Research on Application of Solar Air Heating in Buildings of Villages in Northern China—Based on Experimental Study

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Abstract. In this paper, a test bench was built to study the thermal performance of three typical air collectors. Based on the test data, this paper conducted a comprehensive study on the physical and economic performance of the solar air heating systems including indoor temperature, solar energy guarantee rate, investment payback period and life cycle cost, and gave recommendations for their applications. The research showed that under the specified air flow rate range, the efficiency of the three typical collectors all reached above 45%. When the flow rate increased twice, the efficiencies of the V-groove collector, S-type spoiler collector, seams penetration collector were increased by 16%, 20%, 19%, respectively. This research recommended the ideal flow rate for solar air heating in China was 36 m³/(h.m²) ~ 54 m³/(h.m²). The simulation results in 15 typical cities showed that the solar energy guarantee rate was generally above 20%, and in more than half of cities the solar energy guarantee rate reached 30% or above, with the highest in Lhasa, reached 62%. Economic analysis indicated more than 70% of the cities in northern China have a simple payback period of less than 6 years. The results indicated that solar air heating technology not only has a wide range of adaptability but also yield great financial benefits in northern China. This paper will have a significant impact on guiding the application of solar air heating in rural areas of China.

1. Introduction

In recent years, environmental issues in northern China have been increasingly raised by the government. At the end of 2017, one national plan about clean heating was promulgated by several government departments in China [1]. The action was mainly aimed at phasing out coal-fired heating plant in northern China, and utilized more clean heating sources in the area. A major challenge in the vast rural areas is how to solve the heating problem. Therefore, the development of clean heating methods with good economic benefits, encouraging and guiding the application of clean energy heating in villages is of utmost importance in solving the problems of rural heating regions of China. According to the solar energy resources distribution [2], the severely cold and cold areas in China are mainly in the I, II, and III areas based on solar energy resources, most of them are in the region II, with considerable solar heating potential.

The core technology of solar air heating system is to optimization the thermal performance while reducing the first cost of the system. Gama et al. [3] theoretically described and analyzed the influence of various parameters of the V-shaped groove heat absorbing core on the heat collection efficiency, and discussed ways to improve the thermal performance of the collectors. Gao et al. [4] obtained the optimal geometric parameters of the corrugated plate collector through numerical simulation. Moummi et al. [5]
studied the method to enhance the heat transfer of the collector is studied. The results indicated that adding fins can significantly improve the heat efficiency of the collector. Zheng et al. [6] from Tianjin University studied the dynamic thermal performance of the metal corrugated solar air collectors and the transparent cover solar air collectors in cold regions of China. The results indicated the ideal air flow rate should be lower than 45 m3/h in solar air heating system. Yeh and Ho [7] investigated the thermal efficiency of a double pass external recycle heat collecting plate with fins. The research provided a new method for optimizing the collector thermal performance. Das et al. [8] found that the thermal efficiency of the sand coated absorber collector was improved up to 17% compared with the plain absorber. Wang et al. [9] studied on solar air heater with S-shaped ribs. The research showed that the thermal efficiency of a roughness plate collector can be improved by 13% to 48% compared with a smooth plate. Singh et al. [10] found that there exist optimum roughness parameters at which the exergetic efficiency of the discrete V-down rib collector reaches the highest for a given Reynolds number. Fiuk and Dutkowski [11] found that the maximum thermal efficiency for Waveshaped Type I collector with wavelike baffles was 73.8%±3.4% at mean irradiance I=756 W/m². Hu et al. [12] designed a self-driven mechanical ventilated solar air collector with the average thermal efficiency can be as high as 49.2 %. In order to improve the total heat gain of the device, some scholars have developed phase change heat storage device integrated with the collector. Charvát et al. [13] investigated the effect of phase change materials on improving the thermal performance of air collectors through lab experiments and computer simulations.

The current research on solar air collection focused mainly on the shape and the surface coating optimization of the heat-absorbing elements, the improvement of the heat transfer performance, and the decrease of airflow resistance during operation. These analysis findings pointed to the direction of an experimental research on thermal performance of solar air collector.

