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Comparison and Mechanism Study on the Difference of Collecting Performance of Horizontal and Vertical Evacuated Collectors

Xin Liu[1], Enshen Long [1 *], and Jin Li[1]

[1]School of Architecture and Environment, Sichuan University, Sichuan, China 610065

*Corresponding author's e-mail:longes2@163.com

Abstract. The evacuated collectors are applied widely in engineering for the advantages of good heat preservation and being suitable for cold areas. However, the research on its performance difference remains on some typical days, and rarely reveals the difference mechanism from different time dimensions. This paper established a mathematical model to predict the solar energy absorbed by horizontal and vertical collectors respectively, and analysed the inter-tube radiation occlusion rate under the meteorological conditions in Lhasa. The results show that except in summer, the daily and monthly heat collection of the vertical collector were higher than that of the horizontal collector, and the solar energy gained by two collectors was close in winter. The horizontal collector was not affected by the inter-tube occlusion while the vertical collector was seriously affected. The horizontal collector was recommended in Lhasa.

1. Introduction

Solar collector is part of the most mature and practical applications of solar heat utilization. It can be divided into the flat-plate collector and the evacuated collector. The difference between them is that the surface of the flat-plate collector is a continuous plane, while the surface of the evacuated collector is discontinuous and cylindrical. Therefore, the energy harvesting characteristics of two collectors are quite various. With the advantages of low heat loss and good thermal insulation performance, the evacuated collector frequently operates in diverse weather and low-light areas.

Due to the merits of the evacuated collector, more and more attention has been taken to research it in order to expand its application range and meet the needs of different occasions. According to the orientation of tubes axis in the collector, it can be divided into horizontal collector or vertical collector. When the collector is placed southward, the tube axis of horizontal collector points to the east-west direction, while the tube axis of vertical collector points to the north-south direction. Ge et al. found the vertical collector got more solar energy in spring, summer and autumn, while the horizontal collector secured more in winter [1]. Song found the vertical collector gained more solar energy than that of horizontal collector except on summer solstice [2]. Li et al. found the occasion between adjacent tubes would affect the energy gain [3]. However, almost all of the academic researches stayed on some typical days, and rarely revealed the mechanism from different time dimensions.

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quite various. With the advantages of low heat loss and good thermal insulation performance, the evacuated collector frequently operates in diverse weather and low-light areas.

2. Methods

When the sunlight pass through the atmosphere, they are reflected and scattered by water, particles and dust. The solar radiation energy reaching on the inclined evacuated collector includes three parts: the direct radiation, the sky scattered radiation and the ground reflected radiation [4]. In this section, the solar radiation intensity of typical annual meteorological data (TMY) is the hourly direct radiation and scattered radiation on the horizontal surface. Therefore, the radiation intensity on the horizontal surface must be converted into the radiation intensity on the inclined surface of the collector. The total solar radiation intensity on the collectors is described in Equation 1:

$$I = I_{\mathrm{B}} + I_{\mathrm{D}} + I_{\mathrm{R}} \tag{1}$$

where I is the total radiation intensity, W/m^2; I_B is the direct radiation intensity, W/m^2; I_D is the sky scattered radiation intensity, W/m^2; I_R is the reflected radiation intensity, W/m^2;.

Three formulas for radiations are given by Equations 2 to 4 respectively [4]:

$$I_{\mathrm{D}} = \frac{1}{2} I_{\mathrm{DH}} (1+\cos\beta)(\tau\alpha) \tag{2}$$

$$I_{\mathrm{R}} = \frac{1}{2} \rho I_{\mathrm{SH}} (1-\cos\beta)(\tau\alpha) \tag{3}$$

$$I_{\mathrm{B}} = I_{\mathrm{BD}} \cos\theta_t \psi(\xi)(\tau\alpha) \tag{4}$$

where I_{DH} is the horizontal scattering intensity, W/m^2; β is the installation inclination; τ is the outer glass tube transmittance; α is the absorption rate of the selective absorption coating; I_{SH} is the total horizontal radiant intensity, W/m^2; ρ is the ground reflectivity; I_{BD} is the normal direct radiation intensity, W/m^2; $\psi(\xi)$ is the occlusion coefficient; θ_t is the incident angle of the direct sunlight on the evacuated tube; ξ is the projection incidence angle. ξ_0 is the critical projection incidence angle of the tubes. Only if the projection incidence angle is greater than the critical angle, occlusion occurs. The calculation formula of the critical projection incidence angle is [5]:

$$|\xi_0| = \cos^{-1}\left(\frac{D+D_1}{2B}\right) \tag{5}$$

where D is the outer diameter of the inner tube of the evacuated tube, mm; D_1 is the outer diameter of the outer tube of the evacuated tube, mm; B is the center distance of the adjacent evacuated tube, mm.

