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Transient analysis of a molten salt cavity receiver

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Abstract

A transient analysis of a molten salt cavity receiver is presented. A two-node model, which is the theoretical basis for transient analysis, is developed for the receiver. During the transient process, the energy variation of different part of the model is researched experimentally. Especially, a transient variation process of both the receiver surface temperature and fluid temperature is analyzed detailedly in the paper. The transient process due to the sudden change of input power is divided into three stages. The transient characteristic of the receiver is analyzed based on the three stages. Also the time constant which reflects the influence of the thermal inertia of the receiver is got from the experiment.

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Nomenclature

\begin{itemize}
\item $m_s$: mass of the solid part of the receiver (kg)
\item $m_f$: mass of the fluid inside the receiver (kg)
\item $C_s$: specific heat capacity of the receiver (J/(kg \cdot K))
\item $C_f$: specific heat capacity of the fluid (J/(kg \cdot K))
\item $T_s$: the mean temperature of the solid part of the receiver (K)
\item $T_f$: the mean temperature of the fluid (K)
\end{itemize}

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1. Introduction

In recent years, considerable knowledge is available about Concentrated Solar Power (CSP). The receiver is a key component of a CSP tower power plant. There are many types of receivers. Among these receivers, the molten salt receivers win much attention due to the high performance. The first commercial CSP plant with a molten salt receiver was built in 2011 [1] and the molten salt technology is believed to be a key for solving the problem of discontinuity of solar energy.

Much research into cavity receiver is concerned with the mechanism of heat loss affecting the thermal performance of the receiver [2-5]. Not many studies on the transient analysis of cavity receiver were reported [6-10]. However, the receivers always work in unsteady state conditions. Therefore, it is necessary to research the characteristics of molten salt receivers during the transient process. In this paper, a simplified two-node model of the molten salt receiver is developed. Based on the simplified model, further analysis of temperature and energy are carried out.

2. Theoretical analysis

2.1 Simplified two-node model

The whole receiver is divided into two parts, the solid part (tubes) and fluid part (molten salt). Energy balance for both tubes and fluid are considered separately. The analysis has been performed in a lumped manner for the tube and fluid temperature.

The heat balance on the tubes can be written as follows:

\[
\text{Increments of internal energy of tubes} = \text{Incident power from heliostats field} - \text{Reflection energy loss} - \text{Heat transferred from tubes to fluid} - \text{Total heat loss}
\]

\[
m_s C_s \frac{dT_s}{dt} = (Q_{in} - Q_{L,ref}) - A_{s-f} h_{s-f} (T_s - T_f) - A_s U_L (T_s - T_a)
\]

(1)

Where \( U_L \) [11] is the total heat loss coefficient of the receiver. The coefficient \( U_L \) combined the convection and radiation heat loss together. The air temperature and background temperature is approximately the same during the experiments.

For indoor experiments in this paper, reflection energy loss can be neglected. Equation (1) can be rewritten as:

\[
m_s C_s \frac{dT_s}{dt} = Q_{in} - A_{s-f} h_{s-f} (T_s - T_f) - A_s U_L (T_s - T_a)
\]

(2)

The heat balance of the fluid can be written as follows:

\[
\text{Increments of internal energy of fluid} = \text{Heat transferred from tubes to fluid} - \text{Heat removed by fluid flow}
\]

\[
m_f C_f \frac{dT_f}{dt} = A_{s-f} h_{s-f} (T_s - T_f) - m C_f (T_{f0} - T_{fi})
\]

(3)
It is convenient to define the symbols for each part of energy as follows:

\[
\begin{align*}
Q_{in,f} &= m_f C_f \frac{dT_f}{dt} \\
Q_a &= A_{s-f} h_{s-f} (T_s - T_f) \\
Q_{abs} &= m C_f (T_{fo} - T_{fi})
\end{align*}
\]

The analytical model described by equation (1) and (2) has been proved to be effective in another paper [11].

2.2 Time constant

Time constant is always an important parameter in transient process. With known time constant, it is easy to adjust the control system to keep the receiver operating safely. However, there is no published test method or calculation method for obtaining time constant of the molten salt receivers. Time constant of the solar collector can be obtained through the two established standards: ISO 9806-1 and ASHRAE 93-86 standard. However, the two standards are not suitable for the molten salt receiver because the temperature of inlet fluid \(T_{fi}\) is required to close to the ambient air temperature \(T_a\) in the two standards. The freezing point of molten salt used in our experiments is around 137\(^\circ\)C. Therefore, there is no way to lower the temperature of the salt close to the ambient temperature without freezing. Hou [12] proposed a new method for the measurement of time constant for solar collector. This new method only requires \(T_{fi}\) and \(T_a\) keeping constant during the test process. It is not necessary to adjust the \(T_{fi}\) equal to \(T_a\) as it is needed in ISO9806-1. The basic equation is as follows:

\[
\frac{T_{fo(t)} - T_{fo,initial}}{T_{fo,\infty} - T_{fo,initial}} = \left[1 - \exp\left(-\frac{t}{T}\right)\right]
\]

