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An experimental study: Thermal performance of molten salt cavity receivers

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HIGHLIGHTS

► An indoor molten salt cavity receiver testing system is established.
► The impact of input power and flow rate on receiver is investigated.
► Transient performance of receiver is analyzed due to variation of input power.
► The proportion of each part in total energy is calculated.

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ABSTRACT

In solar power plants, a molten salt receiver always works in unsteady state conditions. Therefore, it is necessary to research the thermal performance of a receiver in an unsteady state condition. For this purpose, an indoor testing system with a molten salt cavity receiver was developed. Experimental research was conducted to determine the thermal performance of a 100 kWt molten salt receiver. The effect of the input power and flow rate on the thermal performance of the receiver was investigated. In addition, a simple unsteady model was established to research the characteristics of the variation of the internal energy of the receiver and the characteristics of the heat loss. The results indicated that the efficiency of the receiver was in direct proportion to the flow rate. However, the influence was small. In the initial stage of the transient process, the increments of the internal energy of the receiver and the fluid were large (approximately 20% in the energy which is not removed by the mass flow of the fluid). Over time, the thermal inertia of the receiver decreased with the transient process. As a result, any energy not taken away by the fluid was transformed into heat loss.

1. Introduction

In recent years, solar power tower technology has been greatly developed [1–4]. As one of the key components of solar power tower plants, the receiver affects the operation of the whole power plant. Depending on the fluid, there are different types of receivers, such as water/steam receivers, molten salt receivers and air receivers. Molten salt receivers have great commercial potential and win much attention from researchers. In 1996, the Solar Two [5] project used a molten salt receiver to take advantage of the insights gained from molten salt experiments. Based on the lessons learned from Solar Two, the Gemasolar power plant [6] was built. It is the first commercial central receiver system (CRS) power plant using a molten salt receiver.

Much research into cavity receiver is concerned with the mechanism of heat loss affecting the thermal performance of the receiver. America was one of the earliest countries to research the molten salt receiver. Sandia National Laboratory conducted lots of research during the 1980's and 1990's. They published many useful results [7–10]. In other research institutes in the USA, there are also many scientists researching on cavity receivers. Clausing [11,12] developed a simple mathematical model to calculate the convection heat loss of cavity receivers, which divided the inner space of the cavity into a convective zone and a stagnant zone. Subsequently, the model was improved and validated with experimental data. The effect of the aperture shape on convective heat-transfer coefficient is also included in the model. Many researchers in China study receivers and have published many papers in recent years. Xin Li [13] proposed an easy-to-use steady model for cavity receiver, which conveniently calculates each part of the heat loss. Qiang Yu [14,15] developed models for cavity receivers and

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Nomenclature

m	mass (kg)
C	specific heat (J/kg K)
T	temperature (K)
t	time (s)
S	input power (W)
A	area (m^2)
h	convective heat-transfer coefficient (W/m^2 K)
Q	power (W)
$\dot{m}$	mass flow rate (kg/s)

Greek symbols

η	instantaneous receiver efficiency

Subscripts

in	internal energy increment
$s-f$	term between receiver surface and fluid
fi	inlet temperature of fluid
abs	absorbed energy
s	stainless steel tubes of receiver
total	total energy which is not taken away by mass flow of the fluid
L	loss
heat	heat loss
f	fluid in the receiver
fo	outlet temperature of fluid

