The required concentration ratio for two stage water/steam cavity receiver

X. Li\textsuperscript{a,}\textsuperscript{*}, Z.F. Wang\textsuperscript{a}

\textsuperscript{a}Key Laboratory of Solar Thermal Energy and Photovoltaic System, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China.

Abstract

The pioneering water/steam cavity receiver CESA-1 is not very successful for that the evaporator and superheater are in the same cavity cause it is very difficult to control the heat flux distribution on the absorber surface and hence the flow stability inside the receiver. The two-stage water/steam receiver is a promising way for separating the evaporator and superheater in two different cavities or parts. Because the two different parts have different thermal performance, the required concentration ratio (CR) of per heliostat projected two different parts will be different. Based on the transient efficiency equation and existed DAHAN solar tower power plant, the paper research the influence principle of many factors such as receiver thermal performance, superheater operation capacity, heliostat size and numbers of heliostats projected to the absorber. The results show that the required CR of per heliostat for superheat part is decreasing with the superheater thermal performance improving. When the receiver operates in lower capacity, the required CR of per heliostat is lower. With more heliostats project to the superheater, the required CR of per heliostat becomes lower. The smaller heliostat size, the lower required CR of per heliostat. The results also give us some inspirations that: 1) using the method in the paper, one can evaluate whether the existing heliostat field is fit for the two-stage receiver. 2) two stage receiver capacity and heliostat size should be in harmony for different CR requirement for evaporator and superheater. 3) the results about how the heliostat size influences the required CR of per heliostat for superheater give the reference to industrial choose of heliostat size. 4) from the required CR point, the smaller heliostat is better than bigger one. Of course, in the real commercialization process, the cost of the heliostat should also be considered.

Keywords: Two stage water/steam receiver; concentration ratio;

* Corresponding author. Tel.: +86-10-62558289; fax: +86-10-62587946.
E-mail address: drlixin@mail.iee.ac.cn
1. Introduction

For the water/steam cavity receiver such as CESA-I, one of the problem is that the evaporator and superheater are in the same cavity cause it is very difficult to control the heat flux distribution on the absorber surface and hence the flow stability inside the receiver, therefore, it is very easier to be overheated or overcooled inside the receiver and other related problems[1–4].

To solve such kind of problem, two-stage receiver is a very promising way. The new Ivanpah solar tower power plant uses the two-stage external water/steam receiver and now in commissioning[5]. The advantages of two-stage water/steam receiver are the following:

- Using different heliostats to separately project onto the evaporator and superheater part of the receiver. Therefore, it is easier to control evaporation and superheating process separately and increase the safety and operation flexibility.
- It is easier to start the receiver and shorten the startup time because it avoids the evaporation and condense process happening at the same time in the same cavity receiver which makes the projecting more or less heliostats onto the receiver surface is a dilemma.

For the two-stage receiver, because the evaporator and superheater operation temperature are different, therefore, the heat loss are different and the required concentration ratios for the heliostats are different. Up to now, there are not papers to show how to calculate the required concentration ratio of per heliostat for two separate part of two-stage receiver. And in the commercialized solar tower power plant, the same size heliostats are used. It maybe cause some waste that the higher CR heliostats is used in the condition that only the lower required CR of per heliostat is needed.

This paper provides an easy-to-use method to evaluate the required concentration ratio for the heliostats projected to the separate receiver stage based on the receiver’s transient efficiency equation. On the basis of the Beijing DAHAN solar tower power plant heliostat field which has 100 heliostats. Every heliostat is 100m². The required concentration of per heliostat for superheater was simulated. And many influence factors such as receiver heat removal factor, numbers of heliostats, superheater heat operation capacity and heliostae area are studied in the paper. The results can give reference to the joint design of two-stage steam receiver and required heliostat concentration ratio.