Solar air heating technology has been widely used all around the world, especially in Europe, America and Japan, and has cumulated rich experience and good results. The formulation of foreign solar air heating technical standards and the construction of demonstration projects have promoted the application of the technology. Within the last 20-30 years Japan has built over 25,000 OM Solar homes [14]. OM Solar homes feature a south-facing roof which is hollow, allowing air heated by the sun to circulate inside. Hastings [15] published "Solar Air Systems-A Design Handbook" in 2000 based on the research results of solar air heating under the framework of IEA TASK19, this handbook guided architects and engineers through the process of designing and selecting and optimizing of the six active solar systems. Hastings [16] compiled "Solar Air Systems-Built Examples" in 2013 which documented the work of 17 experts from the diverse climates of nine countries in Europe and North America. Applications included commercial buildings, gymnasiums, apartment buildings, schools, single-family houses, and large industrial buildings.

In the research and development of solar air heating technology, experts and scholars around the world have done a lot of research in recent years. Gao and He [17] studied the effects of a new flat plate solar air collector system (SACS) with metallic heating panels on the heating effect in kindergarten, finding that the average temperature raise rate nearly 15% and the temperature was about 10°C higher than outdoor air. Chen et al. [18] studied the thermal efficiency of a multi-surface air collector with double-receiver tubes integrated into a greenhouse heating system and found that this equipment satisfied the heat load from 11% to 81%. García-Valladares et al. [19] investigated a direct solar air heating system for greenhouse. The overall energy efficiency of the air heaters was 39.39% with the air temperature increased by more than 30°C over the ambient. Wang et al. [20] proposed a combined solar hybrid inlet air heating system with cycle power plant to improve the space heat capacity in winter. Zhao et al. [21] put forward a solar kang system combined with solar air heating system to meet the heating demand in north China. The result showed that the indoor air temperature could keep at above 18°C and Kang surface temperature can keep above 26°C during the night time. Slimani et al. [22] introduced a collector that simultaneously uses air and water as a cooling system. The experiments showed that the daily efficiencies of Bi-fluid dual-flow air collector was 69.08 %. Touaba et al. [23] invented a new collector used waste engine oil as absorber and heat transfer fluid, and adopted a solar tracking system
to maximize efficiency. Slimani et al. [24] analyzed energy performance of a hybrid PV/T collector which was suitable for air conditioning in a building in cold period. Yu et al. [25] combined hollow ventilated interior wall with solar air collector in residential buildings on Tibetan Plateau to increase indoor environment. Results showed that this system increased the air temperature by 6.5 °C and 3.2 °C with night energy needs reduced by 79.9% and 60.7%, respectively. Choudhury and Baruah [26] found that modular designs of solar air heating in terms of efficiency or maximum output energy could benefit the need of users from different economic levels or regions. Al-damook and Khalil [27] investigated the unglazed solar air collector (UTC) experimentally and theoretically under western Iraq climate conditions and found that the UTC is effective to reduce life cycle cost and offers higher energy savings compared with the traditional solar collector, an electric heater, or fuel-fired heating systems. Fan et al. [28] embedded phase change materials into the air medium evacuated tube collectors (ETCs), found that the energy efficiency of solar hot air heating system can reach 70.6% compared to pure electric heater. This kind of hot air heating system was more suitable for application in the western plateau area of China. Agathokleous et al. [29] presented an air solar collector prototype. The primary energy savings achieved by the proposed system against the traditional buildings ranged between 1.9 and 8.0 MWh/y. In Naples the payback period was equal to 6.2 years.