investigated the dynamic characteristics of the receiver under the sharp disturbance of DNI on the “STAR-90” simulation platform. Xiaoping Yang and Minlin Yang [16,17] of the South China University of Technology studied the heat transfer characteristics of the molten salt tube receiver. They also investigated the interaction between the heat transfer performance and the thermal efficiency of a molten salt receiver. The results showed that the Nusselt number of the spiral tube is on average about 3 times larger than that of the smooth tube. J. B. Fang [18] conducted a numerical study on the cavity receiver under windy conditions, and proposed a new method to calculate surface temperature, i.e. using the Monte-Carlo method to figure out the surface heat flux inside the cavity and the heat flux could be used to calculate the surface temperature with an iterative method. Shuang-Ying Wu [19] performed a 3-D numerical study to investigate the effect of aperture position and size on natural convection of a heat-pipe receiver. A new Nusselt number correlation that can estimate natural convection heat loss with reasonable accuracy is proposed. Some researchers [20,21] in Spain focused on the design and optimization of the receiver structure. Researchers in other countries also did lots of work on the mechanism of the heat loss of receivers. Leibfried and Ortjohann [22] investigated the heat loss of cavity receivers at all inclination angles including upward direction, and gave two new correlations based on correlations proposed by Clausing and Stine. Taumoefolau [23] conducted experimental studies on cavity receivers using electric heating as the heat source, and found the relationship between the natural convection heat loss and the inclination of the cavity. Gonzalez and Palafox [24] numerically studied natural convection and surface thermal radiation in an open cavity receiver. Their results indicated that for large temperature differences between the hot wall and the bulk fluid, radiative heat transfer is more important than convective heat transfer.

In addition, some work is performed on the measurement method of the receiver efficiency. Boehm and Nakhaie [25] proposed a flux-on method to estimate the heat loss of operating receivers. The method was validated with experiments conducted at National Laboratories' molten salt electric experiment (MSEE). The results indicated good agreement with results calculated from other methods. However, the uncertainty of the method is significant. In particular, the results were sensitive to the measurement of the receiver flow rate. Improvement for this method is still needed. M. Carasso and M. Becker [26] mentioned a flux-off method to estimate the heat loss of receiver. This method was designed to be used in the absence of solar radiation. In addition, inlet fluid temperature and flow rate should be kept constant during experimentation. When the outlet fluid temperature was in a steady state condition, the heat loss of the receiver was equal to the change in enthalpy of the working fluid. However, the flux-off method requires a relatively high inlet fluid temperature. The purpose is to make receiver temperature close to those values found in working conditions.

As presented above, there has been lots of work on cavity receivers. However, most of the work is about the mechanism of heat loss. Some thermal performance analysis and testing methods for receivers are based on a steady state condition. However, receivers always operate with variable incident power and flow rate, and these conditions have not been studied widely. This paper developed an indoor molten salt cavity receiver testing system that used electric heating as incident power. The impact of key parameters (such as incident power and flow rate) on the thermal performance of cavity receivers was studied. Additionally, a transient energy analysis of molten salt cavity receiver was also conducted.

2. Experimental research and data analysis

2.1. Experimental set-up

The molten salt cavity receiver testing system is schematized in Fig. 1. The testing system includes the molten salt tank, molten salt furnace, cavity receiver, heavy-current electric heating system, electric control system, and temperature and flow rate detecting system. The photograph of the entire testing system is shown in Fig. 2. Molten salt is stored in the molten salt tank and electric heating melts the salt inside. When V1 is open, molten salt goes into a molten salt furnace to take part in other experiments. When V1 is closed, molten salt goes into the main loop for the purpose of testing the receiver and single tube. In our experiments, molten salt goes through V2 and V3 and enters the cavity receiver. Heat transfers from the electrically heated receiver to the molten salt. High temperature molten salt goes out from the receiver and back into the molten salt tank through V4, finishing a single loop. The experimental space between V5 and V6 is prepared for the single tube experiment, which is not included in this work. When experiments are finished, the electric globe valves M1-M6 are opened to drain out the molten salt from the receiver. The inlet fluid temperature and outlet fluid temperature are measured separately by thermocouple T3 and T4. The ambient temperature is measured by T10, which is installed in a place without direct sunlight. The remaining thermocouples work for the electric tracing control system of the pipeline. Molten salt is drained from the testing system by gravity, so all the horizontal pipes are set at an incline of 10° from the horizontal plane to ensure no molten salt stagnates in the pipeline. Variable-frequency motor C is used to change the speed of molten salt pump B in order to control the flow rate in the pipeline. Molten salt in the tank is composed of potassium nitrate, sodium nitrate, sodium nitrite and a small amount of additive. The melting point of the salt is 137.62 °C. The viscosity of the molten salt decrease as the temperature rises. In a high temperature state, the viscosity of the salt is less than 0.003 Pa s, which is in the same