Analysis of Superheater Tubes with Mutual Irradiation as Applied to a Solar Receiver Steam Generator

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Abstract: The objective of this paper is to analyze the circumferential temperature variations within a superheater tube of a solar receiver steam generator. The tube is heated by concentrated, collimated solar irradiation with major cooling by an internal steam flow. The influence of heat loss by radiation, internal convection, and conduction within the tube on the temperature distribution are considered. Analytical models that may be applied to solar receiver steam generator designs are obtained for an isolated tube, and the significance of mutual irradiation of adjacent tubes is studied using COMSOL Multiphysics. It is found that the maximum temperature of the outer surface of the tubes decreases by over 100K as the internal convective heat transfer coefficient increases by a factor of three. Also, the radiosity decreases as the emissivity of the radiating surfaces increases.

Keywords: Heat Transfer, Radiation, Solar Receiver

1. Introduction

Central solar receiver steam generators consist of dual axis tracking heliostats to concentrate solar radiation onto a tower mounted central receiver [1]. The radiant energy is used to heat the working fluid, high pressure superheated steam, to a high temperature. The working fluid is for use in a turbo generator, as is typical in conventional electricity generating plants. Membrane panels of tangent tubes may be applied to the central receiver of the solar power system as the heat transfer medium between the concentrated solar irradiation and the working fluid. The tube panels are typically flat but arranged to form an approximate cylindrical surface. With the aim of maximizing the use of existing technology, an ideal solar steam generator used for electricity production utilizes the same equipment as a fossil fuel fired electric utility, including high temperature materials and steam turbines.

The tubes of the solar steam generator are heated by the concentrated collimated solar flux from the array of heliostats. As well as the intended heat transfer from the tube to the steam, the tube is also cooled by conduction (axially and circumferentially), internal convection and thermal radiation exchange with the surroundings, consisting of the ambient and adjacent tubes (Figure 1). For solar thermal applications, a selective surface is often applied to the absorber in order to increase the absorptivity for solar irradiation, α, and decrease the emissivity for infrared surface emission, ε.

Analytical models for a two-dimensional system, which may be applied to solar receiver steam generator designs, are developed for an isolated tube. The various modes of heat transfer in the superheater tubes are considered, with a focus on the influence of the radiation interchange between a tube and its surroundings.

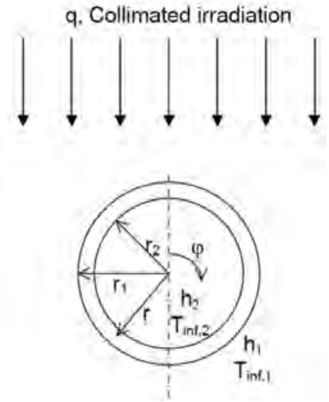


Figure 1. Long, thick walled cylinder with external collimated incident radiation, radial and circumferential conduction, and internal and external convection.

In order to extend the analysis and understand the effect of mutual irradiation of adjacent tubes, a 2D model is also set up in COMSOL Multiphysics.

The influence of different system parameters (external emissivity, internal convection, and the heat losses by radiation and tube conduction) on the temperature distribution and radiosity is analyzed. The radiosity represents the sum of the radiation emitted and reflected by the surface.

2. Analytical model

Mackowski [2] provides an analytical model for a long, annular cylinder with temperature variation in both r and φ, convection on the internal and external surfaces, and the outside of the pipe is exposed to a collimated source of thermal radiation, as shown in Figure 1.

