Reflector Design and Performance Verification Analysis for Solar Vacuum Tubes

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Abstract

Against the backdrop of limited fossil energy sources and rapidly growing global demand, solar energy, as a safe, clean, and sustainable resource, will play a key role in addressing the energy challenges. In this paper, we propose to add left-right and bottom-side reflective panels to vacuum collector tubes to enhance the thermal storage performance, and the performance of different reflective panel models at different incidence angles is simulated and analyzed through optical simulation using TracePro. The data show that the addition of parabolic bottom-side reflector plates can effectively improve the heat collection performance, and when the angle of the sun rays is large, the performance setback can be alleviated by adjusting the parameters; the shortening of the spacing between the bottom plate and the vacuum tube reduces the average energy density value and the received radiant energy. The optimal structural parameters of the left and right side and bottom reflector plates are selected in turn, and the solar radiation parameters of the Shijiazhuang area are used for simulation verification to validate the performance of the optimized system. The results show that the solar vacuum collector system obtains a significant improvement in solar radiation absorption and collector efficiency, with an overall performance increase of about 11%. The results of this study are expected to provide critical numerical support for the design and performance optimization of solar collector systems and provide more efficient solar energy absorption and conversion solutions for future practical applications.

Keywords

Solar vacuum collector tube; Left and right side and the bottom side of the reflector; Heat transfer mathematical model; Heat collection efficiency.

1. INTRODUCTION

As the greenhouse effect intensifies, human demand for the use of renewable natural resources, such as geothermal, solar, wind, and wave energy, continues to grow. Of these resources, solar energy is one of the most abundant on the planet.[1]It is estimated that the annual solar radiation energy received by the land surface of China is equivalent to about 24× 104 million tons of standard coal, of which the Tibetan Plateau region is the most abundant. Solar energy stands out among the many types of clean energy and has received widespread attention for its wide distribution, zero emissions, abundant reserves, and so on. At present, solar energy utilization mainly has two ways photovoltaic power generation utilization and photothermal conversion utilization [2-4], solar photothermal utilization is widely used in production and life, and its basic working principle is to absorb the radiant energy carried in the sunlight through the collector, and through the interaction between the equipment and the heat transfer processor, t is converted into thermal energy for utilization. To overcome the difficulties caused by the shortcomings of solar radiation decentralization and intermittency [*5], it is necessary to use solar aggregation equipment to increase the energy density on the surface of the solar receiver and equip it with an energy storage device, usually an insulated water tank. The concentrator can pool more solar radiation onto the receiver, increase its surface energy density, and make the light and heat conversion more efficient. Concentrators can be categorized as reflective, refractive, hybrid, fluorescent, thermophotovoltaic, and holographic based on optical principles.

The addition of reflective concentrator collectors has been better studied by researchers around the world. Odeh et al [6] developed a heat loss model based on the absorber wall temperature for a trough collector and used it in a simulation model to evaluate the performance of a direct vapor-generating desuperheater under different radiation conditions and different absorber tube sizes.R. Forristall et al [7] developed a heat transfer model to determine the collector performance of a parabolic trough solar collector. The modeling assumptions and limitations are discussed in the paper along with suggestions for model improvement. Zhang et al [8] developed a one-dimensional heat transfer mathematical model for parabolic trough solar collector (PTC). They were analyzing the PTR70 2008 PTC yields that the absorbed solar radiation heat is significantly affected by the solar incidence angle. Wang et al [9] developed a trough solar collector, through the system heat absorption and heat loss of the collector system change rule, and put forward a method to improve its thermal performance through experimental verification. Zhang et al [10] analyze the parabolic surface with a heat pipe vacuum tube through a solar collector system to achieve higher system thermal efficiency, and a one-dimensional heat transfer mathematical model was established. The results showed that the transient thermal efficiency of the parabolic trough collector system with heat pipe evacuated tubes is higher than 70%. Rani et al [11] investigated the temperature profile, heat transfer characteristics, and thermal efficiency of flat plate solar air collectors (FPSAC) at different air mass flow rates and found that the intensity of the solar radiation is positively proportional to the outlet temperature of the collector air. He et al [12] to alleviate the problem of concentrating solar power (CSP) systems in which the collector surface has high thermal efficiency.) system in which there are safety concerns such as high localized temperatures and large temperature gradients on the collector surface, it was suggested that the solar flux distribution and the heat transfer capacity of the heat transfer fluid (HTF) should match each other as much as possible.

