Study on aluminum honeycomb plate solar air collector and its building heating potential in western Sichuan

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Abstract. In this paper, the efficiency of aluminum honeycomb plate solar air collector has been analyzed through both experimental and theoretical methods, followed by a study on the applicability of using honeycomb plate solar air collector in western Sichuan. Solar energy on building vertical wall has been investigated firstly, then the solar heating potential of building facades in three representative regions of western Sichuan has been computed. Lumped parameter method was used to simulate dynamic heating capacity of the collector. The results indicated that aluminum honeycomb plate solar air collector has a relatively large heating potential in western Sichuan.

Keywords: honeycomb plate solar air collector; western Sichuan solar resources; solar heating potential

1. Introduction

According to the statistics, in 2015 the domestic building energy consumption has accounted for 27.5% of total social energy consumption [1]. Heating energy consumption will continue to grow rapidly along with the improvement of living standard and the rising heating demand. Solar air heating technology is a convenient alternative of tradition heating system since building heating requires low-grade thermal energy and solar energy can exactly provide this type of power [2]. Solar air collector, as the main form of solar air heating technology, is simple in structure, easy to install, high in efficiency and therefore worth investigating and promoting. A new type of solar air collector system that introduced a honeycomb plate for enhancing heat transfer is studied, its efficiency is estimated through both experiments and numerical modeling. Its dynamic performance is examined under weather condition of western Sichuan for the purpose of analyzing heating potential of the aluminum honeycomb plate solar air collector.

2. Experimental methods

The experiment was carried out in Chengdu, on the roof of a residential building in Wuhou District. The structure of the collector used in this experiment is shown in Figure 1. The collector is composed of four sections, thermal insulation layer, wooden structural box, aluminum honeycomb core and transparent cover plate (the PC sun board). The aluminum honeycomb is fixed in the middle position of the channel.
as a part of the flow-path, the aperture of the honeycomb hole is 6mm, and the depth of the honeycomb hole is 10mm. The collector has an air inlet and an outlet on the back of the box, which are used for connecting the collector with indoor space and hence circulating air through the collector to heat the room. A radiometer is placed in parallel with the collector panel to measure solar radiation intensity. In order to record airflow velocity, a hot wire anemometer is placed in the center of the inlet and outlet, with its probe in the direction of airflow. Air circulation is mechanically driven by a fan placed at the inlet, providing wind speed that increases from 2m/s to 5m/s by an interval of 0.5m/s. During the experimental period, wind speed of the outdoor environment ranges from 0.15m/s to 1.3m/s, the average is 0.4m/s. Ambient temperature varies form 35℃ to 38℃, the relative humidity is approximately 55%, and solar radiation intensity is 700-800w/m².

In order to study the actual working condition of the collector, temperature distribution and variation of the airflow are measured and recorded by using several thermocouples. Temperature sensing points are arranged both inside the inlet and outlet air duct and at the center of the air channel. The efficiency of aluminum honeycomb collector can be calculated once the inlet-outlet temperature difference is confirmed.

3. Mathematical modeling
Mathematical model of the collector is built on the basis of energy conservation during heat transfer process. As shown in Figure 2, the mathematical model of aluminum honeycomb solar air collector is mainly divided into three parts: thermal insulation, aluminum honeycomb core and transparent cover. The heat transfer process inside the collector is discussed by identifying absorbed and released heat of each section individually (detailed formulas are not presented in this paper). Next, heat balance equations are established to summarize the general process and hence to build up the mathematical model for simulating working condition of the collector. Assume that the heat transfer process between various parts of the collector is steady, the air is incompressible Newton viscous fluid and airflow is uniform and stable. Airflow velocity through each honeycomb hole is assumed to be consistent. Since temperature variation range of the collector is small, it is assumed that the physical parameters of each part are constant.

