{s,s} + \varphi_g I_{s,g} + \varphi_b I_{s,b} \]  

where \( I_{d,t} \) is the total diffuse radiation, \( W/m^2 \); \( I_{d,s} \) is diffuse radiation from the sky, \( W/m^2 \); \( I_{d,g} \) is ground reflection radiation, \( W/m^2 \); \( I_{d,b} \) is the surrounding building surface reflection radiation, \( W/m^2 \). \( \varphi_s \), \( \varphi_g \), \( \varphi_b \) are corresponding angular coefficients. \( I_{s,s} \) is the diffuse radiation from the sky of unsheltered horizontal plane, \( W/m^2 \); \( I_{s,g} \) is the total solar radiation of horizontal plane, \( W/m^2 \); \( I_{s,b} \) is the average total reflection radiation of surrounding buildings, \( W/m^2 \).

For solar transmission radiation, DeST uses a universal recursive algorithm [19] based on the energy balance equation to calculate the absorption rate (shown in Equation (3)) of the radiation energy input from the outermost layer to the dielectric layer, so that the solar radiation absorbed by each layer can be calculated.

\[ \xi(K, K-1) = \frac{\varphi_{K-K+1}}{\Delta_1} = \frac{\varphi_{K-K+1}}{\Delta_K} \times \frac{\varphi_K}{\Delta_1} = \xi_{K-K+1} \times \prod_{i=1}^{K-1} (\alpha_i t_{a,i} + i+1) \]  

3. Modeling and analysis

3.1. Survey data in Western Sichuan
According to the actual situation, Kangding (low altitude) and Litang (high altitude) are selected as the research objects for field investigation. The survey results of the local enclosure structure are shown in Table 1.

**Table 1. Survey data of residential building envelope in Western Sichuan.**

| Location | Building Type       | Building Construction                  | Exterior Wall Building Materials    | Exterior Wall Thickness (mm) | Exterior Window Type                                                      | Floor Material  | Insulation measures |
|----------|---------------------|----------------------------------------|-------------------------------------|------------------------------|--------------------------------------------------------------------------|-----------------|---------------------|
| Kangding | Old residential building | Brick concrete structure               | Reinforced concrete (50%)/brick wall (50%) | 260-300                      | Double-layer plastic steel window (over 70%)/Single-layer plastic steel window (under 30%) | Reinforced concrete | None                |
|          | New residential building | Concrete shear wall                   | Reinforced concrete                 | 260-400 (Around 300)         | Double-layer plastic steel window                                        | Reinforced concrete | None                |
| Litang   | Old residential building | Concrete frame wall (over 80%)/Brick concrete structure (under 20%) | Reinforced concrete (over 80%)/brick wall (under 20%) | 280-320                      | Singel-layer window(50%)/Double-layer window(50%)                        | Reinforced concrete | None                |
|          | New residential building | Concrete frame wall                   | Reinforced concrete                 | 200-380 (Around 280-300)     | Double-layer plastic steel window                                        | Reinforced concrete | None                |

Note: the completion time of old residential building is 2000 ~2010, and the completion time of new residential building is 2010. The survey results show that there is little regional difference in the enclosure structure of residential buildings in West Sichuan. The exterior wall materials of the new and old residential buildings are usually concrete blocks with a thickness of about 300mm and without heat preservation. The exterior windows of the building are usually double plastic steel windows and a few are aluminum alloy window frames. As the results of the survey show that the new style is similar to the old style residential building envelope, the new and old buildings in the West Sichuan area after 2000 are not analyzed in the latter simulation.

3.2. Model establishment

A residential building in Kangding is selected as the research object. The area of the building is about 181 m², about 3000m above sea level. There are 3 floors on the ground, 1 storey is restaurant, 2nd and 3rd floors are residential rooms. It has no basement, and the floor heights are 3m. Because this paper studies residential buildings, it only analyzes 2 and 3 storey. The standard floor plan is shown in Figure 1.