2. Methodology

2.1. Mathematical model and calculation flowchart

In the two stage water/steam receiver the energy equation for the evaporator is:

\[ Q_{\text{sat}} = \dot{m} \Delta h_1 \]  (1)

Where \( Q_{\text{sat}} \) is the output power of evaporator where the heat transfer fluid change the state from subcooling water to saturation steam. The \( \dot{m} \) is the fluid mass flowrate. \( \Delta h_1 \) is the enthalpy change.

The energy equation for the superheater is:

\[ Q_{\text{sup}} = \dot{m} \Delta h_2 \]  (2)

Where \( Q_{\text{sup}} \) is the output power of superheater where the heat transfer fluid change the state from the saturation steam to the superheating steam. \( \Delta h_2 \) is the enthalpy change.

The total energy balance equation is:

\[ Q_{\text{in}} \cdot \eta_{\text{rec}} = Q_{\text{sat}} + Q_{\text{sup}} \]  (3)
Where $Q_{in}$ is the incident power from the heliostat field to the receiver absorber surface. $\eta_{rec}$ is thermal efficiency of the receiver, means the output energy divided by the incident power from the heliostat field.

The transient efficiency equation for the concentrated collector is[6,7]:

$$
\eta_{rec} = F_R \eta_0 - \frac{F_R U_L \left( T_i - T_a \right)}{I_{b,n}} \frac{Q_{useful}}{I_{b,n} \cdot A_n}
$$

(4)

Where $F_R$ is the heat removal factor which indicate that the actual useful energy gain of a receiver to the useful gain if the whole receiver surface were at the fluid inlet temperature. The $U_L$ is the global heat loss coefficient of the receiver. $\eta_0$ is the optical efficiency of the heliostat field. $CR$ is the concentration ratio of the concentrator. $I_{b,n}$ is the direct normal irradiation. $T_i$ is the inlet temperature of the receiver. $T_a$ is the ambient temperature. $A_n$ is the aperture area of heliostat field, which is area of per heliostat aperture area multiple the heliostat numbers. $Q_{useful}$ is the effective heat gain of the receiver, for the evaporator and superheater part the $Q_{useful}$ is equal to the $Q_{sat}$ and $Q_{sup}$ respectively.

In the industrial design, commonly the heat transfer fluid flowrate, inlet and outlet temperature and pressure are known. The efficiency of receiver is also a demanded parameter. Based on these data the superheater and evaporator output capacity can be calculated.

The transient efficiency equation is often used to evaluate the thermal performance of collector not only for the un-concentrated but also for the concentrated one.

From the receiver thermal capacity and transient efficiency equation the required concentration ratio can be deduced. The fig.1 shows the above mentioned flowchart of calculation.
According to the design parameters

\[ Q_{\text{sat}} = m \cdot \Delta h_1 \]
\[ Q_{\text{sup}} = m \cdot \Delta h_2 \]
\[ Q_{\text{an}} \cdot \eta_{\text{rec}} = Q_{\text{sat}} + Q_{\text{sup}} \]

Calculate thermal capacity of superheater

Transient efficiency equation for the receiver

\[ \eta_{\text{rec}} = \frac{F_R \eta_0}{CR} + \frac{F_R U_L}{I_{b,n}} \left( \frac{T_1 - T_a}{I_{b,n}} \right) = \frac{Q_{\text{useful}}}{I_{b,n} \cdot A_{a}} \]

Joint-adjust heliostat area or receiver thermal performance

Calculate the required concentration ratio

No

CR satisfy the demand

Yes

End

Fig. 1. The flowchart of calculation.
2.2. The heliostat field and receiver parameters for the DAHAN solar tower power plant

DAHAN solar power plant is a well constructed 1MWe solar tower power plant in Yanqing Badaling, which has 10000m$^2$ heliostat field and a 7MWh cavity water/steam receiver, as shown in fig 2. The area for per heliostat is 100m$^2$. The cavity water/steam receiver is a single cavity receiver which the evaporator and superheater are in the same cavity.