E.Zambolin and D.Del.Col [13] analyzed and illustrated the different collection efficiencies of two non-concentrating solar collectors under two different conditions. Dhvramvir Mangal [5] analyzed and investigated the effect of collection efficiency of two typical non-concentrating solar collectors and found that the effect of temperature and wind speed is so small that it can be ignored. Vacuum tube collectors produce about 30% more heat per unit area than flat plate collectors.L.MAyompe et al [14] proved through experimental studies that compared to flat plate collectors, the average annual collector efficiency of heat pipe vacuum tube collectors is much higher and their average annual collector efficiency is also higher than the system efficiency. Budihardio et al [15] investigated the effect on the natural circulation flow rate in the tube factor and combined it with the velocity map at the open end of the vacuum tube to predict the thermal performance of the solar water heating system. Mohammad [16] simulated the effect of temperature and fluid flow rate on the performance of the collector by improving the structure of the collector and studied the improvement of the bypass tube with different diameters making the elimination stagnation zone at the bottom of the vacuum tube, which further improves the performance of the collector.

From the current domestic and international research status, the efficiency improvement of medium and high-temperature solar collectors mainly focuses on the collector tubes and concentrators, and the thermal efficiency improvement of low-temperature domestic solar vacuum tube water heaters involves the improvement of vacuum tubes, heat absorbing tube coatings, and sun-tracking devices, while the research on concentrating devices is less. This is because medium- and high-temperature applications usually use multiple tubes in series with collector tubes and complex concentrator systems, which are more costly. Low-temperature applications, on the other hand, require cost control and ease of maintenance, so a simple concentrator system may make more sense. Designing a simple and economical reflector system to be mounted on a solar vacuum tube water heater to improve its thermal efficiency is of far-reaching research value. In this paper, reflective panels are installed on the left, right, and bottom sides of the vacuum tube water heater to absorb more solar rays, increase the intensity of solar radiation received by the vacuum collector tube, improve the thermal efficiency, and the structural optimization and performance verification are carried out using numerical analysis.

2. SOLAR VACUUM COLLECTOR MODEL

In this study, the research method of numerical analysis and simulation is selected, and the software TracePro and ProE software are used for the modeling of the solar vacuum collector tube and the two sides and the bottom reflector plate, and the software TracePro is used to analyze the performance of the model of the solar vacuum collector tube with the addition of the left and right sides and the bottom reflector plate, and to determine the optimal design parameters for the various components in turn.

2.1. Vacuum Collector Model

The structure of the vacuum collector tube is shown in Figure 1, which is composed of the outer glass casing, the annular vacuum region, the surface absorption coating, and the inner glass heat absorber tube in that order.

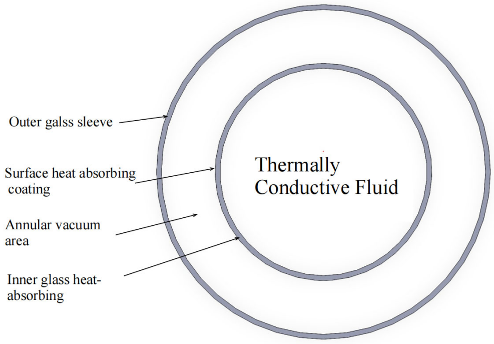


Figure 1. The structure of the vacuum collector tube

This paper adopts the common structure parameters on the market, the coating of the inner glass heat-absorbing tube of the vacuum tube is divided into three layers, the reflection-reducing layer, the heat-absorbing layer, and the reflection layer. Establish the vacuum collector model, the vacuum collector diameter is 58mm, length is 1800mm, according to the vacuum tube parameters for this geometry set, a total of 18 vacuum tube models, named vacuum tube 1 ~ 18, as shown in Figure 2.

