Research on the thermal performance of SAC-HVIW system under the influence of solar transmission and local radiant heater

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Abstract. Solar air collector (SAC) combining with hollow ventilated interior wall (HVIW) system is a new type of energy-saving and environmentally friendly heating system. In engineering applications, it will be affected by solar transmission and local radiant heat sources (external heat gain), but these factors have not been considered in previous studies. In this paper, the series connection of HVIW simplified heat exchange unit model is used to improve the original thermal network of the SAC-HVIW building, and experimental verification is carried out. Results show that the temperature deviation of the air cavity and the wall surface calculated by the model are all within 10%, which can be used for the external heat gain calculation of HVIW. Then, in order to research the influence of the intensity of external heat gain and the position of action on the thermal process of HVIW, seven cases of simulation calculation were designed. Results show that when the external heat gain is the same but the acting position is different, it has little effect on the minimum and fluctuation of the indoor air temperature (all within 0.1°C). However, the change of external heat gain has obvious influence on the minimum temperature. When the external heat gain of cases are 136W and 900W, the corresponding minimum temperature are about 0.5°C and 3.5°C higher than the cases of 82W, respectively.

1. Introduction
In the "Code for Thermal Design of Civil Buildings" [1], the Qinghai-Tibet Plateau is basically in severe cold or cold regions. With the improvement of life, energy consumption in the area is also increasing sharply. Taking Tibet as an example, the per capita energy consumption has increased from 1.17 tons of standard coal in 2010 to 2.86 tons of standard coal in 2020 [2]. China has pledged to reach its peak carbon emissions around 2030 [3]. It urgently needs to be replaced by clean energy represented by solar energy.

SAC-HVIW is a solar heat utilization system that uses SAC to actively store heat during the day and HVIW to passively release heat at night, as shown in Fig. 1.
Fig. 1. Principle of SAC-HVIW system [4]

Our previous research [4-7] has shown that the system can significantly improve indoor temperature, comfort and reduce heating energy consumption at night. Model calculations showed that the indoor air temperature rises by 6.2°C on average, while the minimum temperature rises by 5.8°C [4]. During the non-ventilation period, the heat release rates of the three experimental cases were 43.5%, 43.8%, and 48.0%, which is conducive to improving the indoor thermal environment at night [5]. Experiments showed that the radiant heat transfer of HVIW accounts for more than 60% [6]. The night energy consumption during the entire heating period can be reduced by 79.9% [7].

However, all research results [4-7] showed that only relying on the SAC-HVIW system for heating still cannot keep the indoor temperature in all periods (especially in the early morning) within the heating design requirements, so there is a situation where the auxiliary heat source is turned on during some periods. Meanwhile, most buildings in the Qinghai-Tibet Plateau spontaneously adopt a south-facing large window-to-wall structure, which constitutes a direct benefit solar house [8] and causes a severe disturbance to the indoor dynamic thermal environment by the solar energy. Solar transmission and intermittent auxiliary heat sources (external heat gain) act on HVIW, which will make the indoor thermal environment more complicated due to changes in its storage and thermal processes.

Since the SAC-HVIW system is a new system, there is no direct reference when studying the influence of external heat gain, but other research results can be referred.

First of all, reliable calculation tools are necessary. The research results showed that EnergyPlus, DOE-2.1E, IDA-ICE and TRNSYS can be used for solar transmission calculation, but the model and calculation process are time-consuming [9, 10]. The author used the thermal network model to establish a building calculation model without considering the transmission of the solar on the HVIW in literature [4], and proved its good accuracy. A. K. Athienitis [11, 12] improved the RC calculation model, which can be used to simulate the floor radiant system with the influence of the solar energy.

Regarding the impact of solar transmission, a large number of studies have shown that the solar transmission will cause overheating of the area irradiated by the solar [10-14]. With regard to the influence of intermittent auxiliary heat sources, Wang [15, 16] established an RC dynamic heat transfer model and experimentally verified that the model error is within 0.5°C. Wang et al. [17] found that the heating load caused by the inner wall accounted for more than 65% of all.

In summary, a large number of research results have been made on the SAC-HVIW heating system, the influence of solar transmission, and the intermittent heating, but there are few studies on the coupling effects of the above thermal processes. In this paper, considering the influence of the solar transmission and the uneven distribution of the auxiliary heat source on the SAC-HVIW storage and heat release characteristics and the indoor thermal environment, the calculation model in the previous results [4] has been improved. Then, on the basis of this, the research on the adjustment mechanism of HVIW thermal process and room temperature by external heat gain is carried out.
2. Simulated model
In this section, by improving the thermal network calculation model of literature [4], it can satisfy the
calculation of external heat gain to the SAC-HVIW thermal process, and the reliability of the improved
model is verified through experiments.

