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Study on heat transfer capacity of the solar horizontal heat pipe

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Abstract

In order to study the heat transfer performance of solar horizontal heat pipes, a high-precision experimental apparatus for heat transfer capacity of the solar horizontal heat pipe was developed. It was proved that the system heat balance of the experimental apparatus is less than 10% and the relative error of the heat transfer capacity was less than 6%. By heat transfer capacity test, it was shown that when the liquid level height of working fluid was about 19% ~ 22% of the inner diameter of solar horizontal heat pipes, the optimal heat transfer performance was obtained. In addition, the heat transfer performance of solar horizontal heat pipes was affected adversely by the installation angle.

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Keywords: Solar horizontal heat pipe, heat transfer capacity, working fluid;

1. Introduction

Heat pipes have been widely used in aviation, aerospace, electronics, thermal control, and industrial energy conservation as an effective heat transfer element. In recent years, the emphasis on the energy demand and energy conservation has promoted the use of the heat pipe in solar energy utilizations [1]. Due to high durability and efficient heat production of heat pipe evacuated tube collectors, heat pipe evacuated tubular domestic solar water heaters are favoured widely by customers in Europe and the United States. In China, the market share of the solar hot water for industrial applications is also gradually increasing.

Heat pipe usually refers to the solar gravity heat pipe as the core component of heat transfer of the heat pipe evacuated tubular solar water heating system. In solar gravity heat pipes, the liquefied working fluid returns from

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condenser to evaporator by gravity, so the solar gravity heat pipe can only be installed in the vertical or inclined position and cannot be installed horizontally. However, the complexity and diversity of architectural form and structure require that solar collectors can break through the confines of installation position and orientation and can be installed horizontally. Thus greater harmony with the architectural appearance becomes possible.

In solar thermal collectors, solar horizontal heat pipes may be used for heat transfer from absorber to manifold. Inside the heat pipes a heat driven two-phase dynamic cycle takes place [2]. So in the evaporator section of the heat pipe which is located within the absorber tube, the working fluid is evaporated and transported to the condenser section which is located at the manifold, via an axial vapor channel between liquid level and the heat pipe wall. In the condenser section, the condensation takes place. Due to the continuous axial liquid channel formed by the working liquid in the horizontal heat pipe, the condensate can flow back into the evaporator section slowly where it evaporates again. In order to ensure the existence of the continuous liquid channel, an appropriate volume of working fluid is needed in the heat pipe.

Solar horizontal heat pipes have good freeze resistance because the working fluid of solar horizontal heat pipes does not occupy the entire cross sectional area of the heat pipe at any point and so has larger radial expansion space.

Horizontal solar heat pipes are already available in the market, but there have been very few investigations on heat transfer performance of solar horizontal heat pipes, especially research on the heat transfer capacity has not been reported. KANJI NEGISHI et al. studied the influence of the inclination on heat transfer performance in the paper "Heat transfer performance of an inclined two-phase closed thermosyphon"[3], and concluded that heat transfer performance was decreased and not stable, when thermosyphon was at a small angle to the horizontal, or the horizontal situation. Ge Hongchuan et al. studied the heat transfer principle of solar horizontal heat pipes and the structure designs of horizontal heat pipe evacuated tube collectors [4]. In solar energy utilizations, heat pipes can be used for both glass-metal sealed evacuated tubes and double-glass evacuated tubes.

The heat transfer capacity is also called heat transfer rate and is an important parameter to evaluate the heat transfer performance, so the research on the heat transfer capacity has important theoretical and practical significance.

The present work is to determine the optimum range of volumes of the working fluid for the solar horizontal heat pipe based on research on the heat transfer capacity. In addition, it aims to determine the characteristics of the sensitivity of the heat pipe performance to the installation angle when close to the horizontal. These test results, can provide some guide for the optimal design of the solar horizontal heat pipe collectors.

2. Experimental apparatus and procedure

The solar horizontal heat pipe was made of oxygen-free copper tube. The heat pipe was 1880 mm long. The evaporation tube was 1800 mm long and was 12 mm O.D, with a wall thickness of 0.75 mm. The condensation tube was 80 mm long and was 14 mm O.D, with a wall thickness of 0.80 mm.

The cross-section of the horizontal heat pipe is shown in Fig.1. O was the circle center, r was the inside radius, θ was the $\angle AOC$, h was the height of the working liquid level.