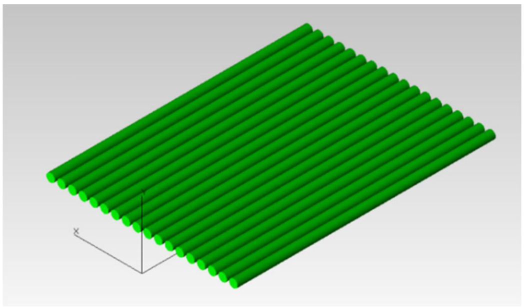


Figure 2. Establishment of vacuum tube model

2.2. Reflector plate model

The design idea of installing a reflector for a solar vacuum collector tube comes from the reflective concentrating effect of a parabolic concentrator to gather more solar rays into the vacuum collector tube. Common solar vacuum tube water heaters due to the existence of gaps between the collector tube caused by the waste of energy can be set up by the back of the vacuum tube reflective plate will reflect the sun's rays to the vacuum collector tube, and at the same time, the introduction of the parabolic reflector to improve the efficiency of solar radiation absorption. Due to the limited space at the back, the reflector plate is divided into three parts, including the reflector plate at the back of the vacuum tube and the reflector plates at the left and right sides, and the construction of the reflector plate is shown schematically in Figs. 3.

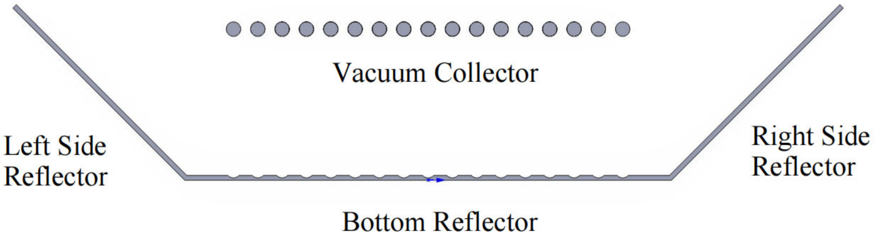


Figure 3. The schematic diagram of the reflector structure

3. OPTICAL SIMULATION

TracePro [19-20] is solid model-based optical analysis software for optical, illumination, and radiance simulation for solar collector models. It incorporates real models for simulation through optical analysis and data transformation. The software follows the laws of optics and uses the Monte Carlo ray tracing method to analyze energy absorption, refraction, reflection, and scattering to calculate the luminous flux.

TracePro software simulation simulation steps:

(1) Create a solid model based on the design parameters;

(2) Define the properties of the model, including material and surface properties, which can directly affect the absorption, reflection, refraction, and scattering of random incident light on each surface;

(3) Define the type of light source, select the appropriate type of light source, and set the position and direction of the light source;

(4) Analyzing and calculating on the observation screen by counting the distribution of light rays to give various data needed;

(5) Analyze the energy density distribution of the light path and the target surface, and compare it with the actual demand, optimize the design of the model, simulate again, and so on many times to achieve the purpose of meeting the design needs.

4. MODEL WORKING CONDITION DESIGN AND OPTICAL SIMULATION ANALYSIS

Design reflective plate model, will be imported into the TracePro software for optical simulation, the light source set to 800W/m2 to keep the same, change the angle of incidence, through the control variable hair successively determines the left and right side and the bottom side of the reflective plate of the optimal design parameters, to obtain the best model after determining the final model parameters by the Shijiazhuang area at various moments of the incident angle and the intensity of solar radiation irradiated to the tilted surface of the simulation again.

4.1. Bottom reflector model design

Firstly, the bottom reflector at the back of the control vacuum tube is unchanged and is designed as a continuous parabolic reflector, and the reflecting surface consists of 18 small parabolic surfaces with a width of 75㎜ and a focal length of 50㎜.