Whether it is a horizontal or vertical collector, when there is no occlusion between the tubes, $|\xi| \le |\xi_0|$, the occlusion coefficient is 1; when there is occlusion between the tubes, $|\xi| > |\xi_0|$, the occlusion coefficient is [6]:

$$\psi(\xi) = \frac{B}{D}\cos\xi + \frac{1}{2}\left(1-\frac{D_1}{D}\right) \tag{6}$$

Due to the different arrangement of the tubes in the horizontal and vertical collectors, the direct sunlight is calculated differently for the angle of incidence.

Vertical collector [7]:

$$\xi = \cos^{-1}\left(\frac{\cos\theta}{\cos\theta_t}\right) \tag{7}$$

$$\theta_t = \cos^{-1}\left\{1-\left[\sin(\beta-\phi)\cos\sigma\cosh+\cos(\beta-\phi)\sin\sigma\right]^2\right\}^{\frac{1}{2}} \tag{8}$$

$$\theta = \cos^{-1}\left\{\sin\sigma\sin(\phi-\beta)+\cos\sigma\cosh\cos(\phi-\beta)\right\} \tag{9}$$

where ξ is the projection incidence angle; θ_t is the incidence angle of the direct light to the evacuated tube; θ is the incidence angle of the direct light to the collector plate; ϕ is the latitude; σ is the declination angle; *h* the solar time angle.

Horizontal collector [7]:

$$\xi = \left|\cos^{-1}\left(\frac{\sinh_s}{\cos\theta_t}\right)-\beta\right| \tag{10}$$

$$\theta_t = \sin^{-1}\left|\cos\sigma\bullet\sinh\right| \tag{11}$$

where h_s is the solar elevation angle.

In summary, the mathematical model for the heat collection of the horizontal and vertical evacuated collectors per unit area is:

$$Q_a = (\tau\alpha)\left[(I_{\mathrm{BD}}\cos\theta_t\psi(\xi)+\frac{1}{2}\rho I_{\mathrm{SH}}(1-\cos\beta)+\frac{1}{2}I_{\mathrm{DH}}(1+\cos\beta)\right] \tag{12}$$

3. Study objects and conditions

3.1. Research objects

The horizontal and vertical collectors with the same area are taken as the study objects, and the influence of the inter-tube occlusion on them have been taken into account. In addition to the different orientation of the evacuated tube axis, all of the parameters of two collectors are identical, such as the installation inclination angle and the azimuth angle. Figure 1 shows the structure of the horizontal and vertical collectors. The outer diameter of the outer tube (D1) is 58mm while the outer diameter of the inner tube (D) is 47mm. The length of the tube (L) is 1800mm, and the center distance between two adjacent tubes (B) is 76 mm.

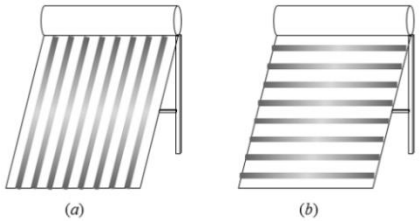


Figure 1. Structure diagrams of the evacuated collector: (a) the vertical collector; (b) the horizontal collector

3.2. Research conditions

The mathematical model is based on the meteorological conditions of Lhasa, which is located in the central region of the Qinghai-Tibet Plateau, adjacent to the Lhasa River Valley. Its coordinates are 29°36′ north latitude and 91°08′ east longitude, and the average altitude is 3650 m. In Lhasa, the annual sunshine hours are 3,000 hours, ranking among the top cities in the country. The annual frost-free period is 100-120 days, which is good for solar energy utilization [8]. In recent years, evacuated collectors have been used more rapidly in Lhasa. Whether using horizontal or vertical collector is more conducive to solar heat collection is still controversial.