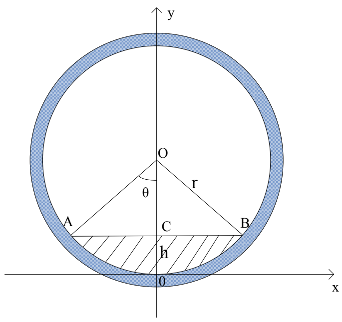


Fig.1. Cross-section of the horizontal heat pipe

Inserting the length L and the working liquid V into equations (1), one can calculate the working liquid level height h.

$$\begin{cases} \left[\frac{2\theta}{360}\pi r^2 - (r-h)\sqrt{r^2-(r-h)^2}\right]\cdot L = V \\ \cos\theta = \frac{r-h}{r} \end{cases} \quad (1)$$

The ratio K between the liquid level height of working fluid and inner diameter 2r of the horizontal heat pipe was calculated as follows:

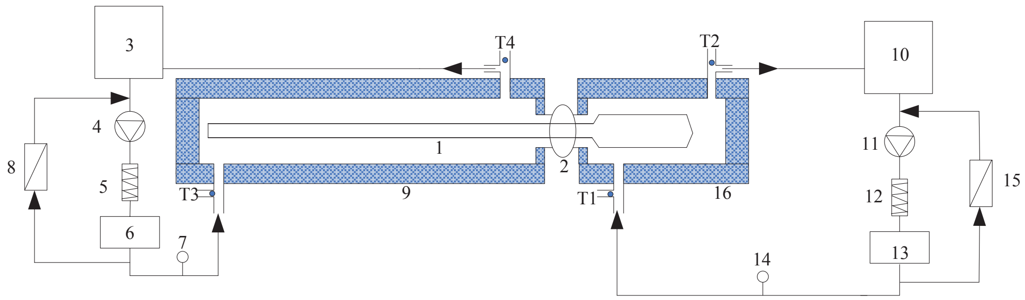
$$K = \frac{h}{2r} \quad (2)$$

The filling amount of the13 horizontal heat pipes was listed in table 1.

Table 1. Filling amount of horizontal heat pipes

NO.	1	2	3	4	5	6	7
Filling Amount /ml	16.4	17.4	19.7	21.8	22.0	23.0	24.7
K	15.6%	16.2%	17.7%	19.0%	19.1%	19.7%	20.7%
NO.	8	9	10	11	12	13	
Filling Amount /ml	27.5	29.6	35.7	37.1	40.7	45.9	
K	22.4%	23.5%	26.9%	27.6%	29.5%	32.3%	

The schematic diagram of the experimental apparatus of the solar horizontal heat pipe was shown in Fig.2. The water heating and water cooling method was used in heat transfer capacity testing. The solar horizontal heat pipe was placed on the apparatus in a horizontal situation. An electronic level instrument was used for setting the angle of the heat pipe with an accuracy of 0.05°. Two water jackets were set on the heat pipe. One was 1500 mm long, used as a heating jacket for an evaporator and the other was 400 mm long, used as a cooling jacket for a condenser.



1 horizontal heat pipe 2 sealing structure 3, 10 buffer tank Ⅰ 4, 11 circulating pump 5, 12 electric heater
6, 13 buffer tank Ⅱ 7, 14 mass flow meter 8, 15 plate heat exchanger 9, 16 water jacket with heat insulation
T1, T2 inlet and outlet water temperature of a cooling jacket
T3, T4 inlet and outlet water temperature of a heating jacket

Fig.2. Experimental apparatus diagram

The heating water flowed into the heating jacket from the lower inlet of the heating jacket and flowed out from the upper outlet of the heating jacket. Similarly, the cooling water flowed into the cooling jacket from the lower inlet of the cooling jacket and flowed out from the upper outlet of the cooling jacket. Water jackets were wrapped by polyurethane insulation material to reduce heat loss. The experimental apparatus image was shown in Fig.3.

Fig.3. Experimental apparatus image

Each water jacket was equipped with an independent temperature control system. Four thermal resistance temperature sensors were placed at inlets and outlets of the two water jackets respectively. Two mass flow meters were used to measure the heating water flow rate and the cooling water flow. The outputs of these sensors were recorded by data acquisition and storage software.

The heat exchange flux of the heating water jacket can be calculated according to equation (3).

$$Q_e = C_e m_e (T_3 - T_4) = C_e m_e \Delta T_e \quad (3)$$

Ignoring the heat loss from the heating jacket, Q_e can be seen as the input power of the horizontal heat pipe.