Heat balance equations of PC sun board, first channel, aluminum honeycomb core, second channel and thermal insulation backboard are established respectively and listed below.
Heat balance equation of PC sun board:

\[ S_{pc} = q_{\text{rad pc-ah}} + q_{\text{rad pc-b}} + q_{\text{rad pc-out}} + q_{\text{con pc-f1}} + q_{\text{con pc-out}} \]  

where \( S_{pc} \) is the solar radiation absorbed by the PC sun board, \( q_{\text{rad pc-ah}} \) is the radiation heat transfer between PC sun board and aluminum honeycomb; \( q_{\text{rad pc-b}} \) is the radiation heat transfer between PC sun board and thermal insulation backboard; \( q_{\text{rad pc-out}} \) is the radiation heat transfer between PC sun board and external environment; \( q_{\text{con pc-f1}} \) is the convection heat transfer between PC sun board and the first channel; \( q_{\text{con pc-out}} \) is the convection heat transfer between PC sun board and external environment.

Heat balance equation of first channel:

\[ q_{f1} = q_{\text{con pc-f1}} \]  

where \( q_{f1} \) is the heat gain of the first channel; \( q_{\text{con pc-f1}} \) is the convection heat transfer between PC sun board and the first channel.

Heat balance equation of aluminum honeycomb core:

\[ S_{ah} = -q_{\text{rad pc-ah}} - q_{\text{rad b-ah}} + q_{\text{con ah-f2}} \]  

where \( S_{ah} \) is the absorption of solar radiation by aluminum honeycomb core; \( q_{\text{con ah-f2}} \) is the convection heat transfer between PC sun board and the second channel; \( q_{\text{rad b-ah}} \) is the radiation heat transfer between aluminum honeycomb core and thermal insulation backboard.

Heat balance equation of second channel:

\[ q_{f2} = q_{\text{con b-f2}} + q_{\text{con ah-f2}} \]  

where \( q_{f2} \) is the heat gain of the second channel; \( q_{\text{con b-f2}} \) is the convection heat transfer between thermal insulation backboard and the second channel; \( q_{\text{con ah-f2}} \) is the convection heat transfer between aluminum honeycomb and the second channel.

Heat balance equation of thermal insulation backplate:

\[ S_{b} = q_{\text{rad b-pc}} + q_{\text{rad b-ah}} + q_{\text{con b-f2}} + q_{\text{con b-out}} \]  

where \( S_{b} \) is the solar radiation absorbed by the thermal insulation back plate; \( q_{\text{rad b-pc}} \) is the radiation heat transfer between thermal insulation backboard and PC sun board; \( q_{\text{rad b-ah}} \) is the radiation heat transfer between thermal insulation backboard and aluminum honeycomb; \( q_{\text{con b-f2}} \) is the convection heat transfer between thermal insulation backboard and second channel; \( q_{\text{con b-out}} \) is the convection heat transfer between PC thermal insulation backboard and external environment.

4. Experimental and mathematical results

Experimental results are shown below in Figure 3 and Figure 4. It can be seen in Figure 3 that the temperature of the inlet keeps relatively stable, while the temperature of the outlet presents a decreasing trend as the flow velocity increases. As a result, the efficiency of the collector increases with the rising of wind speed. When wind speed is 2m/s, the efficiency is 62%. When the speed is 5m/s, the efficiency reaches as high as 79%.
In order to get the numerical simulation results more accurately, the initial conditions of the simulation are taken from the experimental measurements. Solar radiation intensity is 700W/m\(^2\) and the ambient wind speed is 0.4m/s. Similar to the experiment, this paper takes the efficiency of collector and the air temperature of the outlet as the research object in the simulation, and carries out the computation of the mathematical model with flow velocity 0-10m/s through MATLAB programming.

Figure 4 shows the simulation results, it can be seen that the outlet temperature of the collector reduces, and the efficiency increases continuously with the rising of flow rate. Maximum efficiency is 83% and the minimum outlet temperature is 40\(^\circ\)C at 10m/s. Simulated efficiency agrees well with the value obtained from experiment results, with an average error of about 3%. It is proved that the mathematical efficiency calculation model of the collector proposed in this paper is effective and reliable.

5. Heating potential of aluminum honeycomb collector in western Sichuan

In the plateau regions of Sichuan, which are mainly distributed in western part, solar radiation level is much higher than the basin regions due to less clouds blocking. Furthermore, the sunshine in autumn and winter is relatively stronger than that in spring and summer, and the total radiation in most western Sichuan areas is as much as 4500 MJ/m\(^2\)~6400 MJ/m\(^2\)[3]. The weather condition provides a suitable environment of applying solar air collectors for building heating purpose. Therefore the application performance of aluminum honeycomb solar air collector is examined under these conditions.