4.2. Dimensioning and Modeling of Left and Right Side Reflectors

As the design of the parabolic reflector needs to consider the back of the vacuum tube's available space focal length of 400, 450, 500, and 550mm, the vacuum collector is located in the focus of the parabolic reflector at the height of the best, and when the depth of the parabolic reflector exceeds the focal length of the height is too high will lead to oblique sunlight being blocked, so the height of the parabolic reflector is limited to 100mm than the focal length of the value of the parabolic reflector is greater than the depth of the value of 400, 450, 500, 550, 600, 650mm. The depths are 400, 450, 500, 550, 600, and 650 mm, and the installation distance of the back reflector from the vertex of the paraboloid is set to be 300 mm, and a group of vacuum collector tubes without a reflector is set to be the control model, and the final model consists of 11 groups and their structural parameters are shown in Table 1.

Table 1. Structural design parameters of left and right reflectors

Optical reflector plate	Focal length (mm)	Depth (mm)	Length (mm)	Opening width (mm)
0	control group			
1	400	400	1800	1600
2	400	450	1800	1697.06
3	450	450	1800	1800
4	450	500	1800	1897.37
5	500	500	1800	2000
6	500	550	1800	2097.62
7	500	600	1800	2190.89
8	550	550	1800	2200
9	550	600	1800	2297.83
10	550	650	1800	2391.65

4.3. Parameter adjustment of bottom reflector model

After the optical analysis to determine the parameters of the left and right side of the reflector, keep the rest of the parameters unchanged, change the parameters of the paraboloid of the bottom reflector and the distance from the vacuum tube, plus a set of vacuum collector tubes without reflector as a control model for a total of 13 groups of models. The parameter adjustment of the bottom reflector plate is shown in Table 2.

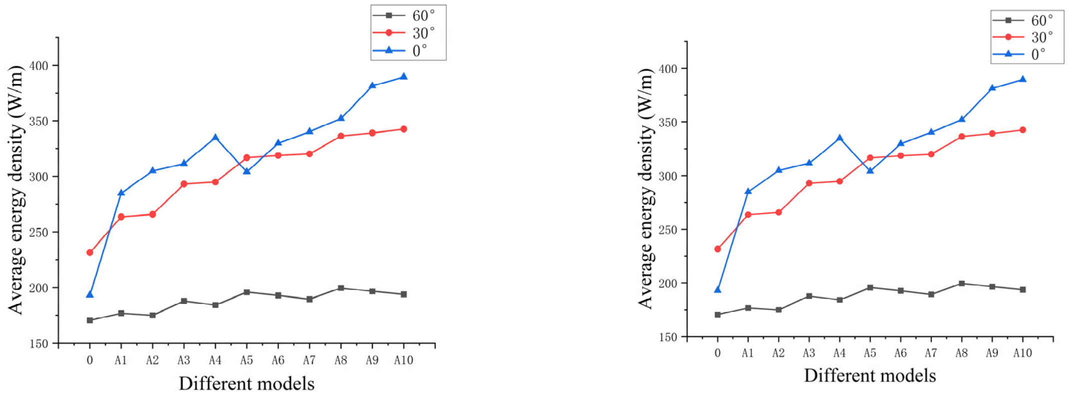
Table 2. Adjusted bottom parabolic parameters

Optical reflector plate	opening width(mm)	Focal length (mm)	Depth (mm)	Distance from vertex (mm)
0	control group			
1	75	50	7.031	300
2	75	50	7.031	350
3	75	50	7.031	400
4	75	100	3.516	300
5	75	100	3.516	350
6	75	100	3.516	400
7	75	150	2.344	300
8	75	150	2.344	350
9	75	150	2.344	400
10	75	200	1.758	300
11	75	200	1.758	350
12	75	200	1.758	400