Similarly, the heat exchange flux of the cooling water jacket can be calculated according to equation (4).

$$Q_c = C_c m_c (T_2 - T_1) = C_c m_c \Delta T_c \quad (4)$$

Where, C_c is the specific heat of the cooling water; m_c is the mass flow rate of the cooling water; T_1 and T_2 are the temperatures at the inlet and outlet of the cooling water jacket, respectively.

Ignoring the heat loss from the cooling jacket, Q_c can be seen as the heat transfer capacity of the horizontal heat pipe.

The heat balance of the heat transfer capacity testing system can be calculated according to equation (5).

$$\Delta = \frac{|Q_e - Q_c|}{\max(Q_e, Q_c)} \times 100\% \quad (5)$$

The precision of the instrument is the key factor of the reliability of the testing results.

The error transfer formula is as follows [1]:

$$E(X) \leq \sqrt{\sum \left(\frac{\partial X}{\partial x_i} dx_i \right)^2} \quad (6)$$

$$\mathrm{E}(\mathrm{Q_e}) = \sqrt{\left[\frac{\partial \mathrm{Q_e}}{\partial(\Delta \mathrm{T_e})} \mathrm{d}(\Delta \mathrm{T_e})\right]^2 + \left(\frac{\partial \mathrm{Q_e}}{\partial \mathrm{m_e}} \mathrm{dm_e}\right)^2} = \mathrm{C_e}\sqrt{\mathrm{m_e}^2 \mathrm{d}^2(\Delta \mathrm{T_e}) + (\Delta \mathrm{T_e})^2 \mathrm{d}^2 \mathrm{m_e}} \quad (7\text{-a})$$

$$E(Q_c) = \sqrt{\left[\frac{\partial Q_c}{\partial(\Delta T_c)} d(\Delta T_c)\right]^2 + \left(\frac{\partial Q_c}{\partial m_c} dm_c\right)^2} = C_c\sqrt{m_c^2 d^2(\Delta T_c) + (\Delta T_c)^2 d^2 m_c} \quad (7\text{-b})$$

The precision of the specific heat from tables is within one part in one thousand, so the influence of the specific heat on the error can been neglected. So the relative error formula can be simplified as follows:

$$\frac{E(Q_e)}{Q_e}=\frac{C_e\sqrt{m_e^2 d^2(\Delta T_e)+(\Delta T_e)^2 d^2 m_e}}{C_e m_e\cdot\Delta T_e}=\sqrt{\left[\frac{d(\Delta T_e)}{\Delta T_e}\right]^2+\left(\frac{dm_e}{m_e}\right)^2} \quad (8\text{-a})$$

$$\frac{E(Q_c)}{Q_c}=\frac{C_c\sqrt{m_c^2 d^2(\Delta T_c)+(\Delta T_c)^2 d^2 m_c}}{C_c m_c\cdot\Delta T_c}=\sqrt{\left[\frac{d(\Delta T_c)}{\Delta T_c}\right]^2+\left(\frac{dm_c}{m_c}\right)^2} \quad (8\text{-b})$$

Where, the temperature differences ΔT are the difference between inlet water temperature and the outlet water temperature of the water jackets. The error is the sum of absolute error of the two temperature sensors of each water jacket.

System heat balance reflects the degree of precision of the testing system. In order to get the smallest possible system heat balance, the temperature sensors selected were PT1000 heat resistance thermometers, with measuring accuracy of ± 0.1 K and the mass flow meters selected were KROHNE mass flow meters with measuring accuracy of $\pm 0.15\%$.

The experimental conditions were set as follows. Set the heating water circulation temperature control system and ensure the heating water inlet water temperature was stable at 70 ± 0.5^{o} C. Set up the cooling water circulation temperature control system and ensure the cooling water inlet water temperature was stable at 30 ± 0.5^{o} C. Set the mass flow rate of the heating water at about 400 kg/h and the mass flow rate of the cooling water at about 25 kg/h respectively. About after an hour, all the experimental conditions were stable. The above condition was close to an actual working condition for a solar water heating system.

The heat transfer capacity was obtained from the temperature rise and the mass flow rate of cooling water through the condenser jacket. Before the heat transfer capacity was determined, the heat balance of the experimental system was verified to be 5% ~ 10%.

3. Results anddiscussions

3.1. Heat transfer capacity results

After the heat transfer capacity test for 5 minutes for every horizontal heat pipe, the heat transfer performance became stable and each test was for at least 20 minutes. Data acquisition frequency was once per second. After the heat transfer capacity test for 10 minutes, take 600 continuous heat transfer capacity values for drawing curves. Abscissa was for time and time starting point was set to zero.