![Fig.1 2 storey plan of residential building in Western Sichuan](image)

![Fig.2 The testing value and simulation value of the room base temperature of the room 2-5](image)

3.3. Boundary conditions of simulated building

The outdoor meteorological parameters are taken from the standard or DeST’s databases, and the enclosure structure is selected according to the survey data in Table 1. The thermal parameters are shown in Table 2. In high altitude area, the physical parameters of the air change greatly due to the low atmospheric pressure. According to the heat transfer theory, the surface convection heat transfer coefficient of the enclosure structure changes greatly. Therefore, the surface heat transfer coefficient is determined according to the Equations (4) ~ (7) \(^{[15]}\). Other parameters are set according to the standards.
Table 2. Enclosed structure thermal parameters of simulation building.

| Enclosure type     | Material and thickness                                     | Heat transfer coefficient (/W/(m² · K)) |
|-------------------|------------------------------------------------------------|----------------------------------------|
| Exterior wall      | Cement mortar 20mm, reinforced concrete 250mm, lime mortar 20mm | 2.773                                  |
| Interior wall      | Cement mortar 20mm, porous concrete 200mm, cement mortar 20mm | 1.308                                  |
| Floor slab roof    | Cement mortar 25mm, reinforced concrete 100mm, cement mortar 20mm | 2.944                                  |
| Outside window     | Plastic steel window frames, double-layer, 3mm thick ordinary glass, air layer 9mm | 2.449                                  |
| Door               | Monolayer solid wood door                                  | 2.4                                    |

\[
h_{in} = 0.282 \left( \frac{\rho^2 \Delta t}{l} \right)^{\frac{1}{6}} + 1.131 \left( \frac{\rho^2 \Delta t}{l} \right)^{\frac{1}{3}}, \quad 10^9 < GrPr < 10^{12}, \quad \text{Vertical wall}
\]

\[
h_{in} = 1.614 \left( \frac{\rho^2 \Delta t}{l} \right)^{\frac{1}{3}}, \quad 8 \times 10^6 < GrPr < 1.5 \times 10^9, \quad \text{Horizontal wall with hot surface upward}
\]

\[
h_{in} = 0.643 \left( \frac{\rho^2 \Delta t}{l} \right)^{\frac{1}{4}}, \quad 10^5 < GrPr < 10^{10}, \quad \text{Horizontal wall with cold surface upward}
\]

\[
\bar{h}_{out} = \frac{\rho_0 0.023 \lambda T_0^{0.891}}{l} l^{-0.109} d l = 0.0258 \lambda T_0^{0.891} L^{-0.109}
\]

Note: the indoor air temperature for heating room is 18 °C, and for non-heating room is 3 °C. (very small items are neglected)

3.4. Correctness verification

3.4.1 Boundary conditions of Actual building

The outdoor meteorological parameters are input according to the measured values, and the residential plan is shown in Figure 1. The actual enclosure structure of the residence is shown in Table 3, with a building facing 25° west to south.

Table 3. Enclosed structure thermal parameters of actual building.

| Enclosure type     | Material and thickness                                     | Heat transfer coefficient (/W/(m² · K)) |
|-------------------|------------------------------------------------------------|----------------------------------------|
| Exterior wall      | North wall                                                 | 3.276                                  |
| Interior wall      | The others                                                  | 2.095                                  |
| Floor slab roof    | Cement mortar 20mm, heavy mortar clay 240mm, cement mortar 20mm | 1.761                                  |
| Outside window     | Plastic steel window frames, double-layer, 6mm thick ordinary glass | 4.503                                  |
| Door               | Monolayer solid wood door                                  | 2.4                                    |

3.4.2 Experimental test

This experiment takes room 2-5 and 3-2 as the test object. During the test, the indoor disturbance of the test was accurately recorded. Indoor disturbance mainly includes three categories: personnel, lighting and equipment. The tested room temperature, adjacent room temperature, outdoor air temperature and humidity were measured by the self recording instrument of temperature and humidity, and the air velocity are measured by temperature and humidity self-recording instrument. The inside surface temperature of enclosure structure and infiltration air velocity are measured by the infrared thermometer and hot ball anemometer, respectively.