In summary, most of current studies on improving the performance of solar air collectors worldwide mainly focus on these aspects: changing the flow channel form (adding a spoiler, or using a special-shaped flow channel (V-type or S-type)); optimizing the heat exchange mode (surface convection or permeation type) of air and heat absorbing core or improving the air flow rate. Some other studies focused on changing the geometric characteristics of the collector, such as the aspect ratio or the thickness of the air layer, and changing the insulation performance of the collector and so on. Theses diversified researches have provided a wide range of thinking space for later researchers and promoted innovation and application in this field. In terms of investigations on solar air heating systems, the mainstream researches are just focusing on individual projects, using solar air heating technology to solve specific problems, such as improving the thermal comfort of single-family rural houses or solving greenhouse heating problems. There is a lack of universal research on technology, and the economic cost of technology is rarely discussed. However, the economic characteristic of technology often determines the application prospects of technology. Therefore, the research in this paper aimed to make up for the deficiencies of the above studies. This paper selected several widely used collectors. Through experimental tests, the relationship between collector efficiency and normalized temperature difference was given, and the relationship between collector efficiency and flow rate was studied. The research conclusions provided data support for the system design of solar air heating. Based on test data, this paper established a simulation platform to study the heating effect of air collectors under different climatic condition from two aspects of energy saving and technology economy. The research indicated that solar air heating technology had obvious energy-saving effects and good economic benefits in northern China. This technology has a wide range of adaptability and promotion value in severe cold and cold regions of China.

2. Research method

In this study, an experimental platform for the performance testing of the heat collecting components was established to obtain the performance parameters of the solar collectors. This paper selected three representative types of air collectors for this experiment, and then compared the test results with the simulation results from the TRNSYS platform using the same operation condition to verify the performance of the heat collector components in Trnsys. The verified TRNSYS computing platform was used to simulate the solar heating effectiveness in typical rural places in different climate regions. As the final research results, this paper evaluated the adaptability of the solar air direct heating technology in the severe cold and cold regions of northern China based on economic and technical implication.

When the cold air flows into the collector, it is heated up by convection from the absorbing plate. The thermal efficiency(\(\eta\)) is used to evaluate the thermal performance of the solar collectors which can
be calculated by Eq. (1). It is the ratio of the heat gain to the amount of solar radiation projected onto the surface of the test piece as a key indicator to quantize the thermal performance.

$$\eta = \frac{\rho \dot{V} c_p (T_{out} - T_{in})}{I A}$$  (1)

Where: $\eta$ is the thermal efficiency based on the lighting area; $\rho$ is the air density, kg/m$^3$; $c_p$ is the specific heat capacity of the air, J/(kg·°C); $\dot{V}$ is the air flow, m$^3$/s; $T_{out}$ is the outlet temperature of the collector, °C; $T_{in}$ is the inlet temperature, °C; $I$ is the solar irradiance density, W/m$^2$; $A$ is the lighting area of the collector, m$^2$.

The thermal efficiency can be expressed by the efficiency equation, see equations (2) ~ (3).

$$\eta = \eta_0 - U T^*$$  (2)

$$T^* = \frac{T_{in} - T_a}{I}$$  (3)

Where: $\eta_0$ is the intercept of the efficiency equation, dimensionless; $U$ is the heat loss coefficient of the collector (obtained by data fitting), W/(m$^2$·°C); $T^*$ is the normalized temperature (m$^2$·°C)/W; $T_a$ is the ambient temperature, °C; for the remaining parameters, see equation (1) above.

The solar energy guarantee rate is introduced to measure the contribution of solar heat gain to the total heating energy consumption, and the calculation method is as follows:

$$g_r = \frac{Q_S}{Q_T}$$  (4)

Where, $g_r$ is the solar energy guarantee rate; $Q_S$ is the total heat provided by the solar collector in the heating season, kWh; $Q_T$ is the total heat consumption in the heating season of the building, kWh.

### 3. Experiment setup

This paper investigated three typical types of air collectors commonly used in China at present: V-groove air collectors, S-type spoiler plate collector, and seams penetration collector. The main parameters of the three components are as follows.

**Table 1. Characteristic parameters of collectors**

| Item    | V-groove air collectors                  | S-type spoiler plate collector          | Seams penetration collector            |
|---------|-----------------------------------------|----------------------------------------|---------------------------------------|
| core    | Black V-shaped heat sink                | Black S-shaped spoiler                  | Slotted permeable orifice plate        |
| size    | 2000 mm×1000 mm×160 mm                   | 2000 mm×1000 mm×180 mm                 | 2000 mm×1000 mm×140 mm                |
| detail  | The width of a single v-groove is 150 mm, the height is 75 mm, and the top Angle is 90 °. | The distance between the black plate and the glass cover is 20mm, with 100mm high baffle on the black of plate. | A total of 22 rows of slotted holes, 6 holes in each row, The small hole is 80mm long and 2.5mm wide |
| profile | Figure 1                                | Figure 2                               | Figure 3                             |
| photo   |                                        |                                        |                                       |