In the horizontal situation, the heat transfer capacity curves of all the 13 horizontal heat pipes are shown in Fig.4. All the heat transfer capacity curves of 1#~12# horizontal heat pipes were smoother than that of 13# horizontal heat pipe.

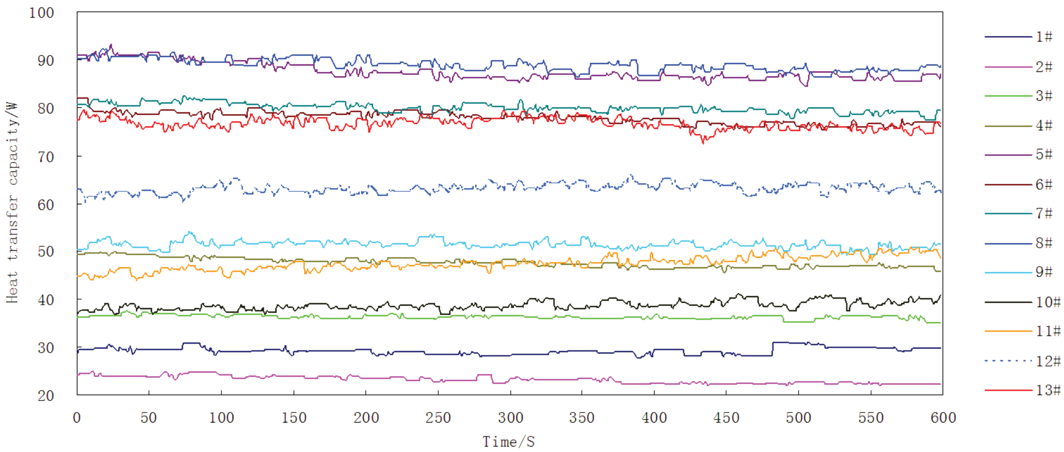


Fig.4.Heat transfer capacity curves in the horizontal situation

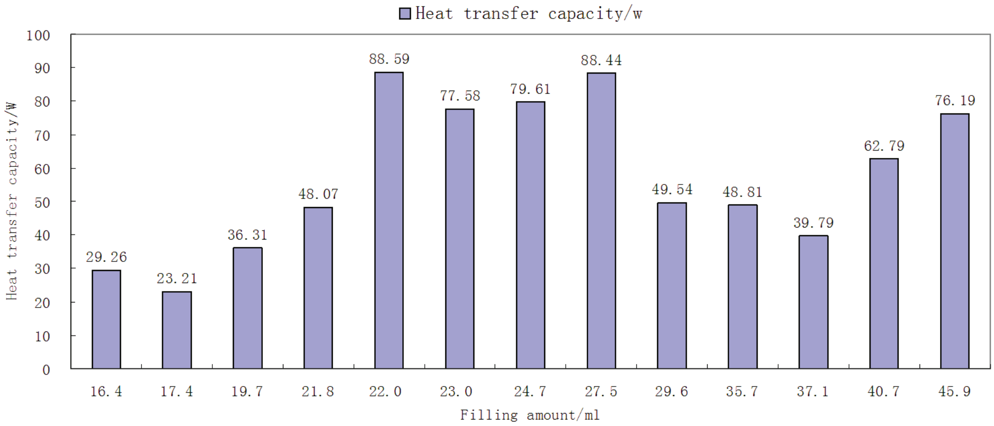


Fig.5.Heat transfer capacity histogram in the horizontal situation

The average heat transfer capacity histogram of the horizontal heat pipes was shown in Fig.5. There were 5 horizontal heat pipes with filling amount of 22.0 ml ~ 27.5 ml and 45.9 ml whose heat transfer performance was better than the others and their heat transfer capacity is 77 W ~ 88 W. But in the process of testing, a kind of serious water hammer or steam hammer sound was heard from the heat pipe with filling amount of 45.9 ml and it caused a large heat transfer capacity fluctuation, and all the other heat pipes had no such problem. So to avoid this problem, the optimum filling amount range of the horizontal heat pipe is 22 ml ~ 28 ml. According to the design parameters of the horizontal heat pipes, the optimum filling amount range was 19.1% ~ 22.4% of the inner diameter of the horizontal heat pipe.