The non-dimensional temperature distribution of Mackowski is given by:

$$\overline{\mathrm{T}}(\overline{\mathrm{r}},\varphi)=\frac{1+\pi.\mathrm{Bi}_1\overline{\mathrm{T}}_{\infty,1}}{\pi.(\mathrm{Bi}_2+\mathrm{Bi}_1(1-\mathrm{Bi}_2\ln(\mathrm{a})))}\left(1+\mathrm{Bi}_2\ln\left(\frac{\overline{\mathrm{r}}}{\mathrm{a}}\right)\right)+$$

$$\frac{1}{2(\mathrm{g}_1'(1)+\mathrm{Bi}_1\mathrm{g}_1(1))}\mathrm{g}_1(\overline{\mathrm{r}})\cos(\varphi)+$$

$$\frac{2}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^{\mathrm{n}}\mathrm{g}_{2\mathrm{n}}(\overline{\mathrm{r}})\cos(2\mathrm{n}.\varphi)}{(1-4\mathrm{n}^2)(\mathrm{g}_{2\mathrm{n}}'(1)+\mathrm{Bi}_1\mathrm{g}_{2\mathrm{n}}(1))}$$

where

$$\overline{T}=\frac{(T-T_{\infty,2})k}{\alpha_{rad}qr_1} \qquad \overline{r}=\frac{r}{r_1} \qquad a=\frac{r_2}{r_1}$$

$$Bi_1=\frac{h_1r_1}{k} \qquad Bi_2=\frac{h_2r_2}{k}$$

$$\overline{T}_{\infty,1}=\frac{(T_{\infty,1}-T_{\infty,2})k}{\alpha_{rad}qr_1}$$

$$g_n(\overline{r})=(\overline{r})^n+a^{2n}\frac{n-Bi_2}{n+Bi_2}(\overline{r})^{-n}$$

$$g_n'(1)=n\left(1-a^{2n}\frac{n-Bi_2}{n+Bi_2}\right)$$

Mackowski model was used to determine the temperature distribution within a thick shell exposed to collimated irradiation (Figure 2). The combined effects of solar irradiation, internal convection and the two dimensional conductivity of the thick walled tube were considered. The temperature variation within the tube wall was shown to be influenced by the material conductivity, wall thickness and internal convection coefficient [3]. The results for the base case, $\alpha_1 = 0.95$, $k = 27.9$ W/(m.K) and $h_2 = 4720$ W/(m^2.K) are shown in Figure 2. However, this model does not take into account the thermal radiation exchange between the surfaces of adjacent tubes.

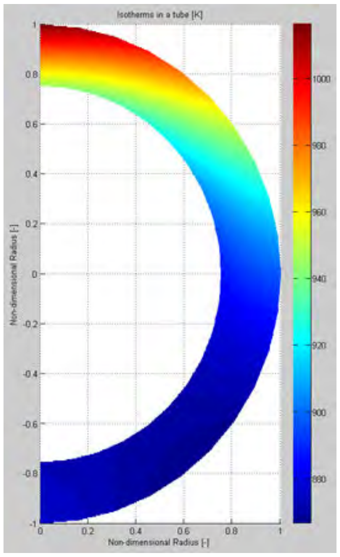
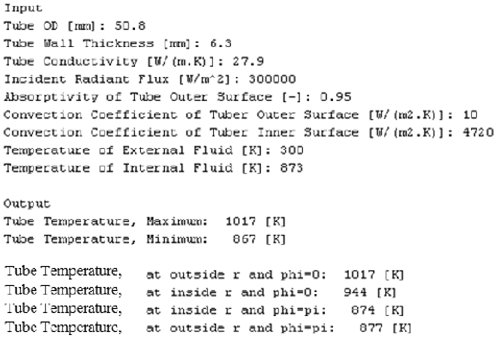


Figure 2. Surface plot of tube temperature at design conditions (Mackowski model).



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Input
Tube OD [mm]: 50.8
Tube Wall Thickness [mm]: 6.3
Tube Conductivity [W/(m.K)]: 27.9
Incident Radiant Flux [W/m^2]: 300000
Absorptivity of Tube Outer Surface [-]: 0.95
Convection Coefficient of Tuber Outer Surface [W/(m2.K)]: 10
Convection Coefficient of Tuber Inner Surface [W/(m2.K)]: 4720
Temperature of External Fluid [K]: 300
Temperature of Internal Fluid [K]: 873

Output
Tube Temperature, Maximum:  1017 [K]
Tube Temperature, Minimum:   867 [K]