2.1 Studied building

In reference [4], a thermal network model was used to establish a calculation model of a three-room
building without considering the transmission of the solar on the HVIW. The model consisted of the
solar air collector model, the hollow ventilated interior wall model and the room and enclosure structure
model, as shown in Fig. 2. The input parameters of the model include the ambient temperature, the solar
radiation intensity, and the air flow velocity in the HVIW. The output includes the hourly temperature
of the interior and exterior walls and air flow channels of the HVIW, the hourly heat storage and release
of HVIW, the heat collection and efficiency of SAC, the hourly indoor temperature, the temperature of
each wall in the room, and so on.

2.2 Improved model for HVIW with external uneven heat coupling
The internal heat gain of HVIW comes from warm air heated by SAC. When the solar transmission or
radiant heat source irradiates a local area of HVIW, this part of the area also has external heat gain. The
overall heat storage and release process of HVIW depends on the coupling of each small part of HVIW
both internal and external heat gain. Since the flow of the warm air in HVIW is a tortuous and serpentine
flow along the air channel, in order to study the influence of the inhomogeneity of external heat gain on
the HVIW, the entire HVIW can be divided into "n" small pieces along the flow direction of warm air.

Fig. 3 is a schematic diagram of a series of simplified heat exchange units of HVIW. HVIW is
composed of "n" simplified heat exchange units connected in series. Each small HVIW simplified heat
exchange unit is used as an independent heat exchange surface, and the warm air outlet of the i-th
simplified heat exchange unit is used as the warm air inlet of the i+1th unit. The thermal units all use
the RC coupled NTU model of reference [4]. The warm air inlet of the first simplified heat exchange
unit at the beginning of HVIW is the outlet temperature of SAC. The warm air outlet of the final n-th
simplified heat exchange unit of HVIW is the inlet temperature of SAC. Then, the thermal process when
different areas of HVIW are affected by the solar transmission or the uneven heat coupling action of the
auxiliary heat source can be calculated through the HVIW simplified heat exchange unit model.
2.3 Validation of the improved model
In order to verify the reliability of the model, experiments are carried out. In the experiment, an electric heating film is used to represent the external heat gain on the HVIW, and the installation position is shown in Fig. 4.

By changing the circulation air flow rate, SAC heating capacity, as well as the heating power and heating method of the electric heating film (intermittent start and stop), 10 dynamic tests that simulate practical applications are carried out.

Fig. 4. Installation position of electric heating film.

Fig. 5 shows the results of a case with the largest deviation of temperature between the experiment and the calculation for the air in HVIW cavity. The relative error of the outlet air temperature of all series simplified heat exchange units is within 5%.

Fig. 5. Comparison of air temperature at each measuring point.

Fig. 6. Comparison of interior wall surface temperature at each measuring point.
Fig. 6 shows the comparison between experimental and calculated about HVIW’s surface temperature of the 4th and 5th units, where the temperature of HVIW changes drastically. The maximum deviation of the outlet air temperature of the 4th unit is 1.8 °C at 9:34, and the relative error is 7.7%. The maximum deviation of the output air temperature of the 5th unit is -1.3°C at 16:52, and the relative error is -3.2%.

All experimental results show that the error between the model calculated and the actual measured of air temperature and wall temperature at each point is within 10%, so it can be used to calculate.

3. Results of simulation

In this section, model calculations are used to analyze the influence about heating and acting position of solar transmission and radiant heater on the SAC-HVIW system and the indoor thermal environment.

3.1 Calculation model

The building in the literature [4] of Ganzi Prefecture of China is still selected for the analysis, and the same meteorological parameters are used as well. The building structure is shown in Fig. 7, and the south-facing window-to-wall ratio of the building is 0.19.

3.2 Analysis of the influence of external heat gain

According to the analysis of solar radiation, the maximum solar transmission in the room in Fig. 6 is 272W throughout the day. Considering the use of reflective shutters and other architectural components, it is believed that the proportion of the solar transmission on the HVIW can be adjusted. For the situation that the radiant heat is unevenly distributed on the HVIW throughout the day, 7 cases are analyzed. The operation parameters and main results are shown in Table 1.

| Case | Heat source | Acting on the position of HVIW | Power (W) | minimum indoor air temperature (°C) | Indoor air temperature fluctuation (°C) |
|------|-------------|-------------------------------|-----------|-------------------------------------|----------------------------------------|
| 1    | Solar       | Top                           | 82        | 14.2                                | 2.5                                    |
| 2    | Solar       | Middle                        | 82        | 14.2                                | 2.5                                    |
| 3    | Solar       | Bottom                        | 82        | 14.3                                | 2.5                                    |
| 4    | Solar       | Top                           | 136       | 14.8                                | 2.6                                    |
| 5    | Solar       | Bottom                        | 136       | 14.9                                | 2.6                                    |
| 6    | radiant heater | Top                          | 900       | 17.7                                | 2.4                                    |
| 7    | radiant heater | Bottom                       | 900       | 17.6                                | 2.3                                    |

