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Original Research

Thermal properties of high temperature vacuum receivers used for parabolic trough solar thermal power system☆

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ABSTRACT

The receiver's emittance and vacuum pressure are the two of great significance issues on the heat-loss which is the main factor reducing the efficiency of the parabolic though systems. In this paper, the thermal steady-state equilibrium method was used to test the receivers' heat-loss. The receivers with increasing emittance were tested to study the variation of heat-loss. Meanwhile, the variable vacuum pressure in the annulus that affects the efficiency of the system was investigated. The influence of vacuumizing rate and getters on the vacuum pressure and heat-loss were discussed. The result shows that the emittance and vacuum pressure affect the receiver's heat-loss dramatically, and the emittance is the major influence factor on the thermal properties. The receiver with 0.08 emittance and 10^{-3} Pa vacuum pressure has a satisfactory heat-loss of 215.6 W/m at 400 °C. The analysis further reveals that the synergistic effect of both emittance and vacuum pressure on the heat-loss can be reflected by the packaging temperature of the glass tube, and a fitting formula has been established to estimate the receivers' heat-loss according to the packaging temperature of the glass tube.

1. Introduction

Nowadays, the parabolic trough solar thermal power system with vacuum receivers seems to be the most economic industry large scale production technology available in solar power generation after several decades' rapid development [1,2]. The high temperature vacuum receiver is a core photo-thermal transfer component in the system to absorb solar radiation reflected by the parabolic trough. The receiver consists of a stainless steel tube coated with a selective absorbing coating, an antireflective coatings and an evacuated glass tube surrounding the absorber tube [3,4]. In current design, the annulus space between the absorbing coatings and the glass tube is vacuumed during the manufacturing process to reduce thermal loss under high operating temperature and to protect the surface of the absorber from oxidization [5,6]. In this system, the receivers should be able to work under a high temperature of 400 °C for more than 20 years and tolerate different heat transfer fluids, such as organic conduction oil or fused salt. The photo-thermal transfer efficiency of the receiver determines the efficiency of the whole system while the heat-loss significantly affects the efficiency of the receiver. The current researches reveal that the degradation of the photo-thermal transfer efficiency of the solar power plants mainly depends on the coatings themselves [7–9] and vacuum failure induced heat-loss [10]. In this work, the study on the influence of the heat-loss on the thermal properties is focused.

The receivers' heat-loss includes two parts: one is the radiation heat-loss from the emittance of selective absorbing coatings, which could be reduced by applying some lower thermal emittance coatings on the absorber tube, and the other one is the convection heat-loss induced by the residual gases in the vacuum annulus, which can be eliminated by vacuumizing the annulus space of the receivers [11]. Zhang et al. [12] studied the heat-loss of 13 m pipelines which consists of six two-meter receivers, and the results showed that the radiation heat-loss occupied for 70–90% in the total heat-loss while the convection heat-loss took up only 10–30%, however, the heat-loss of four-meter receivers was not researched in their study. Siqueira et al. [13] adopted the VB.NET programme to calculate the thermal efficiency of receivers under different temperatures, and the numerical simulation showed that the efficiency of the receiver decreased from 77% to 65%, meanwhile the inlet temperature of the heat transfer fluid increased from 100 °C to 400 °C. However, only the numerical simulation was discussed in their research, and the reason for the degradation of the heat-loss was insufficient. Lei et al. [14] studied the thermal characterization of three different receivers, and the results showed that the thermal emittance ascended over increasing absorber temperature. Wu

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et al. [15] found that the heat-loss of a degraded receiver with sharply declined vacuum pressure was 4 times higher than the one with a good vacuum pressure. To remain a satisfactory vacuum pressure, Jun Wang et al. [16] filled the vacuum annulus of the receivers with some specific gases, and the result presented that the heat-loss was restricted by these specific gases and a satisfactory vacuum pressure was obtained. However, in their work, only the influence of the vacuum pressure to the heat-loss was discussed, the influence of emittance to the heat-loss was not considered.

In most of current studies, the researchers usually focus on the effect of only one factor (emittance or vacuum pressure) on the heat-loss rather than on the synergistic effect of both emittance and vacuum pressure. The reason is that the study of the synergistic effect needs long-term experiment and pretty trivial process. Besides, the reason that four-meter receivers have seldom been studied in China is due to the lack of reliable high temperature solar receiver with independent property rights. In this work, the heat-loss behaviour of the four-meter receivers with different emittance of selective coatings and different vacuum pressures is studied in detail, and the synergistic effect of both emittance and vacuum pressure on the heat-loss analysed under the support the Ministry of Science and Technology of China..

2. Material and experimental

The length of the receivers used in the present investigation was 4.06 m, the diameter of the stainless steel tube coated with solar absorbing coatings was 70 mm, and the diameter of the antireflective vacuumed glass tube was 125 mm. The photograph of the receivers is shown in Fig. 1.