Tube Temperature,   at outside r and phi=0:  1017 [K]
Tube Temperature,   at inside r and phi=0:   944 [K]
Tube Temperature,   at inside r and phi=pi:   874 [K]
Tube Temperature,   at outside r and phi=pi:   877 [K]
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3. Use of COMSOL Multiphysics

A heat transfer in solids model with surface-to-surface radiation was setup using COMSOL Multiphysics to include the heat transfer by mutual irradiation of adjacent tubes (Figure 3). Stationary conditions were assumed with the main parameter values indicated in Figure 2. The radiation source was assumed to be a black body, while the emissivity of the tube external surface was varied from ε = 0.05 to ε = 0.15. The results for the base case (ε = 0.09) are shown in Figures 4 and 5.

Figure 4 shows the heat flux distribution at the inner surface of the tube as a function of the y-coordinate. It can be seen that the flux at the bottom half of the tube is quite low, but it increases significantly in the upper half.

The temperature variations along the outer and inner surfaces of the tube are shown in Figure 5. In the bottom half of the tube, the inner surface temperature is quite close to the steam temperature, and both surface temperatures are quite uniform. On the other hand, in the upper half of the tube, both surface temperatures and their difference increase significantly with the y-coordinate.

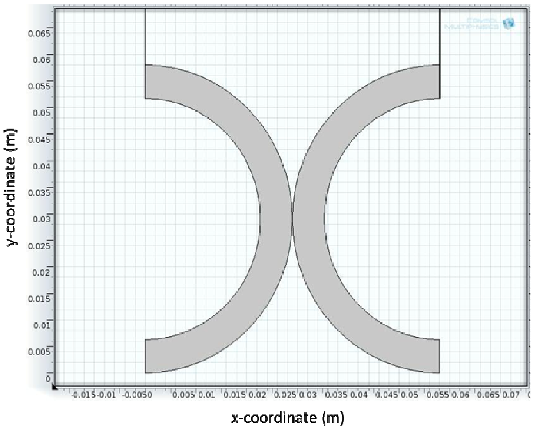

Figure 3. Schematic of superheated tubes section.

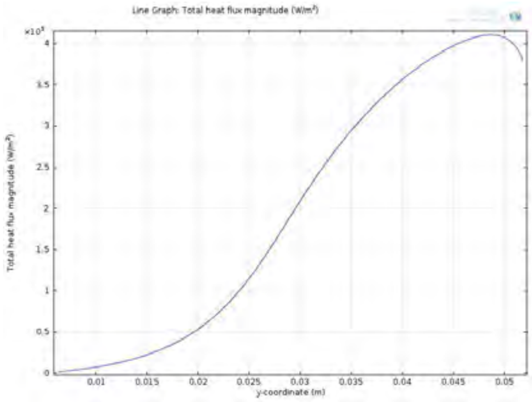

Figure 4. Heat flux distribution at the inner surface of a 6.3 mm thick tube – base case.

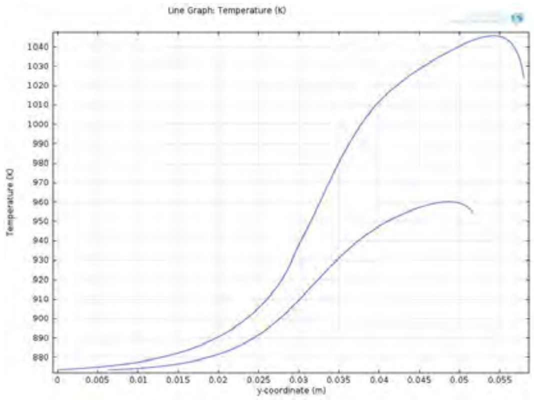

Figure 5. Temperature distribution at the outer and inner surfaces of a 6.3 mm thick tube – base case.