In order to study the principle of required concentration ratio for two-stage water/steam receiver with the influence factors, the DAHAN was used as the case studies. The table 1 is the parameters of the DAHAN water/steam receiver.

<table>
<thead>
<tr>
<th>DAHAN water/steam receiver</th>
<th>Inlet temperature /°C</th>
<th>Outlet temperature /°C</th>
<th>Pressure /MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporator</td>
<td>104</td>
<td>231.8</td>
<td>2.89</td>
</tr>
<tr>
<td>Superheater</td>
<td>231.8</td>
<td>400</td>
<td>2.8</td>
</tr>
</tbody>
</table>

The designed receiver efficiency is 90% and design point for the DNI is equal to 796kW/m$^2$. The aperture area of the DAHAN cavity is 25m$^2$. The nominal flowrate of receiver is 8.7t/h.

3. Results and discussion

During the real operation of solar tower power plant, with the change of DNI, the steam temperature and pressure, water level in the drum change. The fluid flowrate in evaporator and superheater are different. Because the required
The concentration ratio for superheater is determined in the design process, we simplify these real complex transient conditions to steady state condition and all the above mentioned parameters are in stable. Therefore, the capacity percentage of superheater in total receiver capacity is \( \frac{\Delta h_2}{\Delta h_1 + \Delta h_2} \) which is equal to 15.41%. Based on the DNI and receiver inlet and outlet parameters, the superheater nominal thermal capacity can be calculated as 1037kW.

The \( F_R, U_L \) are concerned with the thermal performance of the receiver. \( Q_{\text{useful}} \) is concerned with the thermal capacity of the receiver, \( A_a \) is the multiple of per heliostat area and numbers of heliostats which are concerned with the heliostat field and every heliostat structure. All these parameters strongly influence the required concentration ratio of the superheater.

3.1. The influence of receiver thermal performance

Normally, the \( F_R \) for the concentrator collector is bigger than the flat plate collector. For example, the \( F_R \) for parabolic trough collector is about 0.91, but for the flat plate collector this value is 0.8. Therefore, for the solar tower receiver, it is possible that the \( F_R \) is bigger than 0.91. For the solar dish collector the \( U_L \) is bigger than 186 \( W / (m^2.K) \) \(^{[7]} \).

The fig.3 shows the required CR of per heliostat versus \( F_R \) and \( U_L \) at the condition that the receiver superheat thermal capacity is nominal 1037kW, the per heliostat area is 100m\(^2\) and the numbers of heliostats projected to the superheater is 20. As shown in fig.3, at the given \( U_L \), with the \( F_R \) increasing, the required CR of per heliostat decreasing. It is similar that with the \( U_L \) decreasing the required CR of per heliostat decreasing. \( F_R \) increasing and \( U_L \) decreasing mean that the receiver superheater thermal performance becomes better. In other words, when the receiver superheater thermal performance becomes better, the required CR of per heliostat becomes lower, it will make the heliostat manufacturing easier.

For the DAHAN power plant, the per heliostat CR is 100/25=4. For the calculation results in fig.3, when the receiver in the best thermal performance, the \( F_R \) and \( U_L \) is 0.99 and 170kW/m\(^2\) respectively, the required CR of per heliostat is 14.82, it is obvious that the existed heliostat and heliostat field is not fit for the two-stage water/steam receiver superheater with nominal thermal capacity 1037kW. Of course, increasing the numbers of heliostat is one of candidate way to decrease the CR of per heliostat, but it will also cause too fewer heliostats projected to evaporator hence not enough output thermal energy from the evaporator. This condition will be discussed in section 3.3.
3.2. The influence of superheater thermal capacity

Fig. 3. The required concentration ratio of per heliostat vs heat removal factor at different receiver heat loss coefficients.