**Figure 1. V-groove collector profile**
The thermal performance of the three kinds of solar collectors were tested according to “method of testing to determine the thermal performance of solar collectors ASHRAE standard 93-2003” [30] and “test method for thermal performance of solar collector” (GB/T4271-2007) [31]. The schematic diagram of the thermal performance test system of the solar air collector is shown in Figure 4, and the photo of testbed is shown in Figure 5. The air flow rate was measured using a vortex flow meter with an accuracy of ±1% and a resolution of 0.01 m³/h. The inlet temperature, outlet temperature and ambient temperature were measured by thermocouple thermometers with an accuracy of ±0.1 ℃. The inlet and outlet pressure of the collector was measured by differential manometer. A pyranometer was used to measure the solar radiation intensity with accuracy of ±5 W/m². According to the relevant standards and the above evaluation indexes, the test parameters and the description of required equipment were determined as shown in table 2. The latitude of about 40° in Beijing area is used as the typical slope of collector.

### Table 2. Description of required equipments

| Instrument                  | Range         | Accuracy | Uncertainties |
|-----------------------------|---------------|----------|---------------|
| Pt100 thermal resistance    | -25°C~100°C   | ±0.75%   | ±3.9%         |
| Pyranometer                 | 0~2000W/m²    | ±5%      | ±4.3 W/m²     |
| Vortex flow meter           | 50~500m³/h    | ±2.5%    | ±0.36%        |
| Differential manometer      | 0-100 hpa     | ±0.1pa   | ±5.1pa        |
| Tape ruler                  | 0-3000mm      | ±1mm     | ±0.5mm        |

Jacek Jan Fiuk detailedly described the calculation method for uncertainty of heat collection efficiency of air collector the level of uncertainty can be calculated using method proposed by (Kline and Mcclintock, 1953) [32]. In general, uncertainty of value X can be expressed as:

\[
\omega_X = \left[ \frac{\partial X}{\partial y_1} \omega_{y_1} \right]^2 + \left[ \frac{\partial X}{\partial y_2} \omega_{y_2} \right]^2 + \ldots + \left[ \frac{\partial X}{\partial y_n} \omega_{y_n} \right]^2 \right]^{1/2}
\]

(5)

where \( y_1, y_2, \ldots, y_n \) are variables affecting the value of X and \( \omega \) stands for uncertainty. So according to formula 1 in this article, the uncertainty of thermal efficiency can be calculated as follow:

\[
\omega_\eta = \left[ \left( \frac{\rho \cdot V_p \cdot \Delta T}{A} \omega_p \right)^2 + \left( \frac{\rho \cdot V_p \cdot c_p \cdot \Delta T}{A} \omega_{c_p} \right)^2 + \left( \frac{V_p \cdot p \cdot \Delta T}{A} \omega_{p \cdot \Delta T} \right)^2 + \left( -\frac{\rho \cdot V_p \cdot c_p \cdot \Delta T}{A^2} \omega_A \right) \right]^{1/2}
\]

(6)

After calculation, the uncertainty of the collector's thermal efficiency is about ±4.4%.
Figure 4. Composition of solar air collector performance testbed

The performance testbed included an electric heating device which could achieve 0~100% output adjustment of electric heating power at the forefront of the entrance section in the experiment platform. The inlet air temperature of the solar collector was adjusted by the PID temperature controller. The fan speed was adjusted by the inverter to achieve different air volume flowrate conditions.

Figure 5. Photo of solar air collector performance testbed

During the experiment, the inlet air temperature was controlled by adjusting the output power of electric heating device. The inlet temperature was controlled to be 10 ℃, 15 ℃, and 20 ℃ respectively. The air flowrate was controlled to be 72 m³/h, 108 m³/h, and 144 m³/h. Thus, the thermal performance at different inlet temperatures and different air flow conditions could be obtained by this testbed.