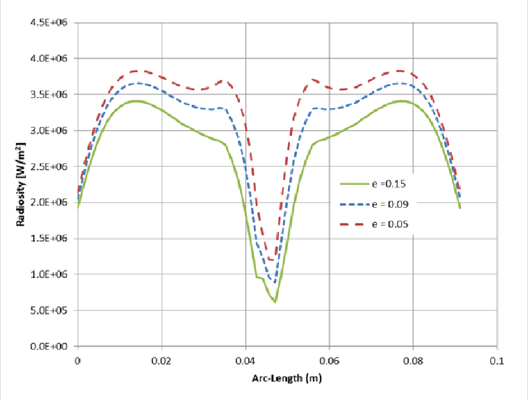

Figure 6. Effect of emissivity on the radiosity distribution at the tubes outer surfaces.

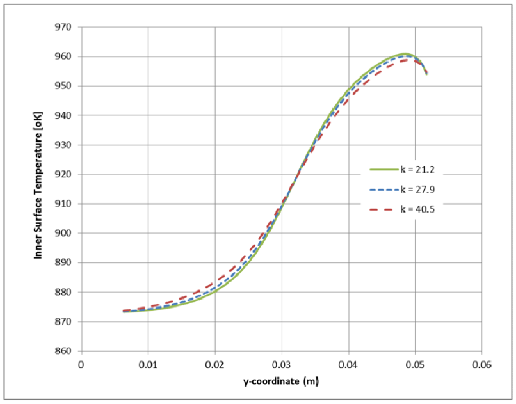

Figure 7. Effect of tube thermal conductivity on the inner surface temperature (k in W/(m.K)).

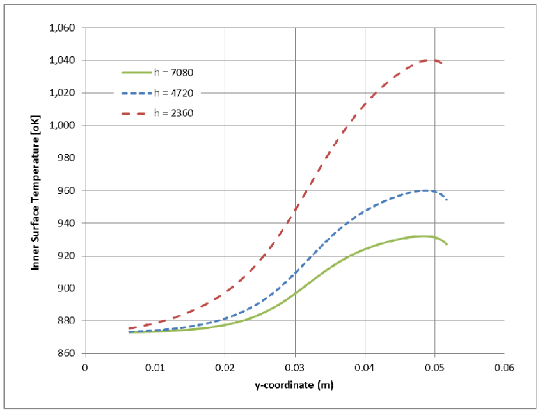

Figure 8. Effect of internal heat transfer coefficient on the inner surface temperature (h_2 in $W/(m^2.K)$).

The effects of the emissivity, the tube thermal conductivity and the convective heat transfer coefficient on the system behavior are shown in Figures 6 - 8.

The radiosity of the tubes outer surfaces that are exposed to the radiation are shown in Figure 6 as a function of the coordinate along the surfaces. A maximum is observed at a distance of about D/4 from the azimuth, while a significant decrease is noted as the point of contact of two adjacent cylinders is approached. Also, as the emissivity of the radiating surfaces increases the radiosity decreases.

Different qualities for the material of construction of the tubes were considered. The thermal conductivity of the tubes increases from that of SA213 TP316N steel to SA213 T91 steel and finally to carbon steel, and the effect on the thermal behavior of the system was analyzed. As expected, a slightly more uniform temperature distribution along the tube circumference is observed for the more conductive material (Figure 7). Also, as the thermal conductivity of the steel increases from 21.2 to 40.5 W/(m.K), the maximum outer surface temperature of the cylinder decreases by about 55K. There is also a slight shift in the point at which the maximum occurs.

Since the convection heat transfer coefficient to the steam is a function of temperature, flowrate, etc., an analysis of the effect of the variation of the coefficient was carried out. The effect on the inner surface temperature is more significant than that of the thermal conductivity, with a more uniform temperature for the highest heat transfer coefficient (Figure 8). It can also be seen that, as the heat transfer coefficient increases from 2360 to 7080 W/(m.K), the maximum outer surface temperature of the cylinder decreases by about 105K. Again, there is a slight shift in the point at which the maximum occurs.

4. Conclusions

Two dimensional analytical and numerical models were developed to predict temperature distribution, heat fluxes and mutual irradiation of adjacent tubes in a central solar receiver steam generator. The results obtained help understand the effect of different system parameters and can lead to the optimization of a steam generator design.

5. References

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6. Acknowledgements

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