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Numerical simulation and experimental study of the tube receiver's performance of solar thermal power tower

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Abstract

A water-vapor tube receiver is a significant component in the solar thermal power tower plant. However, the tube flow performance is much different from others. Because semi-circumference of the tube is heated with an uneven heat flux, which is into a Gaussian distribution in this paper, and the other semi-circumference is insulated. A 5kW-Xe-arc lamp was used to simulate a solar light source. In this study, the effect of different entrance velocity on the flow performance and thermal efficiency of the tube receiver are investigated with numerical and experimental methods. The results of experiment and simulation agree well. The results show that the temperature distribution of water and tube wall are very uneven both in the axial and radial directions. The thermal efficiency of the tube receiver increases with the increase of entrance velocity.

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Keywords: Tube receiver; Heat flux; Numerical simulation; Experimental study; Thermal efficiency

1. Introduction

A solar power tower plant uses thousands of heliostats installed around the tower to concentrate sunlight onto a receiver, where the heat transfer medium goes inside taking away the heat, converting to electrical energy eventually [1]. The receiver is a significant component in the solar thermal power tower plant. The tube receiver with water-vapor as working medium has high heat conductivity, no corrosion and low technical risk. Roldán investigated the tube wall temperature distribution characteristics under the condition of uneven solar irradiation by numerical methods [2]. Garbrecht presented a novel hexagonal pyramid-shaped receiver, the thermal efficiency of which could reach 91.2% through numerical calculation [3]. Yang studied the heat transfer characteristics of a single molten salt tube receiver by numerical and experimental methods [4]. However, these studies were based on the assumption that the heat flux was uniform, or they simplified the problem as semi-circumference of the tube was uniform and the other was insulated.

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In fact, the heat flux distribution is much complex, which is very uneven both in the axial and radial directions. In this paper, an experiment table was built to test the flow and thermal performance of the tube receiver. In order to verify the experimental results, a numerical model was established.

Nomenclature

q_h	irradiation heat flux (W/m^2)	Q_h	irradiation power (W)
ε_{eff}	absorber-tube wall effective emissivity	A_p	areas of absorber-tube (m^2)

2. Experiments

2.1. Experimental setup and methods

The schematic of the experimental system is shown in Fig.1 (a). It consists of the testing tube receiver, the data acquisition system, concentrating solar simulator system, water tank and valves, etc. Heat transfer medium of water flows from the tank, into the heat-absorbing tube, being heated by the concentrating solar simulator. The inlet and outlet water temperature and the absorber-tube back side wall temperature are gathered by the data acquisition system.

Fig.1 (b) shows schematic sectional views of the testing tube receiver. The exterior structure is formed from stainless steel, with a 50mm thick insulation layer (rock wool) wrapped tightly on the back of the absorber-tube, to minimize heat losses. An array of ten copper pipes (100mm long, 10mm and 8mm of exterior and interior diameters, respectively) is placed at an equal interval (2mm). Twelve calibrated K-thermocouples are installed in the prototype, as shown in Fig.1 (b). P_1-P_{10} correspond to ten absorber-tubes from left to right. T_{bx} corresponds to the temperature of absorber-tube back side wall at the center point. T_{outx} is the temperature of outlet water. T_{in} is the inlet water temperature and T_{air} is the room air temperature (not shown in Fig.1 (b)), are measured by a digital thermometer. The temperature of absorber-tube front wall (T_{wx}) is measured by an infrared thermal imager (ThermaCAMS65).

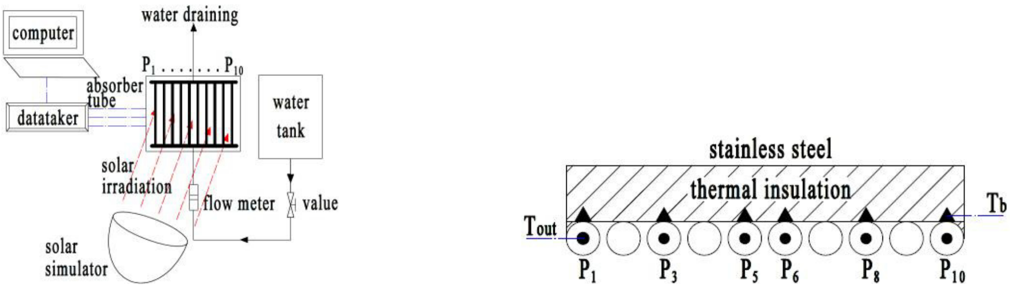


Fig. 1. (a) The schematic diagram of experimental system; (b) Cross section of the receiver

A solar simulator is used to simulate concentrated solar irradiation. The solar simulator consists of a 5kW-Xe-arc lamp (light source), an ellipsoidal reflector with rhodium nickel-based and an adjustable power supply. The irradiation heat flux was measured by an optical power sensor (30A-P-17), produced by Ophir Company, Israel.

2.2. Irradiation heat flux measurement

As the area of the receiver is 120mm×100mm, the arrangement of the measure points is shown in Fig.2 (a). Measure points were arranged at 10mm intervals at both the X-axis and Y-axis. The measurement points were used to calculate the irradiation flux of the whole surface using the MATLAB software. The experiment site on a 84.2 A electrical current and a 22.8 V voltage is shown in Fig.2 (b).