5. ANALYSIS OF SIMULATION RESULTS

5.1. Left and right lateral reflex plate control group

Using TracePro software, the maximum, minimum, and average energy densities on the surface of the vacuum tubes as well as the received solar radiation energy can be calculated simultaneously. Due to the large number of vacuum tubes, to reduce the error, we calculate the average energy density of each vacuum tube at different incidence angles, then summarize and take the average value, and finally calculate the total luminous flux received by all vacuum tubes. By counting the energy density and radiant energy on the surface of the vacuum tubes at different angles it is possible to compare the model performance of each reflector to determine the optimal parameters of the left and right reflectors. According to the data to draw the change line graph, Figure 4 shows the average energy density change and the change of received solar radiation energy of each group of models.



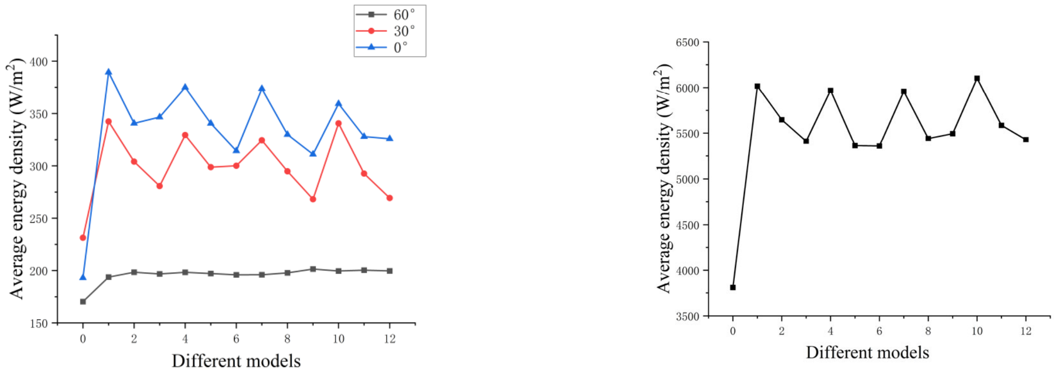
(a)Average energy density of each group of models at different incidence angles **(b) Integration of solar radiation energy received by each group of models from each angle**

Figure 4. Plot of average energy density and variation of received solar radiation energy for each group of models

The analysis shows that at a certain focal length of the left and right reflector plates, an increase in depth leads to a significant increase in the value of the average energy density. In contrast, the increase in the average energy density slows down significantly when the angle of oblique projection of the sun rays is large. An increase in depth reduces the number of incident rays, although it does not cause shading. Therefore, the solar radiation energy received by the vacuum tube with the added reflector is significantly higher than that of the control group, in which the solar radiation energy received by the tenth model group is the most. The parameters of the parabolic reflector plates on the left and right sides of the vacuum tube will be selected with a focal length of 550㎜ and a depth of 650㎜.

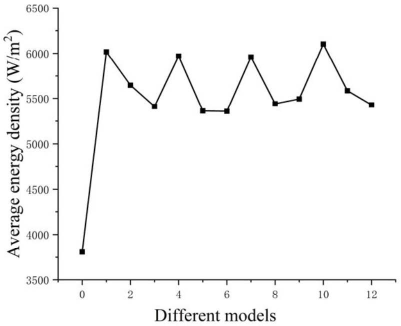
5.2. Bottom reflector control group

According to the design parameters determined above to adjust the reflector plate model, the TracePro software derives the energy density distribution on the surface of the vacuum tube and the solar radiation energy data received on the surface of the vacuum tube. Under the same light source conditions, due to the different parameters of the bottom reflector plate, there will be a gap in the radiant energy absorbed on the surface of the vacuum tube, according to the data plotted in line graphs, Figure 5 shows the average energy density of each group of models, the received solar radiation energy, the optical polymerization ratio and the change of optical efficiency. By statistically analyzing the energy density, received radiant energy, optical convergence ratio, and optical efficiency of the reflector plate on the surface of the solar vacuum tube at different angles [21-22], the advantages and disadvantages of the performance of each group of reflector plate models are compared, to select the appropriate parameters of the bottom reflector plate.



