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Allowable flux density on a solar central receiver

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ABSTRACT

The allowable flux density on a solar central receiver is a significant receiver parameter and is related to the receiver life span and economics. The allowable flux density has gradually increased as receiver technologies have developed and is related to various factors, such as the material characteristics, tube sizes, and internal tube flow conditions. A mathematical model was developed to calculate the allowable flux density for the Solar Two receiver which agrees well with published data. The model was then used to show that a higher allowable flux density can be obtained by increasing the allowable strain of the tube material and the fluid velocity and decreasing the tube thermal resistance, the convective thermal resistance, and the tube diameter and wall thickness. A sensitive analysis shows that the most important influence is the wall thickness, followed by the tube diameter and fluid velocity. Finally, a molten salt receiver gives a much higher allowable flux density than water/steam receivers and is even better than a supercritical steam receiver.

1. Introduction

Concentrating solar power (CSP) stations that have the potential to supply base load electrical power [1] are one of the most promising renewable energy sources. Solar power towers, use thousands of heliostats mirrors to focus sunlight on the receiver absorption surfaces to achieve high heat flux densities and high temperatures. Accordingly, solar power towers have better efficiencies than parabolic troughs which are another important significant CSP method [2].

In solar power tower plants, the receiver that accounts for about 15% of the total plant investment cost [3] is an essential component. Almost all cavity receivers and external receivers are tube-type receivers using tubes to absorb the highly concentrated solar energy and to transmit the energy to the heat transfer fluid, such as water/steam, steam, a molten salt or air [4–7]. The incident flux density focused on the outside surfaces of the receiver tubes by the heliostat field is hundreds times that of direct normal irradiation. During the passage of clouds, start-up and shut-down, the concentrated sunlight flux density goes through considerable changes [8] that result in large temperature gradients and thermal strains which can result in elastic and plastic deformation of the tubes. Accumulated deformation, especially plastic deformation, can lead to receiver failure. Generally, the flux density to the outside surfaces of the receiver tubes is quite limited to give a reasonable life time. The maximum flux density allowed (allowable flux density), q''_{omax}, has progressively increased for many years. For example, the receiver in the Solar One pilot plant, completed in 1981, had a q''_{omax} of 350 kW m^{-2} [9]. The most famous plant Solar Two, built in 1996, had a receiver minimum q''_{omax} of 800 kW m^{-2} [10]. More recently, the q''_{omax} of the DIAPR multistage is more than 2000 kW m^{-2} [11].

The q''_{omax} is a significant parameter for the receiver since it is directly related to the heliostat field working strategy concerning how many heliostats can be put into use and what aiming point strategy should be used. The q''_{omax} also strongly influences the receiver size and economies [12]. A larger q''_{omin} gives a smaller receiver area and less heat losses, which increases the efficiency and lowers the electricity cost [4]. Smith [13] used a cubic profile for the molten salt temperature to calculate the q''_{omax}, but Vant-Hull [9] pointed out that the q''_{omax} depends not only on the salt temperature and velocity, but also on the tube properties and receiver parameters. With a 30-year target lifetime and temperatures of more than 600 °C for normal conditions, the receiver design must be able to stand with creep due to thermal strains at high temperatures during steady operation and cycling fatigue resulting from daily start-ups, shut-downs and cloud transients. Experiments by Grossman et al. [14] showed that creep has less effect

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than thermal cycling. Zavoico [15] noted that receiver tubes will undergo 36,000 thermal cycles during a 30-year life time. Cycle accumulation strain, which is determined by several factors including the tube material, tube size, and tube wall temperature distribution, must be limited to prevent failure of the receiver. The tube wall temperature distribution results from the insolation heat flux concentrated on the outside tube surface with the cooled working fluid flowing inside the tube. The receiver q''_{omax} is then a function of the tube material, tube size and flow conditions.

Although some previous studies have analyzed the tube heat theories, few have clearly predicted the q''_{omax} [14,16–18]. Results of these previous studies were used here to build mathematical model to predict the q''_{omax}. The model is compared to data for the q''_{omax} of the Solar Two receiver. Then, the modeling is used to analyze the effects of key factors, including the tube thermal resistance, the convective flow thermal resistance, the tube diameter, the wall thickness and the working fluid velocity. A sensitivity analysis illustrates the influences of these parameters. Finally, the model is used to compare the q''_{omax} of three different types of receivers include using molten salt, water/steam, and just steam receiver as the working fluid.