3.4.3 Comparison between simulation and testing values

Input the relevant information to DeST. The testing value and simulation value of the room base temperature of the room 2-5 are shown in Figure 2. The calculation value (according to Equation (1)) and simulation value of the heating load of the room 3-2 are shown in Figure 3.
Fig. 2 shows that the simulation temperature is gradually consistent with the actual natural temperature from the third day. Because of the different wall heat storage before the experiment, the testing temperature is larger than the simulation temperature at the beginning. As the influence of the heat storage weakened with time, the gap gradually becomes smaller. According to the calculation of relative error, from 12 pm in the fourth day, the largest relative error appears at 19 pm in the fourth day (11.9%). And for most of the time, the relative error is less than 10%, which can meet the requirements of engineering application. It means that the parameter setting is correct. Fig. 3 shows that the simulation value and calculation value are quite different at first because of the different wall heat storage, too. But the change law of the two is almost the same. And the gap gradually becomes smaller with time, the final relative error is about 6%. Therefore, the DeST software calculation model can be applied to the load calculation in Western Sichuan.

4. Analysis of simulation results
By changing the orientation of buildings, solar radiation and other parameters, the influence of solar radiation on existing residential buildings in West Sichuan is analyzed. According to the standard, combined with the actual situation, the heating season is unified from November 15th to March 15th for a total of 120 days.

4.1. Influence of solar radiation on room base temperature
Take the south room 2-2 as the research object. The room base temperature during heating season in two working conditions (whether or not consider the solar radiation) is shown in Figure 4.

Figure 4 indicates that considering the solar radiation, the room base temperature is greater than that of the other condition. Moreover, the solar radiation is positively correlated with the difference of room base temperature between the two working conditions. Besides, when the solar radiation is greater than 600W/m², the room base temperature can be kept above 8°C. And when the solar radiation is greater than 800W/m², the room base temperature can be kept above 10°C.

4.2. Influence of solar radiation on building heating load
4.2.1 Influence of solar radiation on total heating load of building
Comparing the simulation values in two working conditions (whether or not consider the solar radiation), the simulation values of heating energy are shown in Tables 4 and 5. The hourly loads of north rooms (room 2-1 to 2-4) and south rooms (room 2-6 to 2-8) from January 30th to February 1st are shown in Figures 5 and 6.

Table 4. Rooms and building heating energy in heating season.

|                   | North rooms | South rooms | The whole building |
|-------------------|-------------|-------------|--------------------|
|                   | Before the change | After the change | Before the change | After the change | Before the change | After the change |
| Heating energy / (kW·h) | 8391.81     | 10856.97    | 4431.03            | 6202.44         | 40097.98         | 50577.16         |
| More than before the change /% | 29.38       | 39.98       | 26.12              |                 |                 |                 |

Table 5. Building heating energy in the daytime and nighttime in heating season.

|                  | Daytime heating energy | Nightime heating energy |
|------------------|------------------------|-------------------------|
|                  | Before the change | After the change | Before the change | After the change |
| Heating energy / (kW·h) | 15992.25     | 21699.14    | 24105.73         | 28878.02        |
| More than before the change /% | 35.69        | 19.80       |                 |                 |

Note: Before the change means considering the solar radiation and after the change means no considering the solar radiation.

Tables 4 and 5 show that solar radiation is converted into heat directly through the window in the daytime, and the solar radiation mainly relies on wall heat storage to provide heat to the building in the nighttime. So the heating load increase ratio in the daytime is greater than that in the nighttime if solar radiation is not considered. Figures 5 and 6 demonstrate that the greater the solar radiation is, the greater the increase in daytime hourly heating load is when the solar radiation is not considered. Among them, the influence of solar radiation on the south rooms is more obvious than that on the north rooms.

To further analyze the effect of solar radiation on the heating load of south rooms, take room 2-7 as an example. Figure 7 shows the hourly loads of room 2-7 under 3 conditions from January 30th to February 1st. According to the calculation, the original room window to wall ratio is about 0.25. And according to the standard, take the Kangding energy-saving building south window to wall ratio as 0.5. The figure indicates that when the window to wall ratio as is 0.5, the hourly heating load during the day is much lower. Therefore, increasing the window to wall ratio within a certain range can significantly reduce the heating load of residential buildings in Western Sichuan.

4.2.2 Influence of solar radiation on heating load of different number of external walls
Room 2-2 (a room with one exterior wall) and room 2-1 (a room with two exterior walls) are compared in this paper. The area of the two room is the same by adjusting the parameters, and the area of south exterior wall of the room 2-1 is the same as that of the room 2-2. The simulation values of heating energy per unit exterior wall of the two rooms in the heating season are shown in Tables 6 and 7.
The hourly load of the building increases by 26.12% without considering solar conditions. In the daytime and nighttime, the heating load increases by 35.69% and 19.80%, respectively. This means the south exterior wall is affected little by the solar radiation. Thus, the solar radiation has no direct influence on the heating load of different number of exterior walls, and the outdoor air temperature is also one of the main factors.