a) Average energy density for each group of models at each incidence angle

b) Integration of solar radiation energy received by each group of models at each angle of incidence



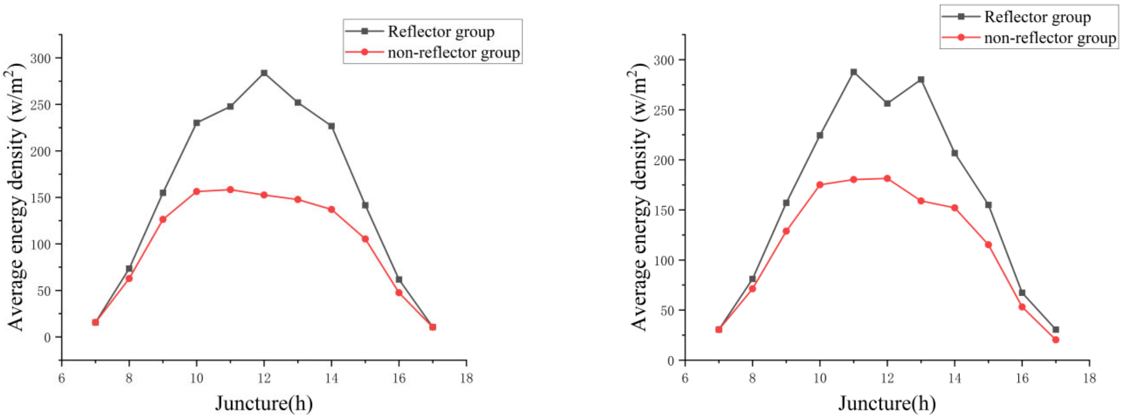
c) Optical efficiency of the model for each group

Figure 5. Comparative Performance Reference Chart for Groups of Models

The analysis shows that when the focal length of the paraboloid of the bottom reflector is kept constant, the average energy density value and the received radiant energy decrease with the decrease of the distance of the bottom plate from the vacuum tube; when the distance of the bottom reflector from the vacuum tube is constant, there is no stable law for the change of the average energy density value and the change of the radiant energy with the change of the focal length of the paraboloid. According to the optical concentration ratio and optical efficiency of each group of models, it can be seen that the vacuum tube of the 10th group of models receives the most radiant energy, and the optical efficiency is the highest, so the parameters of the reflective paraboloid of the bottom reflector plate are selected, with a focal length of 200 mm, a depth of 1.76 mm, an opening width of 75 mm, and a distance from the vertex of 300 mm.

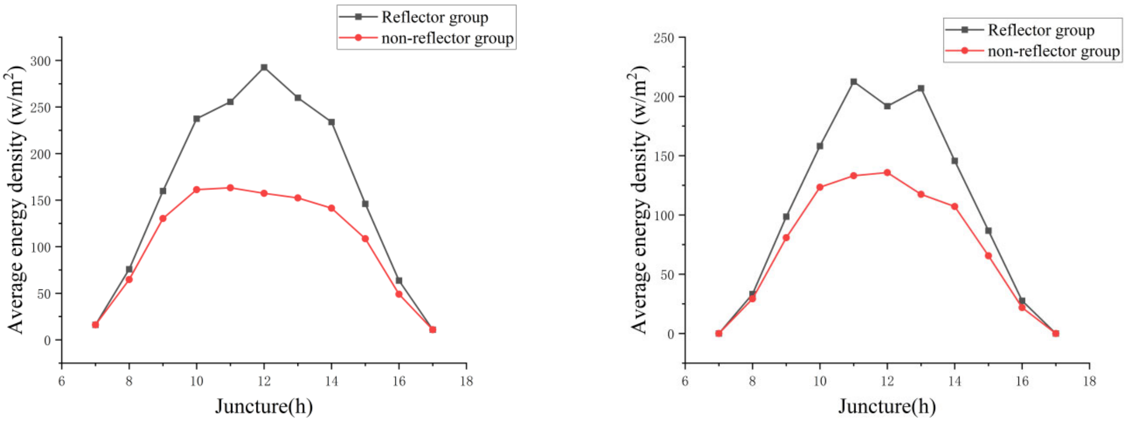
5.3. According to the simulation results of solar radiation intensity in Shijiazhuang area analysis