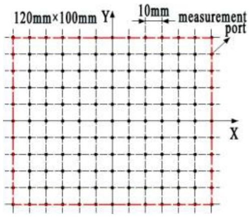
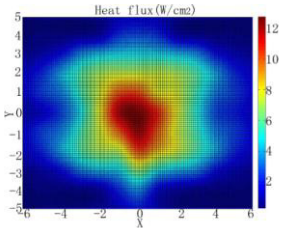


Fig. 2. (a) Measurement of sports distribution; (b) Photo of experiment site

As shown in Fig.3, the irradiation heat flux distribution is close to the Gaussian distribution on the whole and the maximum can attain 12.4W/cm^2. The correlation between the irradiation heat flux (q_h) and X-Y axis is approximate to formula (1), and the irradiation power (Qh) is about 456.8W by the normalization and integration method using the MATLAB and 1stOpt software.

$$q_h = 0.1725 + 0.1092 * e^{0.5*\left(\frac{x+0.0047}{2.6232}\right)^2} + 0.3905 * e^{0.5*\left(\frac{y+0.1185}{2.341}\right)^2} + 11.0319 * 0.5 * \left(\left(\frac{x+0.0047}{2.6232}\right)^2 + \left(\frac{y+0.1185}{2.341}\right)^2\right) \quad (1)$$



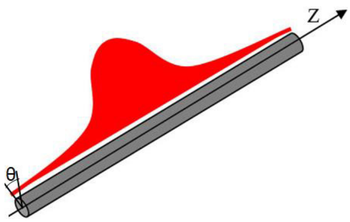


Fig. 3. Irradiation heat flux distribution Fig. 4. Irradiation heat flux distribution on the absorber-tube

3. Numerical simulation

For simplification, a single absorber-tube (P5) according to the actual size was simulated by FLUENT 14.0. The heat flux distribution corresponds to Gaussian distribution along the tube direction (Z-axis) and cosine function ($-90° \leq \theta \leq 90°$) along the radial direction as shown in Fig.4. The Gaussian distribution was known from the front experiment.

4. The results of experiments and numerical simulation

Fig.5 (a) shows the temperature distribution of the absorber-tube (P5) wall along the Z-axis at different volume flow rates when the inlet temperature of water is 283K. The left was measured by the infrared thermal imager in an experiment and the right was obtained by the simulation. The absorber-tube wall temperature is the highest when Z is about 0.05m because of the heat flux distribution. The temperature of the upper part of absorber-tube is higher than the lower part. Because the temperature difference between the absorber-tube and the water decreases along the Z-axis, this weakens the heat exchange intensity. Fig.5 (b) clearly shows temperatures correspond to the different Z values. The results of experiment were consistent with simulation, with a deviation within ±4.7%.

Fig.6 shows the water temperature at different volume flow rates. Both the temperature of the absorber-tube wall and water increases with the decrease of volume flow rate. The average temperature of the outlet water was 313.7, 320.6 and 336.7K when the volume flow rate was 20, 15 and 10L/h separately.

The radiation (Q_{rad}) and convection (Q_{conv}) losses could be calculated according to the formulas [5]:

$$Qrad= \varepsilon_{eff} \cdot \sigma \cdot (T_w^4 - T_{air}^4) \cdot A_p \quad (2)$$

$$Qconv=0.48 \cdot (G_r \cdot P_r)^{1/4} \cdot \lambda/L \cdot (T_w - T_{air}) \cdot A_p \quad (3)$$

As thermal losses are positively correlated with temperature, they decrease with the increase of volume flow rate, shown in Fig.7. The convection loss is about 0.64W and radiation loss is 0.35 at 10L/h. The convection loss is about twice as radiation loss.

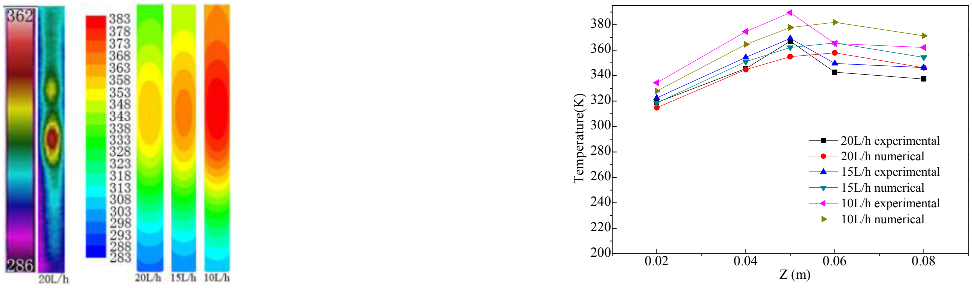
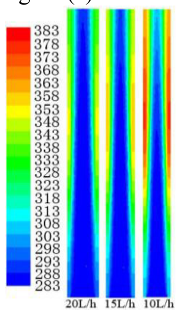


Fig. 5. (a) The temperature distribution of absorber-tube wall; (b) The temperature curves at different Z value



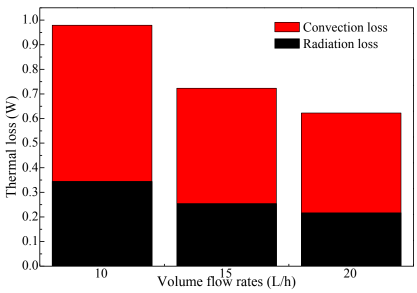


Fig. 6. The temperature distribution of water in the tube Fig. 7. Thermal losses at different volume flow rates

5. Conclusions

Numerical simulation results agreed with experimental data well. The temperature distribution of the absorber-tube wall and water were very uneven in the case of Gaussian distribution of heat flux. The absorber-tube wall temperature at 10L/h was 23K higher than 20L/h. The thermal efficiency of the tube receiver decreases with the decrease of volume flow rate. The convection loss is about twice as radiation loss. The temperature of the central water was lower than on either side in the tube.

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