We select three typical cities of western Sichuan, Xichang, Jiulong, Ganzi, and build a room model for simulating the actual performance of introducing aluminum honeycomb solar air collector as its heating system. Assume the collector operates at the attainable highest efficiency from the study above.

5.1 Physical model

Assume that the room is in standard heating floor, heating load is only caused by south exterior wall and windows and air infiltration, while the solar energy source of the collector also only comes from south exterior wall (window excluded). The outer layer of the wall is made of clay bricks with cement mortar plastering on both sides, the floor is reinforced concrete. In addition, the external wall is equipped with a polyethylene foam insulation layer, and a hollow double-layer structure is used for the outer window. All interior walls of the room and upper and lower floors are treated as an insulated boundary along their center lines. Structural dimensions of the building envelope are shown in Table 1.
According to heat balance principle, the volume of room,

\[ V = \tau \times \sum (V_i \rho_i C_i + V_f \rho_f C_f) (t_i^\tau - t_i^{\tau-1}) \]  

where \( V \) is volume of room, \( V_i \) is volume of wall, \( \rho \) is density of the wall, \( C_i \) is heat capacity of wall, \( t_i^\tau \) is indoor temperature at time \( \tau \), \( t_i^{\tau-1} \) is indoor temperature at time \( \tau - 1 \), \( V_f \) is Floor volume, \( \rho_f \) is density of floor, \( C_f \) is Floor heat capacity.

Wall and floor heat loss \( \Delta U \):

\[ \Delta U = \sum (V_i \rho_i C_i + V_f \rho_f C_f) (t_i^\tau - t_i^{\tau-1}) \]

where \( V_i \) is the volume of wall, \( \rho_i \) is the density of wall, \( C_i \) is heat capacity of wall, \( t_i^\tau \) is indoor temperature at time \( \tau \), \( t_i^{\tau-1} \) is indoor temperature at time \( \tau - 1 \), \( V_f \) is floor volume, \( \rho_f \) is density of floor, \( C_f \) is floor heat capacity.

Time-varying heat consumption:

\[ Q_1' = k_1 A_1 (t_i^\tau - t_o^\tau) \]  
\[ Q_2' = 0.287 C_p V \rho_w (t_i^\tau - t_o^\tau) \]  
\[ Q_3' = l' A_2 \sigma (t_i^\tau - t_o^\tau) \]

where \( Q_1' \) is the basic time-varying heat consumption of the envelope, \( Q_2' \) is the time-varying heat consumption of air penetration, \( Q_3' \) is the time-varying heat consumption of window, \( t_o^\tau \) is outdoor temperature at time \( \tau \), \( A_1 \) is outdoor structure area, \( K_1 \) is the total heat transfer coefficient of building envelope, \( C_p \) is the specific heat capacity of dry air, \( \rho_w \) is the density of air, \( V \) is the volume of room, \( A_2 \) is the area of window, \( \sigma \) is the transmissivity of glass.

According to heat balance principle, (7) - (11) is written together as:

\[ Q_1' + Q_2' + Q_3' + \Delta U = Q_s \]  

5.3. Results of solar air collector heating potential dynamic analysis
From November 1st to March 15th is assumed to be the heating period in this section in order to discuss the influence of the heat collection area on the indoor temperature. In final analysis, suitable area of solar air collectors that satisfy the residential indoor heating design condition in "Public Building Energy Efficiency Design Standards is discussed consequently. The design condition requires room temperature keeps above 18℃ (comfortable heating temperature). It can be seen from Figure 5, Figure 6, and Figure 7 that 3m² of heat collector can meet the heating needs of the three districts of Sichuan.

![Figure 5. Xichang’s heating dynamic analysis.](image1)

![Figure 6. Jiulong’s heating dynamic analysis.](image2)

![Figure 7. Ganzi’s heating dynamic analysis.](image3)

6. Conclusion
The new type of aluminum honeycomb plate solar air collector has been tested both experimentally and numerically, and the result verifies its high efficiency as up to 80%. For the actual room case studied in this paper, the collector shows good performance in energy conservation through dynamic heating potential analysis. With the continuous optimization and improvement of the solar collector technics, aluminum honeycomb plate solar air collector has revealed its considerable potential in the application aspect in western Sichuan.

7. References
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