The model was modified according to the optimized design parameters and imported into TracePro software. When the light source is set, the radiation intensity is adopted from the solar radiation intensity data of Shijiazhuang City on four typical days (spring equinox, summer solstice, autumn equinox, and winter solstice), and the direction of the light is set according to the angle of incidence of the sun's rays at each moment. Figure 6 shows the value of energy density on the surface of the vacuum tube at each moment of the four typical days.



a) Comparison of average daily energy density values in spring

b) Comparison of average daily energy density values in summer



c) Comparison of average daily energy density values in summer

d) Comparison of average daily energy density values in winter

Figure 6. Comparison of average energy density on the surface of vacuum tubes in four typical days

Analysis shows that the overall trend of the intensity of solar radiation irradiated to the light surface with time is first increasing and then decreasing, reaching a maximum at noon. The average energy density on the surface of the vacuum tube on the summer and winter solstice days in Fig. 4-3 (b) and (d) decreases at noon because part of the light incident on the bottom reflector plate is reflected and re-emitted to the sky, and does not reach the surface of the vacuum tube. The average thermal efficiency of the vacuum tube on four typical days is calculated and plotted in Figure 4-4, which shows that the thermal efficiency of the vacuum tube with a reflector plate is significantly improved by about 11%.

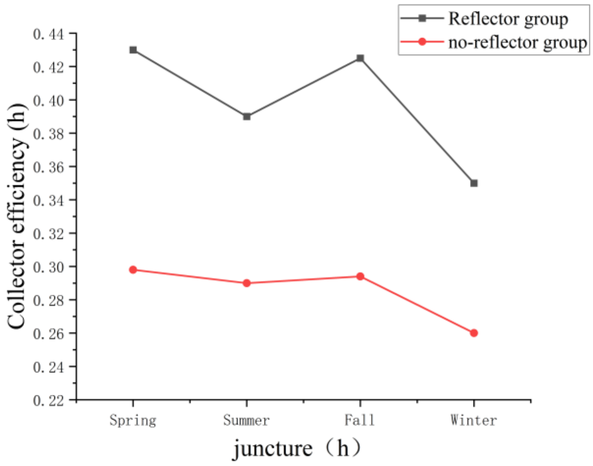


Figure 7. Average thermal efficiency of two groups of models on four typical days

6. CONCLUSION

In this paper, the performance of different collector vacuum tube models with reflector plates is evaluated by numerical analysis. The structural parameters of the left- and right-side and bottom-side reflector plates are successively determined, and then the solar radiation intensity data of Shijiazhuang City are imported into TracePro software to evaluate the effect of the additional reflector plates on the energy density distribution and collector efficiency of the vacuum tube.

(1) When the focal length of the left and right side reflectors is kept constant, an increase in the depth will lead to an increase in the average energy density value, and when the angle of the sunlight is larger, the number of incident light lines will be reduced, resulting in a decrease in performance;

(2) When the focal length of the paraboloid of the bottom reflector is certain, with the decrease of the distance of the bottom plate from the vacuum tube, the average energy density value and the received radiant energy are also decreasing; when the distance of the bottom reflector from the vacuum tube is certain, with the change of the focal length of the paraboloid, the change of the average energy density value and the radiant energy is not regular;

(3) Through comparative analysis with vacuum tubes without reflector plates, it is concluded that vacuum tubes retrofitted with reflector plates can substantially increase the received solar radiation energy, enhance the heat collection efficiency by about 11%, and exceed the overall level of the model without reflector plates even in winter when the intensity of solar radiation is low.

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