4. Experiment results

It can be seen from the experimental data that the instantaneous efficiency of solar air collector is in a linearly relationship with the normalized temperature difference (Equation 2). As shown in Figure 6 to Figure 8, under the specified air flowrate range, the intercept efficiency of the three components all reached above 45%. As the flow rate increased, the efficiency increased. When the flow rate was doubled, the intercept efficiency of the V-groove collector is increased by 15.5%; the intercept efficiency of the S-type spoiler collector was expanded by 19.98%, and the intercept efficiency of the seams penetration collector was increased by 19.33%.
Figure 6. Efficiency equation of V groove collector

Figure 7. Efficiency equation of S-type spoiler plate collector

Figure 8. Efficiency equation of seams penetration collector

Through the efficiency equation curve, the thermal efficiency of the collectors under any inlet
temperature, any outdoor temperature, and any solar irradiation intensity could be obtained. For example, when the operating flow rate is 72m$^3$/h, the component inlet temperature is 14 ℃, the outdoor temperature is 3.6 ℃, and the solar radiation intensity is 800W/m$^2$, the thermal efficiency of the three typical collectors are 35.90% (V-shaped groove collector), 38.83% (S spoiler plate collector), and 42.45% (seams penetration collector) respectively. The research results show that the seams penetration collector exhibited the best thermal performance under the same conditions.

Figure 9. Thermal performance at different flow rates

Figure 9 shows the influence of the air flow rate on the thermal efficiency. As the flow rate increased, the thermal efficiency improved. The flow rate had a more significant effect at the lower flow rate state. When the flow rate increased from 40 m$^3$/h to 268 m$^3$/h, the thermal efficiency of V groove collector increased from 33.40% to 48.5%, the S-type spoiler plate collector increased from 35.2% to 54.1%, and the seams penetration collector increased from 39.2% to 58.5%.

Figure 10. The temperature difference at different flow rates

Figure 10 shows the influence of the air flow rate on the temperature difference between the inlet and outlet when the inlet temperature was 15 ℃. As the flow rate increased the temperature difference decreased. The flow rate had a more significant effect on the temperature difference at lower flow rate state. When the flow rate increased from 40m$^3$/h to 268 m$^3$/h, the temperature difference of the V groove collector reduced from 27.6 ℃ to 5.9 ℃; the temperature difference of the S-type spoiler plate collector reduced from 29.1 ℃ to 6.7 ℃, with seams penetration collector reducing from 32.4 ℃ to 7.2 ℃.

According to analysis above, the operating air volume flow rate of the collectors per unit area was
recommended to be 36 m$^3$/h·m$^2$—54 m$^3$/h·m$^2$, which can basically ensure the temperature difference under normal weather conditions greater than 15 ℃. The temperature meets the requirements of hot air heating in China. In this flowrate range, the thermal efficiency of the V-groove collector, S-type spoiler plate collector and seams penetration collector were about 34.9%—40.5%, 37.9%—43.3%, 41.6%—46.9% respectively. The research conclusions provided a calculation basis for the design of air heating systems using these types of collectors.

5. Application of solar air heating in rural buildings in north China

5.1. Model verification

The rural residential buildings in the severe cold and cold areas of northern China are mainly single-story buildings. In this study, the Sanheyuan was selected with the layout shown in Figure 11. The building area was 148 m$^2$. At present, the rural external walls have basically been implemented with energy-saving renovations to meet the energy conservation requirements. The main parameters of the building are shown in the table below. The simulation zone layout is shown in Figure 12.

![Figure 11. Rural courtyard layout](image)

| Envelope          | Wall (W/m$^2$K) | Roof (W/m$^2$K) | Ground (W/m$^2$K) | Window (W/m$^2$K) | Window to wall ratio | Air change |
|-------------------|-----------------|-----------------|-------------------|-------------------|----------------------|------------|
| Cold              | 0.65            | 0.5             | 1.5               | 2.6               | 0.4(S)0.3(E/W)       | 0.5        |
| Severe cold       | 0.5             | 0.4             | 1.0               | 2.2               | 0.4(S)0.3(E/W)       | 0.5        |