4. Results

In order to meet the actual situation, the occlusion effect between the adjacent tubes was taken into account firstly, then using the energy prediction model to simulate the heat collection. On this basis, the absorbed energy of two collectors was contrasted from daily and monthly dimensions.

4.1. Daily heat collection

Figure 2 (a) and (b) show the daily heat collection of the horizontal and vertical collectors. It can be seen from the figure that (1) the daily heat collection rules of two collectors are completely different. The ridgeline formed by the daily heat collection of the horizontal collector shows an obvious parabolic, while that of the vertical collector shows a double hump. The peak of the horizontal collector occurs on the 180th day, while the peaks of the vertical collector occur on the 90th day and 240th day. The peak of the vertical collector is greater than that of the horizontal collector. (2) There are some scatter points appeared below the ridge. In the transition season, the scatter points are relatively dense while sparse in winter. The reason is that day was overcast or rainy, then the solar radiation was weak due to cloud cover. This phenomenon indicates that there are fewer rainy days in winter, which is beneficial to heat collection. (3) The average value of the heat collection by the horizontal and vertical collectors are 16.6 MJ/m^2, 17.4 MJ/m^2 respectively. Indicating that the heat collection capacity of the vertical collector is slightly higher.

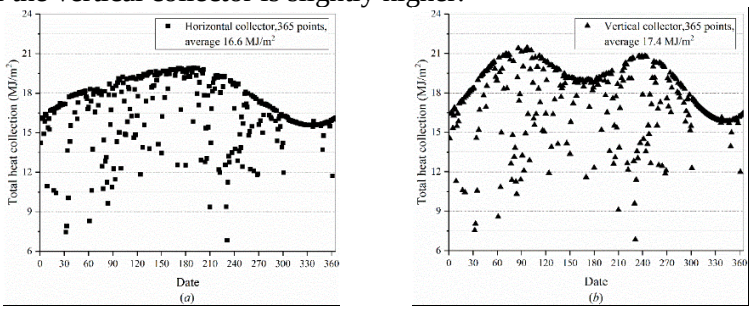


Fig 2. Daily heat collection: (*a*) the horizontal collector; (*b*) the vertical collect*or*

4.2. Monthly heat collection

Figure 3 shows the monthly heat collection of the horizontal and vertical collectors. It is not difficult to find that: (1) the heat collection of two collectors is higher in summer months while lower in winter months, and the monthly heat collection difference is obvious. (2) The heat collection peak of the horizontal collector appeared in June, while that of the vertical collector was in May. (3) Except for the hottest summer months, the monthly heat collection of the vertical collector is always higher than that of the horizontal collector, but the maximal peak value of the horizontal collector is higher. It shows that the vertical collector's ability to track solar radiation is stronger for most of the year.

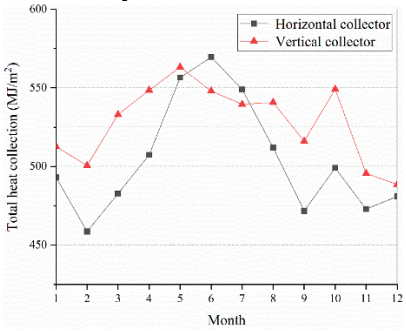


Fig 3. Monthly heat collection of the horizontal and vertical collectors

4.3. Comparison of heat collecting performance between the horizontal and vertical collectors

Figure 4 shows the difference of the monthly heat collection of the horizontal and vertical collectors. The difference curve is a double hump with the mean value being 23.5 MJ/m^2. The peak appears in

spring and autumn, while the trough appears in summer. In May, July and December, the heat collecting difference of two collectors approaches 0, indicating that the heat collecting performance difference of the horizontal and vertical collectors in transitional season is more obvious while smaller in summer and winter sections.