The preparation process of the receivers is as follows: using the TEA-10480TF full automatic ultrasonic cleaner to rinse the stainless steel tubes and glass tubes with de-ionized water, then the stainless steel tubes were deposited the selective coating by magnetron sputtering process. The detailed deposition process has been reported in the authors' previous work [17]. The emittance of the selective coatings was measured by emissometer detector. The thermal steady-state equilibrium method was used in the heat-loss tests. Two copper pipes (length of 2.10 m; diameter of 5.4 cm) with built-in heaters were symmetrically inserted into the receiver from both ports. The maximum power of the copper heating pipes was 2000 W. Two auxiliary heaters resided inside the receiver to compensate the heat-loss. Besides, each end of the receiver was insulated with asbestos fibre to depress the port heat-loss. This evens out the temperature profile of the absorber tube in both longitudinal and circumferential directions. To measure the internal temperature of the receiver, four thermocouples were tied up on the outer surface of the copper pipes, another two were placed at each end of the receiver to obtain the temperature of the receiver's end, and the last one was put on the outer surface of the glass tube to measure its surface temperature. The heating process started at room temperature and was hold at 250 °C, 300 °C, 350 °C and 400 °C respectively for 6 h to test the heat-loss. The thermal steady state was achieved, where the glass and absorber temperatures remain constant (variation less than 0.5 °C) after heating for 15 min. The temperatures tested by the thermocouples and the heater outputs power was

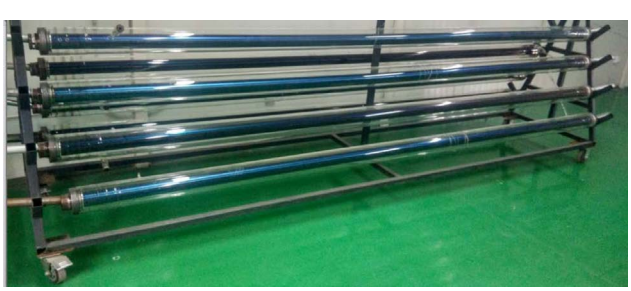

Fig. 1. Receivers tested in this study.

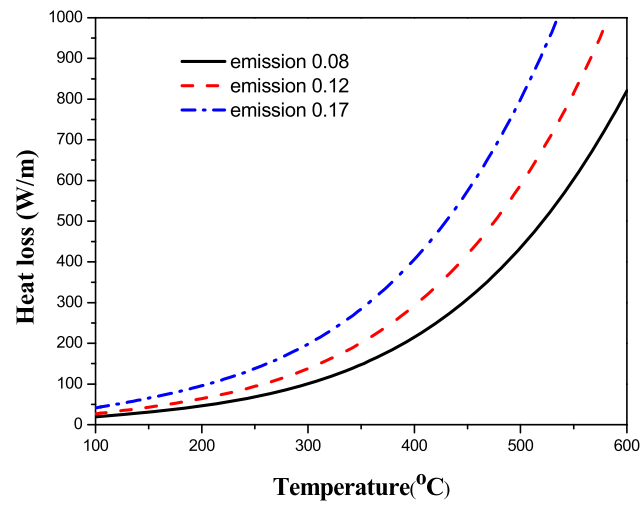

Fig. 2. The influence of temperature and emission on heat-loss.

recorded. The heat-loss was calculated based on the sum of the power of all heaters.

During the test, several groups of tests were designed to test the effect of various factors on the heat-loss. Three receivers with different emittance of 0.08, 0.12 and 0.17 at 400 °C under 10^{-3} Pa were designed as the first group experiment to investigate the influence of the emittance. The second group experiment was designed to study the effect of the vacuum pressure, adopting the same receivers while the emittance was 0.08 at 400 °C, and the vacuum pressure in the annulus of receivers is 10^{-1} Pa, 10^{-2} Pa and 10^{-3} Pa, respectively. The third group experiment adopted another two receivers with the degassing rate of 1.4×10^{-4} m^3/h and 0.9×10^{-4} m^3/h to study the effect of the vacuumizing rate to heat-loss. Besides, another three receivers with different quantity of getters were prepared to find out the effect of getters on the heat-loss.

3. Results

3.1. Emittance effect on the heat-loss of the receivers

Figs. 2 and 3 show the variation of three different receivers' heat-loss and glass tube's surface temperature under different temperatures. The values of the emittance of the receivers at 400 °C were 0.08, 0.12 and 0.17, and the vacuum pressure of them was 10^{-3} Pa. As shown in

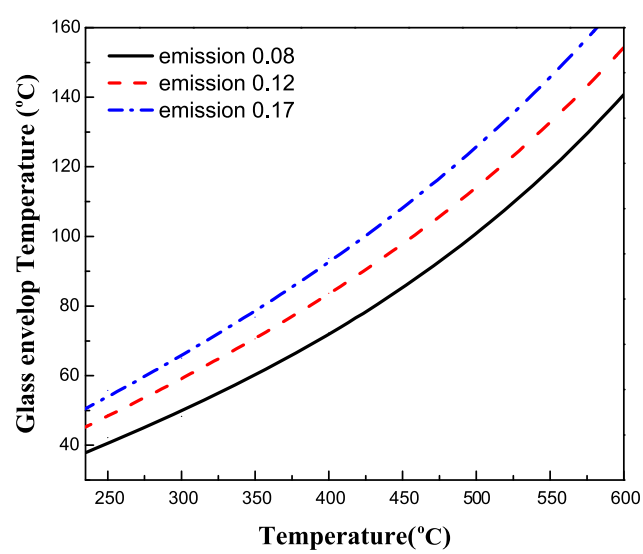

Fig. 3. The influence of temperature and emission on surface temperature of glass tube.