The operating strategy of solar air heating system was as follow: During the daytime, when the outdoor irradiance was greater than 100 W/m$^2$, the solar heating system was turned on to heat the room. If the indoor temperature could not reach 15 ℃, the auxiliary heat source began to work. When the solar irradiance was less than 100W/m$^2$, the system worked in night mode. In this mode, when the indoor temperature could not reach 15 ℃, the duty boiler was turned on to supply hot air to the room. Both the auxiliary heat source and the duty boiler adopted on-off control, with an accuracy of ±1 ℃. The simulation system diagram is shown in Figure 13.
The parameters of the solar air collector model in the TRNSYS software mainly include the solar absorption coefficient of the heat absorption plate, the comprehensive heat transfer coefficient of the flow channel, the long wave radiation coefficient to space, the long wave radiation coefficient of the back plate, and the thermal resistance of the frame. Through the appropriate setting of these parameters, the performance of the air collector module of the TRNSYS platform can be made consistent with the test result of the samples.

**Figure 13.** TRNSYS simulation platform

The deviation between the experimental and the simulated value

Figure 14 shows the deviation between the experimental value and the simulation value. It could be seen that by adjusting the parameters of the air collector module in TRNSYS, the simulated value and the measured value were close. The maximum deviation between the two value was 3.21% (same irradiance density, inlet temperature and outdoor temperature), which was less than 5%. The result proved that the thermal performance of the adjusted TRNSYS module was close to the test sample. So the TRNSYS platform could be rational to conduct the simulation in typical cities to study the climate
adaptability of solar air heating technology.

5.2. Climate adaptability of solar air heating

In this paper, the seams penetration collector was applied to simulate the heating effectiveness in typical cities in China. For severe cold areas, the heating seasons were set from October 15 to April 15 of the following year, which in total are 6 months, while for cold areas, the heating season were set from November 1 to March 31 of the following year, 5 months in total. The slope of the collector was set to the local latitude.

Taking Beijing as an example, as shown in Figure 15, during the whole heating season, the temperature of the west bedroom was above 15 °C (when the floor area was 30 m² and air collector area was 6 m²). The ambient temperature and the west bedroom temperature are shown in Figure 16 below. When the solar irradiance was very good, the heat provided by the air heating system was sufficient to maintain the indoor temperature above 15 °C, therefore meeting the indoor thermal comfort requirements.

![Figure 15. Western bedroom temperature and outdoor temperature](image)

The heat collection from the solar collector in the west bedroom was 1270.4 kWh, the auxiliary heat source supplied 505.2 kWh, and the duty boiler's heat supply was 1829.5 kWh. The cumulative solar radiation in the collector plane during the heating season was 3786.1 kWh. The energy consumption results are shown in Figure 16.

In this paper, 15 representative cities in northern China were selected for calculation. The distribution is shown in Figure 17, including 7 cities in severe cold areas and 8 cities in cold areas. These parameters including the heat gain of the collectors, the heat consumption of the auxiliary heat source, the duty boiler energy consumption and the total solar radiation were calculated. The average indoor temperature in the heating season and the monthly average outdoor temperature in December were counted. The calculation results are listed in table 4.

![Figure 16. Hourly heat supply and cumulative energy consumption](image)
Figure 17. Typical city distribution map