Where \(T\) is the time constant defined as:

\[
T = \frac{(mc)_e K}{m C_f}
\]

Two experiments are conducted to measure the time constant of the molten salt receiver according to this method. A non-dimensional parameter is defined as follows:

\[
R = \frac{T_{fo(t)} - T_{fo,initial}}{T_{fo,\infty} - T_{fo,initial}}
\]

When \(R\) reached 63.2% or 0.632, the time \(t\) is considered as the time constant of the molten salt cavity receiver. However, there is no published test method for obtaining time constant of the molten salt receiver. So these experiments are aimed to verify whether this method can obtain a parameter which can characteristic the transient response of molten salt receivers.

3. Experimental set-up

3.1 Test platform

The molten salt cavity receiver testing system is schematized in Fig. 1. The testing system includes the molten salt tank, cavity receiver, heavy-current electric heating system, electric control system, temperature and flow rate detecting system. Molten salt is stored in the molten salt tank. Electric heating melts the salt inside the tank. 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.
3.2 The molten salt cavity receiver

The cavity receiver is composed of seven panels that are installed in series. Each panel includes four stainless steel tubes. There is a header on either side of the panel with clapboard in the centre of the bottom header. The rear space of the receiver is full of rock wool for thermal insulation. The whole receiver is covered with a layer of thin stainless steel plating. Each header has a stainless steel electrode welded onto it so as to heat the panel with a heavy-current. The photograph of the receiver is shown in Fig. 2. There are three temperature measuring points on each panel. The locations of these points are shown in the Fig. 2b (located in the top header, the middle of each panel and bottom header).
3.3 The heavy-current electric heating system

The heavy-current electric heating system mainly includes two components, an induction voltage regulator and a heavy-current transformer. The induction voltage regulator (Fig. 3a) can provide a continuous variable output voltage. The induction voltage regulator is connected to the heavy-current transformer. The maximum output voltage and current of the transformer are 10V and 20kA. The connection between the transformer and the receiver is shown in Fig. 3b. Heavy-current flows into the receiver through copper and electrodes. Seven panels act like seven shunt resistances. The heat generated is enormous and raise the temperature of the tubes.

![Fig. 3. (a) The photograph of the induction voltage regulator; (b) The connection between the transformer and the receiver](image)

4. Results and discussion

4.1 Energy analysis in transient process

An experiment is conducted to analyze the energy variation in transient process. The input power rise to 73.39kW at the beginning and the volume flow rate keep constant at 7.6 l/min.

The $Q_{in}$, $Q_{in,f}$ and $Q_{abs}$ in equation (3) are analyzed in the transient process. Fig. 4 shows their variation. It is shown clearly from the Fig. 4a that the $Q_{in}$ increased over time mainly due to the increase of $Q_{abs}$. From the Fig. 4b, the $Q_{in,f}$ was only effective in the initial stage of the transient process due to the quick rise of the temperature. However, the effect of $Q_{in,f}$ is limited by the small mass of fluid inside the receiver.

![Fig. 4. (a) The variation of $Q_{in}$ and $Q_{abs}$ during the experiment; (b) The variation of $Q_{in,f}$ during the experiment;](image)
4.2 Variation of the receiver and fluid temperature in transient process

The data of experiment mentioned in section 4.1 is also used to analyze the temperature variation in the transient process. The input power rose to 73.39kW in the beginning of transient process. Figure 5a shows the temperature variation when input power suddenly rise. The whole variation process can be divided into three stages.

During \( t_{0,\text{rise}} - t_{1,\text{rise}} \), the rising speed of input power \( Q_{in} \) was larger than the rising speeds of both the heat loss and heat transferred from the receiver to fluid \( Q_{abs} \). Therefore, it is indicated from equation (2) that the internal energy increments of receiver \( (m_c C_p dT_r/dt) \) become larger in this stage. As a result, the \( T_r \) increased faster and faster. Unlike \( T_r \), the fluid temperature \( T_f \) still kept unchanged in this stage due to the thermal inertia of the molten salt.

During \( t_{1,\text{rise}} - t_{2,\text{rise}} \), the input power \( Q_{in} \) almost kept constant. The heat loss and heat transferred from the receiver to fluid \( Q_{in} \) were still increasing due to the rising \( T_r \). Therefore, it is indicated from equation (2) that the internal energy increments of receiver \( (m_c C_p dT_r/dt) \) decreased. As a result, the gradient of \( T_r \) decreased. In this stage, the \( T_f \) just began to response the increasing of \( T_r \), so the heat transferred from receiver to fluid \( Q_{in} \) increased faster than the heat removed by fluid flow \( Q_{abs} \). It is indicated from equation (3) that the internal energy increments of fluid \( Q_{in,f} \) become larger and larger. Therefore, the fluid temperature \( T_f \) began to rise faster and faster.