For a solar water heater, the heat flux density is quite small on the surface of the heat absorber. Usually, the solar radiation energy density is less than 1000 W/m^2 on the horizontal surface, so each heat pipe only requires a heat transfer about 80 W~ 100 W, or even smaller, and so the heat transfer of the heat pipes is quite adequate.

3.2. Influence of installation angle on heat transfer capacity

The horizontal heat pipe is sensitive to angle, when the inclination angle of the horizontal heat pipe was 0.5^o (i.e., condenser higher than evaporator), there was very frequent water hammering inside each inclined heat pipe, leading to the unstable heat transfer capacity. The heat transfer capacity curves are shown in Fig.6. The heat transfer capacity of these inclined heat pipes is significantly higher compared to the horizontal heat pipes, but the heat transfer capacity showed large fluctuation.

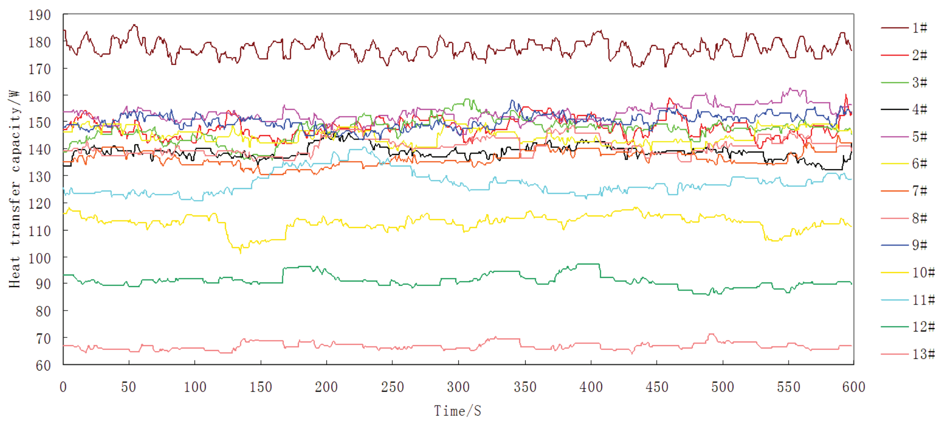


Fig.6. Heat transfer capacity curves in the inclination angle of 0.5^o

For the inclination angle of 0.5°, the average heat transfer capacity histogram is shown in Fig.7. From Fig.7, the heat transfer performance of the first 10 heat pipes with filling amount of 16.4 ml~35.7 ml was better. The heat transfer performance of the remaining 3 heat pipes became worse. Due to frequent water hammering, the container wall will be damaged if the horizontal heat pipe runs for a long time, so the horizontal heat pipe should be installed in the horizontal state.

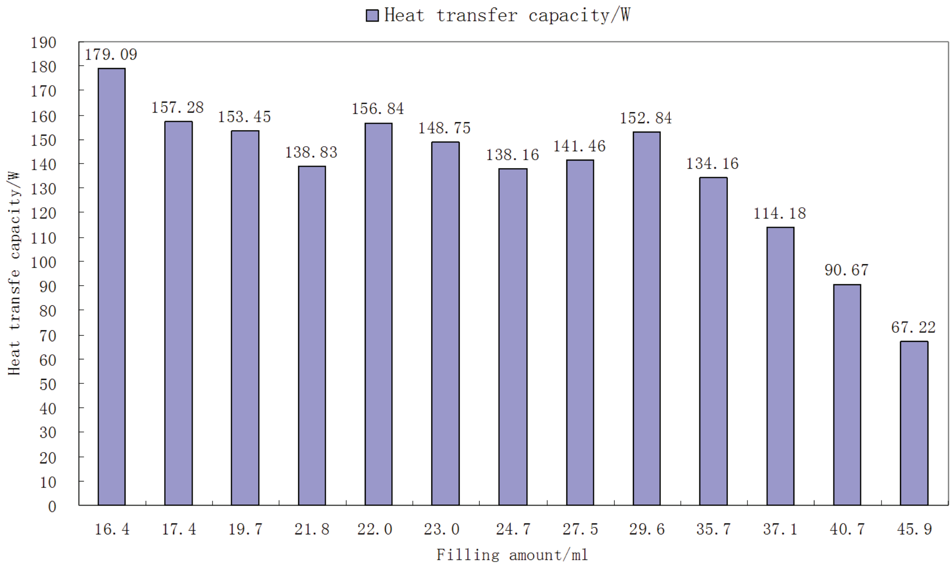


Fig.7.Heat transfer capacity histogram for the inclination angle of 0.5°

For the inclination angle of -0.5°, the heat transfer capacity curves are shown in Fig.8 and the average heat transfer capacity histogram is shown in Fig.9. The heat transfer capacity was less than 16 W, and heat transfer performance was seriously reduced. For this orientation the condenser will be completely filled with fluid, so poor heat transfer capacity is expected.