Table 4. Building heat consumption and indoor and outdoor temperature statistics

| Cities     | Solar heat gain(kWh/m²) | Auxiliary heat(kWh/m²) | Heat at night(kWh/m²) | Total radiation(kWh/m²) | Average outdoor temperature in Dec.(℃) | Average indoor temperature(℃) |
|------------|-------------------------|------------------------|-----------------------|-------------------------|----------------------------------------|-----------------------------|
| Qiqihar    | 53.10                   | 24.37                  | 99.53                 | 155.63                  | -15.88                                 | 14.73                       |
| Harbin     | 38.73                   | 38.90                  | 115.93                | 130.80                  | -14.83                                 | 14.61                       |
| Shenyang   | 46.33                   | 25.98                  | 69.77                 | 133.33                  | -7.50                                  | 15.57                       |
| Urumqi     | 30.86                   | 39.17                  | 95.80                 | 104.80                  | -9.50                                  | 14.41                       |
| Hohhot     | 52.70                   | 25.93                  | 75.40                 | 151.43                  | -8.90                                  | 15.11                       |
| Al tai     | 41.60                   | 28.77                  | 110.50                | 127.83                  | -12.94                                 | 14.55                       |
| Xining     | 62.27                   | 16.04                  | 57.60                 | 165.27                  | -6.30                                  | 15.28                       |
| Beijing    | 42.35                   | 15.53                  | 60.90                 | 127.33                  | -0.67                                  | 15.28                       |
| Lanzhou    | 28.56                   | 28.14                  | 74.67                 | 99.40                   | -3.12                                  | 14.22                       |
| Lhasa      | 69.87                   | 4.92                   | 37.70                 | 193.37                  | -0.57                                  | 16.43                       |
| Jinan      | 33.70                   | 15.53                  | 53.53                 | 100.70                  | 1.30                                   | 15.53                       |
| Shijjazhuang| 28.24                  | 23.24                  | 63.90                 | 92.93                   | -0.89                                  | 14.58                       |
| Xi'an      | 23.14                   | 24.05                  | 61.57                 | 77.43                   | 1.33                                   | 14.98                       |
| Yinchuan   | 47.97                   | 19.12                  | 70.77                 | 134.67                  | -5.43                                  | 15.25                       |
| Taiyuan    | 38.27                   | 22.44                  | 69.70                 | 110.37                  | -2.21                                  | 14.56                       |

The four indicators in the table above are counted as the heat per unit heating area during the entire heating season.
Figure 18. Solar energy guarantee rate and average thermal efficiency in typical cities

As shown in Figure 18, in the severely cold and cold areas of China, the solar energy guarantee rate of each city is consistent with the average thermal efficiency change of the collector in the heating season. The guarantee rate was generally higher than 20%. More than half of the cities were higher than 30%, the highest guarantee rate reached 62.11% in Lhasa. In cities with low solar energy guarantee rate, on the one hand, the total solar radiation in the heating season is low, and on the other hand, the outdoor temperature in the heating season is relatively low. For example, the guarantee rate of Urumqi was 18.61%, which is the lowest. The total solar radiation in Urumqi was only 104.8 kWh/m², which is only 69.2% of Hohhot. However, Hohhot's solar energy guarantee rate was as high as 34.21% under the condition that the average outdoor temperature did not differ much. The correlation analysis of the data shows that the solar energy guarantee rate is related to the local solar radiation density and ambient temperature. The regression analysis result is shown below. The comparison between simulated value and fitted value is shown in Figure 19.

\[ g_r = 0.004Q_U + 0.013T_Y - 0.106 \quad (R^2=0.974) \]  

(7)

Where, \( g_r \) is the solar energy guarantee rate; \( Q_U \) is the total solar radiation per unit heating area; \( T_Y \) is the typical monthly average temperature in heating season (this article uses the average temperature in December). The comparison chart of the \( g_r \) obtained by calculation and regression is as follows.
The guarantee rate of solar air heating in villages and towns in China is linearly related to the local irradiance and the average outdoor temperature. Solar air heating technology has universal adaptability in China's severe cold and cold regions. The guarantee rate of Qiqihar in the northeast severe cold region, Xining in the northwest severe cold region, Lhasa in the plateau region, Jinan in the east cold region, and Taiyuan in the mountainous region could reach nearly 30% or above. Especially in the Qinghai-Tibet Plateau, the guarantee rate exceeded 60% because of the abundant solar energy resources.

An economic analysis was performed to study the economics of the solar air heating technology. One way is to examine the life cycle cost of the technology. It can be calculated by the Equations (8).

\[ C = A_C \cdot \frac{[1+(i)^n-1]}{i(1+i)^n} + P \]

where \( C \) is the life cycle cost, RMB; \( P \) is the initial cost, RMB; \( A_C \) is the annual operating cost, RMB; \( n \) is the life cycle year; \( i \) is the discount rate, this article uses the bank commercial loan interest rate of 4.6%. The design lifecycle of the solar air collector is 15 years. Annual operating cost should consider the annual investment and the benefits of technology application. In this paper, the heat gain of the solar collector is the benefit, which is converted to electricity fee saving.

The simple payback period method is also used to assess the returnability of the technology, the calculation method is as follows:

\[ B = \frac{P}{R} \]

Where, \( B \) is the simple payback period; \( P \) is the initial cost, RMB; and \( R \) is the annual net income from solar air heating. The annual cost and benefit should be considered at the same time.