After \( t_{2,\text{rise}} \), the receiver surface temperature \( T_r \) was almost stable. Figure 5a shows that the temperature difference between the \( T_r \) and \( T_f \) was decreasing slightly in this stage, which indicated the \( Q_{in} \) was decreasing. However, the heat removed by fluid flow \( Q_{abs} \) still increased slowly due to the rising of \( T_{fo} \). It is indicated from equation (3) that the internal energy increments of fluid \( Q_{in,f} \) become smaller in this stage. Therefore, the gradient of the fluid temperature \( T_f \) decreased. If the input power and other parameter (such as \( T_{fo} \) and \( T_o \)) kept unchanged, the receiver would finally achieve a steady state condition.

Another experiment is conducted to research the temperature variation when input power suddenly drops. Figure 5b shows this temperature variation process. The input power dropped from 120kW to 73.39kW in less than 25s. The flow rate kept constant at 7.6 l/min. Corresponding to the rising transient process, the dropping transient process can also be divided into three stages.

During \( t_{0,\text{drop}} - t_{1,\text{drop}} \) the input power \( Q_{in} \) suddenly dropped while the heat loss and heat transferred from the receiver to fluid \( Q_{in} \) almost kept unchanged due to the thermal inertia of the receiver. For keeping energy balance, instead of the input power, the internal energy of receiver began to transform into the energy source. The \( Q_{in} \) dropped over time and the transforming speed of internal energy of the receiver was higher and higher. As a result, the receiver surface temperature \( T_r \) decreased faster and faster. However, the fluid temperature \( T_f \) almost kept unchanged due to the thermal inertia of the molten salt.

During \( t_{1,\text{drop}} - t_{2,\text{drop}} \) (\( t_{2,\text{drop}} \) is not shown in Fig. 5b), the heat transferred from receiver to fluid \( Q_{in} \) decreased due to the decreasing of \( T_r \). The heat removed by fluid flow \( Q_{abs} \) didn’t change much in the first stage. As a result, the \( Q_{in} \) was smaller than the \( Q_{abs} \). It is indicated from equation (3) that the internal energy of fluid has to transform into the
energy source in order to keep energy balance of the fluid. Therefore, the internal energy of fluid began to decrease and the fluid temperature $T_f$ began to drop faster and faster.

After $t_2^\text{drop}$, the output power (heat loss and heat transferred from receiver to fluid) decreased close to the new input power $Q_{in}$. Therefore, the receiver surface temperature $T_s$ would almost keep stable. Due to the decreasing of heat removed by fluid flow $Q_{abs}$, the difference between the $Q_{abs}$ and $Q_u$, which is known as the decrement of internal energy of fluid $Q_{in,f}$ became smaller and smaller. Therefore, the fluid temperature $T_f$ would decrease more and more slowly. Finally, the whole receiver would be in steady state if the input parameters (such as $S$, $T_{fi}$ and $T_a$) kept constant.

4.3 Time constant test of the receiver

According to Hou’s [12] method, a time constant test is conducted. The flow rate kept constant at 7.6 l/min. The inlet temperature was around 232°C. The input power of receiver rose suddenly to 118.91kW and kept constant during the test. The nearly-steady-state was assumed to exist when outlet temperature changed less than 0.2°C in one minute. Figure 6 shows the variation of non-dimensional parameter $R$. The time constant measured is around 123s. According to the definition of time constant, the flow rate affects the time constant greatly. Therefore, another test is conducted to verify the time constant in the same flow rate. The two tests have different input power and different inlet temperature. The time constant measured in the second test is around 140s. Although the conditions in the two tests vary a lot, they lead to almost the same value of time constant. This value is believed to represent the response characteristics of the receiver in transient process.

![Fig. 6. Time constant test of receiver](image)

5. Conclusion

A transient analysis is presented for a molten salt receiver. Several conclusions have been obtained.

1) The internal energy increment of fluid $Q_{in,f}$ can only affect the energy removed by fluid flow $Q_{abs}$ in the initial stage of transient process. In addition, the effect is limited by the mass of fluid inside the receiver.

2) A detailed analysis of both receiver surface temperature and fluid temperature in transient process are presented in the paper. Both the rising and dropping transient processes can be divided into three stages.

3) Two time constant tests are conducted according to Hou’s method. The measured values are close to each other. Therefore, the measured value can represent the response speed of the molten salt receiver in transient state.

However, further theory work should be done for calculating the time constant of the receiver. In addition, the input power, flow rate and inlet temperature should be controlled more effectively in order to stabilize outlet temperature.
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