In Table 1, Results show that when the external heat gain is the same but the acting position is different, it has little effect on the minimum and fluctuation of the indoor air temperature (all within 0.1°C). However, the change of external heat gain has obvious influence on the minimum temperature.
When the external heat gain of cases are 136W and 900W, the corresponding minimum temperature are about 0.5°C and 3.5°C higher than the cases of 82W, respectively.

It can be seen in Fig. 8 that when 50% of the solar transmission is allocated to the HVIW, the indoor temperature is about 0.5°C higher than that of 30% throughout the day. Since the window-to-wall ratio of this calculation model is only 0.19, as the window-to-wall ratio in the actual project increases or the solar radiation intensity at the location of the project increases, the HVIW will get more solar transmission heat (Fig. 9). The hourly indoor temperature will also increase more (for example, cases 6 and 7).

![Fig. 8. Hourly indoor temperature of each case.](image)

![Fig. 9. Accumulated heat storage of HVIW](image)

For cases 1 to 5 where the external heat gain of the HVIW is little, the minimum indoor air temperature when acting on the bottom of the HVIW (the end of the warm air process) is slightly better than acting on other positions. Comparing the same case in Fig. 8, Fig. 9 and Fig. 10 at the same time, when the SAC outlet temperature in Fig. 10 is higher, the heat storage of this case in Fig. 9 is lower, corresponding to the indoor temperature in Fig. 8 is also lower. This is because the higher the SAC outlet temperature, the higher the heat loss in the SAC and the lower the heat collection efficiency.

According to Fig. 9, the reason is that the external heat gain of HVIW caused by radiant heater in cases 6 and 7 occurred at night. The heat storage by HVIW at night from the radiant heater is too large, which is not conducive to storing heat from SAC during the day (from 1:00 at night to 9:00 in the morning, the corresponding accumulated heat storage rises from 180KJ to 4200KJ). However, in cases 6 and 7 where the external heat gain is large, the minimum indoor air temperature when acting on the bottom of the HVIW is slightly worse than that at the top. Because when the directional heat storage is concentrated at the bottom of the HVIW, the outlet air temperature of the HVIW will be higher, resulting in a decrease in the heat storage of SAC-HVIW during daytime working hours.
In this calculation, HVIW is divided into 18 units along the air flow. According to Fig.8, the minimum indoor air temperature in all cases occurred at 9:30 in the morning, and the maximum occurred at 17:00 in the afternoon. Fig. 11 shows the exterior surface temperature of 18 units along the air flow at 9:30, and Fig. 12 at 17:00. It can be found that the higher of the average temperature about the exterior surface of the entire HVIW, the higher indoor temperature at the corresponding moment. There is an increase of temperature at the location where the external heat gain. The greater the heat, the greater of the temperature increase. Where there is no influence of external heat gain, the temperature of the exterior surface decreases along the air flow.
4 Conclusions
The SAC-HVIW system applied to the Qinghai-Tibet Plateau will be affected by the solar transmission and heater. In this paper, the influence of the above factors is studied through the improved model of a building thermal network in Ganzi Prefecture, and some important conclusions are summarized as follows:

1) The series connection of SAC-HVIW system simplified heat exchange unit and improved RC thermal network model can calculate the influence of solar transmission and auxiliary heat source. The experimental results prove that the error rate of all air outlet temperatures is within 5%, and the wall error rate is within 10%.

2) When the external heat gain is the same and acting on different positions of the HVIW, there is little difference between the lowest indoor air temperature and the temperature change throughout the day (about 0.1°C). When the solar transmission heat of 82 W and 136 W are distributed to the HVIW, the difference is 0.5~0.6°C, and the maximum difference is 3.5°C when there is a 900W locally acting radiation type intermittent heat source.

3) Under the same external heat gain, the SAC outlet temperature increases, while the heat storage capacity and the corresponding indoor temperature decrease.

In general, the amount of heat applied by the solar transmission and the local radiant heat sources has a greater impact on the thermal performance of the SAC-HVIW system, while the location of the action has less impact on it. In the future, it is necessary to develop a SAC-HVIW system heating control strategy based on solar transmission and local radiant heat sources, which is an effective way to improve indoor thermal comfort and reduce heating energy consumption. In addition, the applicability of this new system needs to be further studied.

Acknowledgments
This research work was financially supported by the Sichuan Science and Technology Program (grant No. 19ZDYF0452).

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