In this system, when the air collector runs, the fan consumes electricity. The annual operating cost should consider the fan power consumption and the energy saving by the solar collector which bring economic benefits. The auxiliary energy is electrical energy. The air collector saves the power consumption, which is equivalent to electricity costs reduction. The current electricity price in rural area in China is about 0.52 yuan/kWh, and the heating area of the west bedroom is 30 m²; the collector area is 6 m²; the manufacturing cost of the collector system is 2430 yuan, and the installation cost is 500 yuan. The power of pipe fan is 80 W with a rated air volume of 265 m³/h. The TRNSYS platform calculated the fan power consumption. The calculation results are as follows.

\[\text{Figure 20. Economic benefits of typical cities}\]
Figure 20 shows that more than 70% of the cities in northern China had a static payback period of less than 6 years, and the economic benefits were considerable. In Lhasa, Xining, Qiqihar, Hohhot and other regions rich in solar energy, the static payback period was less than 4 years. The value of promotion and application is great. The use of solar air collectors lead to lower operating costs and produce significant energy savings. From the perspective of the whole life cycle, it has good economic benefits.

6. Conclusion
This paper first collected the experimental results for three representative solar air collector to derive the thermal efficiency equations of the systems and then used these data to calibrate the efficiency of the solar collector module in TRNSYS to evaluate the cost effectiveness of this environmental friendly technology in providing space heating in rural area in northern china.

The main conclusions are as follows:

1) Through the experimental tests, the efficiency equation of three typical air collectors were obtained. The equation can be used for future design of a solar air heating system.

2) The research indicated that the thermal efficiency increases as the air flow rate increases. When the air flow rate increases from 40 m$^3$/h to 268 m$^3$/h, the thermal efficiency of the V groove collector increases from 33.4% to 48.5%; and the S-type spoiler plate collector increased from 35.2% to 54.1%, the seams penetration collector increased from 39.2% to 58.5%. The recommended operating air volume of the collector per unit area is between 36 m$^3$/h.m$^2$ – 54 m$^3$/h.m$^2$.

3) In the 15 representative cities, the solar energy guarantee rate was generally higher than 20%, and more than half of cities reach 30% or above, with the highest in Lhasa, reaching 62.11%. The solar energy guarantee rate is linearly related to local solar radiation density and ambient temperature.

4) The life cycle cost and the simple payback period are strongly correlated to the local solar energy resources. More than 70% of the cities in northern China have a simple payback period of less than 6 years, In Lhasa, Xining, Qiqihar, Hohhot and other regions rich in solar energy, the simple payback period are less than 4 years.

This research indicates that the application of solar air heating technology in rural areas of northern China has great energy-saving potential with fast payback period and therefore should be considered for future deployment on a large scale.

Abbreviations

- $\eta$ the thermal efficiency based on the lighting area;
- $\rho$ the air density, kg/m$^3$;
- $c_p$ the specific heat capacity of the air, J/(kg·℃);
- $V$ air flowrate, m$^3$/s;
- $T_{out}$ outlet temperature of the collector, ℃;
- $T_{in}$ inlet temperature of the collector, ℃;
- $I$ the solar irradiance density, W/m$^2$;
- $A$ the lighting area of the collector, m$^2$;
- $\eta_0$ the intercept of the efficiency equation;
- $U$ the heat loss coefficient of the collector, W / (m$^2$·℃);
- $T^*$ the normalized temperature (m$^2$·℃)/W;
- $T_a$ ambient temperature, ℃;
- $g_r$ solar energy guarantee rate;
- $Q_S$ total heat provided by the solar collector in the heating season, kWh;
- $Q_T$ total heat consumption in the heating season of the building, kWh;
- $Q_U$ total solar radiation per unit heating area; kWh/m$^2$;
- $T_T$ typical monthly average temperature in heating season, ℃;
- $C$ the life cycle cost, RMB;
- $P$ the initial cost, RMB;
- $A_c$ the annual operating cost, RMB;
- $n$ the life cycle year;
- $i$ the discount rate, 4.6%;
- $B$ The static payback period;
- $R$ the annual net income from solar air heating.
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