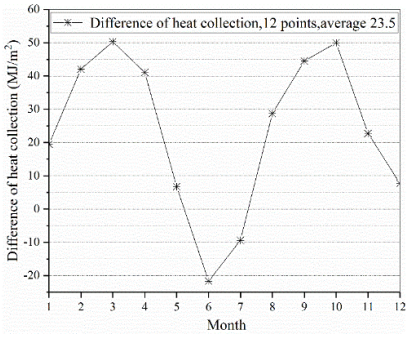


Fig 4. The difference of monthly heat collection between the horizontal and vertical collectors

5. Mechanism analysis

In order to meet the actual situation, this paper considered the influence of the inter-tube occlusion. On this basis, this section counted the absorbed heat without considering the occlusion, and proposed the concept of the radiation occlusion rate (the value is equal to the difference under the occlusion and without the occlusion and then divided by the energy collected without the occlusion), which reflected the negative impact of the inter-tube occlusion on the horizontal and vertical collectors.

5.1. Daily occlusion impact comparison

Figure 5 shows the daily occlusion rate of two collectors. As can be seen, the occlusion rate of the horizontal collector is close to 0 all year around, while that of the vertical collector increased firstly, achieving its peak in summer and then decreased, getting to its minimum in winter. It illustrates that the horizontal collector is not affected by the occlusion between the tubes while the vertical collector is acting exactly the opposite.

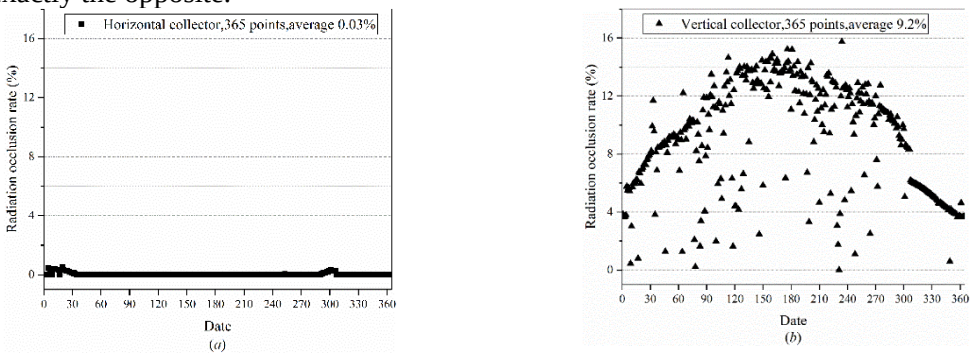


Figure 5. Daily radiation occlusion rate: (*a*) the horizontal collector; (*b*) the vertical collector

5.2. Monthly occlusion impact comparison

According to the comparison of the daily occlusion rates, it can be found that the horizontal collector is almost unaffected by the occlusion, so the monthly occlusion of the horizontal collector is no longer analyzed. Figure 6 shows the variation of the monthly occlusion rate of the vertical collector. The monthly heat collection of the vertical collector was affected seriously in summer and the occlusion effect was weakened in winter.

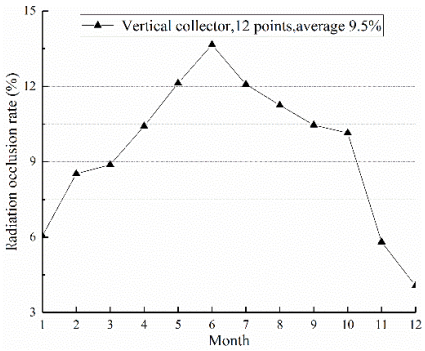


Figure 6. Monthly occlusion rate of the vertical collector

In Lhasa, the huge demand for heating is the main contradiction in winter, when two collectors have similar energy collecting capacity. However, the occlusion effect is slightly in the horizontal collector while seriously in the vertical collector. In order to avoid the energy wasting and give full play to energy gain of the collector, it is recommended to use the horizontal collector in Lhasa.

6. Conclusion

This article described an energy harvesting model for predicting the absorbed solar energy of the horizontal and vertical collectors. The following conclusions are obtained:

(1) The daily energy gain of the horizontal collector reached its peak in summer while that of vertical collector was in spring and autumn, and the peak value of the vertical collector was higher.

(2) Except in summer, the daily and monthly heat collection of the vertical collector are higher than that of the horizontal collector. In the transition season, the difference between two collectors is obvious, and the difference reached its minimum in winter.

(3) Compared with no occlusion, the energy gain of the horizontal collector was almost unaffected when considering occlusion, and the occlusion rate was close to zero. The energy gain of the vertical collector decreased when considering occlusion, and the occlusion rate was large throughout the year.

(4) The horizontal collector is recommended in Lhasa.

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