2. Mathematical model

Grossman et al. [14], Kolb [17] and Pacheco et al. [19] gave preliminary mathematical models for the allowable flux density, q''_o. The receiver tubes are heated by sunlight concentrated by the heliostat field and cooled by the working fluid inside the tube. This can be simplified to a one-dimensional radial heat transfer process as shown in Fig. 1.

In practice, as illustrated in Fig. 1, only the sunward sections of the receiver tubes absorb the sunlight, so there is a non-uniform flux distribution on the outside tube surfaces. A cosine distribution is assumed in this paper as:

$$q''_\theta = q''_o \cos(\theta) \tag{1}$$

where θ ranges from $-90°$to $90°$ on the sunward section.

The outer and inner surface temperatures on the sunward section are calculated as:

$$T_i(\theta) = T_f + q''_\theta \frac{D_o}{D_i}\frac{1}{h} \tag{2}$$

$$T_o(\theta) = T_i(\theta) + q''_\theta\left(\frac{D_o}{2k_w}\right)\ln\left(\frac{D_o}{D_i}\right) \tag{3}$$

The Nusselt number for turbulent flow inside the tubes is determined from the Gnielinski correlation [20]:

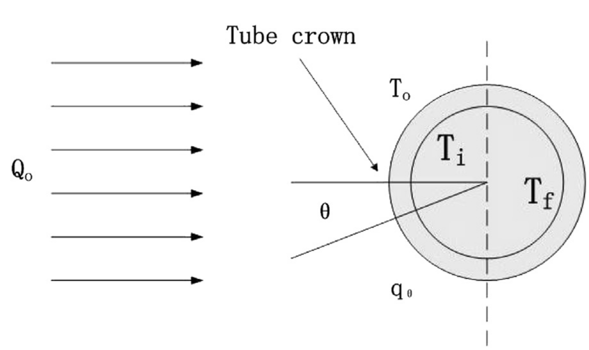

Fig. 1. Concentrated sunlight heats the receiver tube [17].

$$\mathrm{Nu} = \frac{\frac{f}{8}\left(\mathrm{Re} - 1000\right)\mathrm{Pr}}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(\mathrm{Pr}^{\frac{2}{3}} - 1\right)} \tag{4}$$

where Re is defined as:

$$\mathrm{Re} = \frac{\rho V_f D_i}{\mu} \tag{5}$$

Then, the convective heat transfer coefficient is defined as:

$$h = \mathrm{Nu}\frac{k_f}{D_i} \tag{6}$$

According to test data from the Solar Two receiver [17], f was estimated to be 0.054.

In general, the axial thermal strains in the receiver tubes can be eliminated by proper design. Consequently, the thermal strains in the tubes are analyzed as a plane-radial strain problem, with the strain due to the tube wall front-to-back temperature difference [19]. The tube crown has the highest temperature, so the highest thermal strain will also be at this location. The strain is determined as [21]:

$$\varepsilon = \alpha\left[\frac{T_o - T_i}{2(1-\nu)} + \left(\frac{T_o - T_i}{2} - T_{ave}\right)\right] \tag{7}$$

which assumes that the temperature of the backside of the tube wall, opposite the sunward section, is the same to the working fluid temperature, T_f. The average tube temperature can be approximated as:

$$T_{ave} = \frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{T_o(\theta) + T_i(\theta)}{2} d\theta + \pi T_f}{2\pi} \tag{8}$$

Combining Eqs. (1)–(8) gives:

$$\varepsilon = \alpha q''_o\left[\frac{2}{1-\nu}R_{cond} + \frac{\pi}{\pi - 1}\left(\frac{1}{2}R_{cond} + R_{conv}\right)\right] \tag{9}$$

where R_{cond} and R_{conv} are defined as:

$$R_{cond} = \frac{D_o}{2k_m}\ln\left(\frac{D_o}{D_i}\right) \tag{10}$$

$$R_{conv} = \frac{D_o}{D_i}\frac{1}{h} \tag{11}$$

These equations show that, for a given receiver, the thermal strain is directly related to the working fluid temperature. The tube strain, ε, is limited, so each fluid temperature has an allowable flux density, q''_o, which is limited by the ε_{as}. There is then a minimum allowable flux density, the receiver q''_{omax}, at some fluid temperature in the receiver as shown in Section 3.

3. Results and discussion

3.1. Model verification

The mathematical model is further used to calculate the q''_{omax} of Solar Two receiver. The parameters are listed in Table 1 and the heat transfer fluid is a molten nitrate salt (60% $NaNO_3$ and 40% KNO_3) [19]. The ASME Boiler and Pressure Vessel Code Section III [22]