### 4.3. Influence of solar radiation on heating load of different orientation rooms

Change the orientation of the building, the room facing the north (room 2-1 to 2-4) is turned south. The simulation values of the rooms in the heating season are shown in Table 8. The hourly loads under two conditions from January 30th to February 1st is shown in Figure 8.

**Table 8. Room heating energy in heating season.**

| Heating energy / (kW \cdot h) | Daytime heating energy Before the change | After the change | Nighttime heating energy Before the change | After the change | Total heating energy Before the change | After the change |
|------------------------------|--------------------------------------|-----------------|----------------------------------------|-----------------|--------------------------------------|-----------------|
| Heating energy / (kW \cdot h) | 3301.86                              | 2115.92         | 3966.21                               | 3966.21         | 8391.81                              | 6082.13         |
| Less than before the change /% | 35.92                                | 22.08           | 27.52                                  |                 |                                     |                 |

Note: Before the change the room is toward the north and after the change means the room is toward the south.

Table 8 shows that the heating load in the heating season decreased by 27.52% after changing the room orientation, and the heating load in the heating season decreased by 35.92% in the daytime, which’s rate is more than that in the nighttime (22.08%). Figure 8 indicates that from 8:00 am to 14:00 pm, the reduction ratio of the heating load gradually increased after the change. From 14:00 pm to 8:00 am the next day, the reduction ratio of the heating load gradually decreased after the change. Besides, the change reduction ratio of the heating load in the nighttime is more slow than that in the day after changing the orientation.

### 5. Conclusion

The heating load during the day and night in a heating season under different working conditions are simulated with DeST in this paper, and the simulation values are verified by experiments. The impact of solar radiation on heating load in different conditions is analyzed in this paper, and the conclusions arising from this study are summarized as follows:

1. Solar radiation will greatly increase the room base temperature. When the solar radiation is greater than 800W/m², the room base temperature can even be kept above 10 °C. Therefore, for some areas with high solar radiation in Western Sichuan, residential buildings may even have no heating load during the day.
2. In Western Sichuan, solar radiation is an important parameter affecting the thermal load of the enclosure structure. The heating load of the building increases by 26.12% without considering solar radiation. In the daytime and nighttime, the heating load increases by 35.69% and 19.80%, respectively.

### Table 6. Heating energy per unit exterior wall of the two rooms

| Heating energy per unit exterior wall / (kW \cdot h/m) | Room 2-1 | Room 2-2 |
|------------------------------------------------------|----------|----------|
| Larger than room 2-1 /%                              | 361.40   | 382.89   |

### Table 7. Heating energy per unit exterior wall of the two rooms in the daytime and nighttime in heating season

| Heating energy / (kW \cdot h/m) | Daytime heating energy | Nighttime heating energy |
|---------------------------------|------------------------|--------------------------|
| Room 2-1                         | 146.92                 | 214.48                   |
| Room 2-2                         | 150.87                 | 230.02                   |
| Larger than room 2-1 /%          | 2.69                   | 7.25                     |

Note: heating energy per unit exterior wall = heating energy / length of exterior wall.

Tables 6 and 7 show that the heating energy per unit exterior wall of room 2-2 is 5.95% larger than that of room 2-1, with 2.69% larger in the daytime and 7.25% larger in the nighttime. This means the non-south exterior wall is affected little by the solar radiation. Thus, the solar radiation has no direct influence on the heating load of different number of exterior walls, and the outdoor air temperature is also one of the main factors.
Therefore, residential buildings in Western Sichuan should consider increasing window to wall ratio in a certain range to increase solar radiation heat and reduce heating load.

(3) The influence of solar radiation on the heating load of is mainly related to the area of the south exterior wall, but has little to do with the number of external walls.

(4) For typical residential buildings in Western Sichuan, the heating load of the south rooms is 27.52% less than that of the north rooms. Among them, the heating load of south rooms is 35.92% less in the daytime and only 22.08% less in the nighttime than that of north rooms. Therefore, the heating rooms of residential buildings in West Sichuan should be set to the south if possible.

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