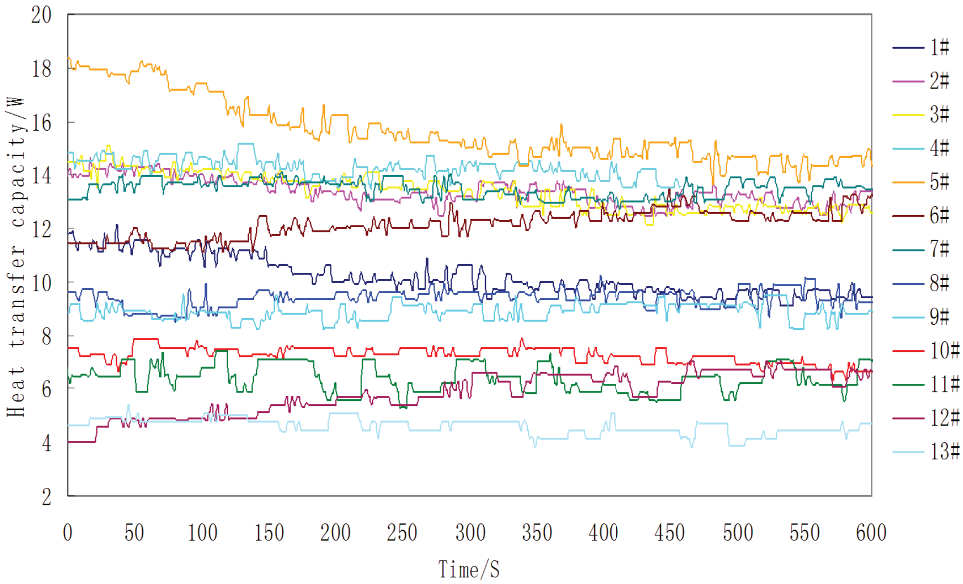


Fig.8. Heat transfer capacity curves for the inclination angle of -0.5°

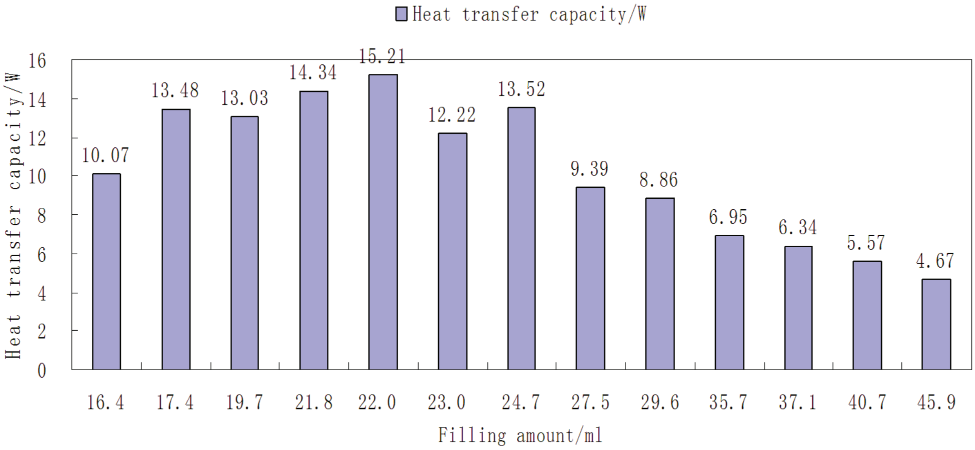


Fig.9. Heat transfer capacity histogram for the inclination angle of -0.5°

4. Conclusions

Filling amount has significant influence on the heat transfer performance of the solar horizontal heat pipe and is one of the key parameters of the solar horizontal heat pipe. When the level height of working fluid is about 19% ~ 22% of the inner diameter of the solar horizontal heat pipe, the solar horizontal heat pipe can obtain optimal heat transfer performance.

In addition, the solar horizontal heat pipe is sensitive to angle. At a small negative angle, the heat transfer capacity decreased significantly; at a small positive angle, the heat transfer capacity increased significantly, but the heat transfer capacity showed larger fluctuation, so solar horizontal heat pipes have greatest benefits for installation.

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