Fig. 4. The required concentration ratio of per heliostat vs heat removal factor at different receiver superheater thermal capacity.
From the section 3.2 we know that the existed DAHAN heliostat and heliostat field is not fit for the two-stage water/steam receiver. If the thermal capacity of the superheater become lower, maybe the required CR of per heliostat become lower. As shown in fig. 4, when the superheater thermal capacity changes from nominal capacity 1037kW to 60% capacity 622kW with the $U_L$ equal to 200W/(m².K), the number of heliostats is 20, the per heliostat area is 100m², the required CR of per heliostat reduce to the minimum value 6.22. It is obvious that with the superheater thermal capacity decreasing, the required CR of per heliostat decreasing. In fact, even 60% superheater thermal capacity, the existed DAHAN heliostat is still not fit for the two-stage water/steam receiver.

### 3.3. The influence of heliostat field

It can be imagined that if we put more heliostats to the superheater as mentioned in section 3.1, it will reduce the required CR of per heliostat. As shown in the fig. 5, with the number of heliostats projected to the superheater increasing, the required CR of per heliostat decreasing. When $n$ is equal to 28 at the condition that $Q_{\text{useful}}$ is 1037kW, $U_L$ is 200W/(m².K) and area of per heliostat is 100m², the minimum required CR of per heliostat is 6.71. If we project more heliostats to the superheater, the required CR of per heliostat will be lower. But the heliostats projected to the evaporator will be not enough to produce the nominal output power.

Therefore, form section 3.1~3.3 we can see that for the existed DAHAN power plant without any structural changes, improving the thermal performance of the receiver, projecting more heliostats to the superheater and reducing the superheater thermal capacity all can’t meet the required CR of per heliostat.

![Fig. 5. The required concentration ratio of per heliostat vs heat removal factor at different numbers of heliostats projected to the superheater.](image)

### 3.4. The influence of per heliostat area

The concentration ratio for the receiver is the multiple of per heliostat concentration ratio with the numbers of heliostats. When keep the receiver can reach the nominal thermal capacity 1037kW, the fig. 6 showed that with the smaller heliostat, the required CR of per heliostat become lower. When the per heliostat area is 1m², the required CR of per heliostat is only from 0.17 to 0.31. It means that the 1m² heliostat need not to be concaved to meet the
required CR. When the per heliostat area is 11m², the required CR of per heliostat is only from 1.91 to 3.34. It means that the 11m² heliostat only need to be very little concaved, it is very easy to be realized in manufacturing.

![Graph](image)

Fig. 6. The required concentration ratio of per heliostat vs heat removal factor at different per heliostat area when the nominal superheater thermal capacity can be satisfied.

Therefore, if we use smaller heliostats, it will be very easier for the heliostat to meet the required CR of per heliostat. And there must be a area, the simple flat heliostat mirror can meet the required CR, it will significantly reduce the production cost.

4. Conclusions

In the solar tower power plant, the heliostat field and receiver design is a joint design process. For the two-stage water/steam receiver, because the evaporator and superheater are in different operation temperature, different thermal performance, hence the requirement for per heliostat concentration ratio will be different. The receiver thermal performance and heliostat size and heliostat field influence the required CR of per heliostat.

- The receiver heat removal factor, the receiver heat loss coefficient are the main factors of receiver thermal performance. With the receiver performance better namely the heat removal factor bigger and heat loss coefficient lower, the required CR of per heliostat is lower.
- When the superheater operate in the lower capacity, the required CR of per heliostat is lower.
- The bigger and smaller heliostat which one is better, is a very common question in solar tower power plant design. In the paper, the results showed that the smaller heliostat has lower required CR of per heliostat, it will make it easier to be produced and it is easier for the heliostat field to realize the multi-target control. The superheater thermal capacity and per heliostat area should be in harmony. Too bigger heliostat cant meet the required CR of per heliostat. Anyway, form the required CR of per heliostat point, the smaller heliostat is better. Of course, in the real commercialization process, the cost of the heliostat should also be considered.
Acknowledgements

The author thanks to Dr. E.Xu and F.Bai for good discussion with me about the topic of required CR of per heliostat.

References