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

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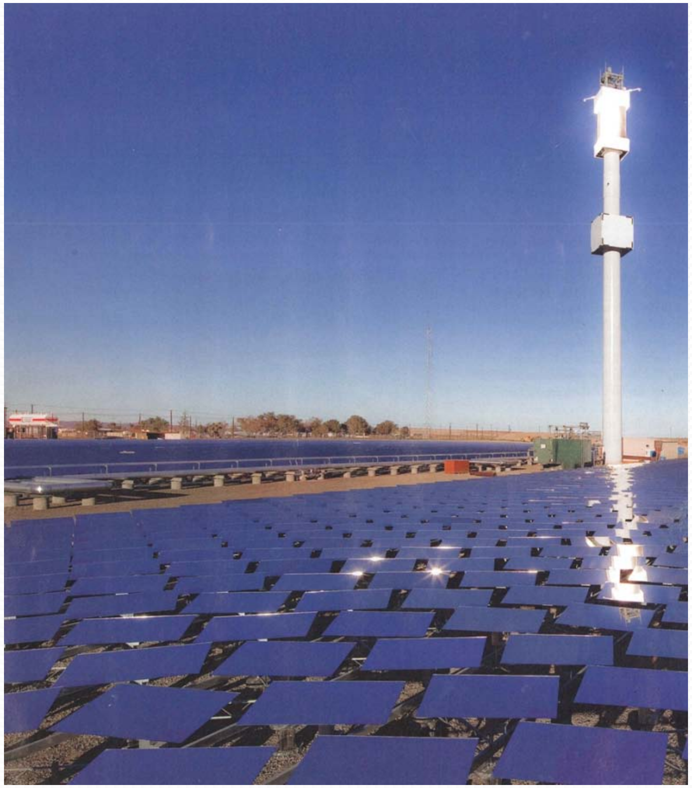
Background

Central solar receiver steam generators consist of dual axis tracking heliostats to concentrate solar radiation onto a tower mounted central receiver. The radiant energy is used to heat the working fluid to a high temperature. The working fluid is high pressure superheated steam for use in a turbo generator, as is typical in conventional electricity generating plants.

Concentrating Solar Power (CSP) is being widely commercialized, with about 740 MW of generating capacity added between 2007 and end of 2010, bringing the global total to 1,095 MW. Spain added 400 MW in 2010, while the U.S. added 78 MW, including two fossil-CSP hybrid plants.



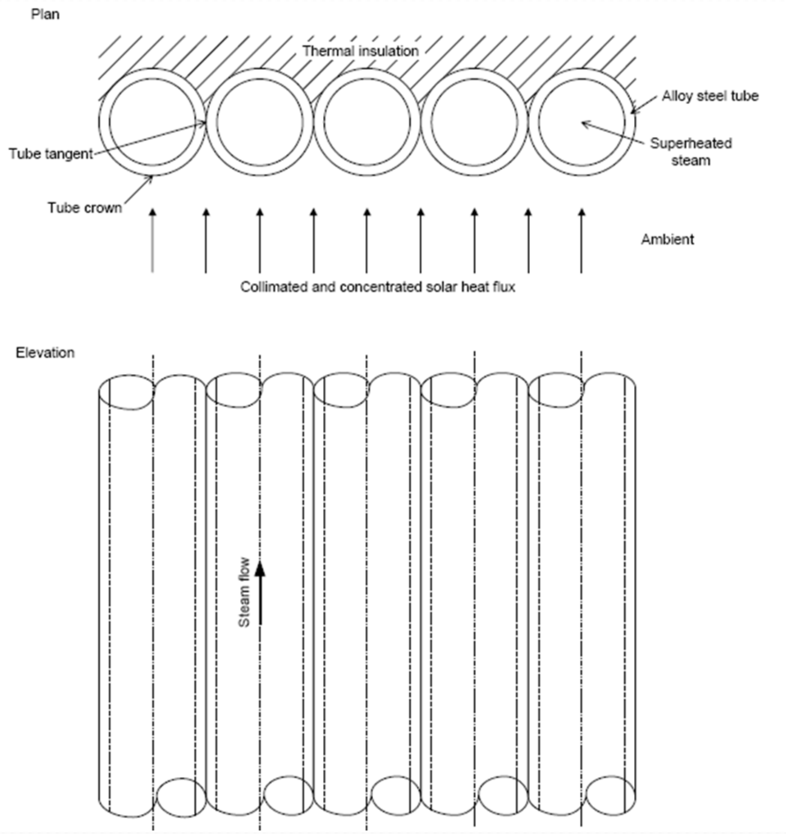
Central solar receiver steam generator and heliostat array (Boulden 2012).

Background

The tubes of the solar receiver steam generator are heated by a concentrated collimated solar flux from the array of heliostats to increase the temperature of the superheated steam flowing within.

As well as the intended heat transfer from the tube to the steam, the tube is also cooled by conduction (axially and circumferentially), external convection, and thermal radiation exchange with the surroundings, consisting of the ambient and adjacent tubes.

The resulting equilibrium temperature distribution within the tube is of interest to the designer of steam generators, as the maximum mean tube metal temperature defines the maximum allowable stress to be used for the design of cylindrical components under internal pressure.



Objective

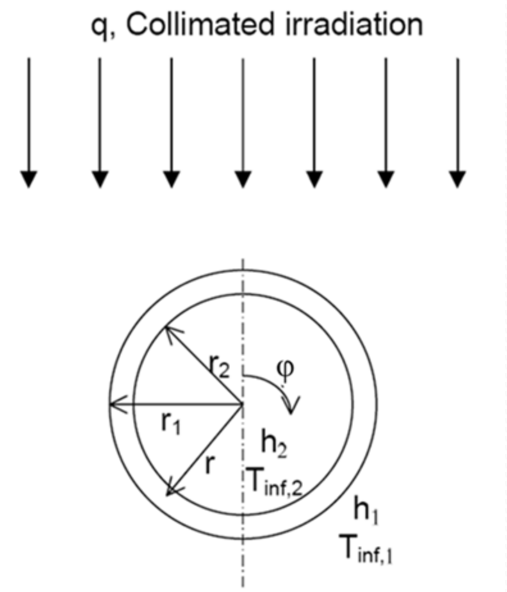
- The objective of this paper is to analyze the circumferential temperature variations within a superheater tube of a solar receiver steam generator.

- Analytical models that may be applied to solar receiver steam generator designs are used to study the behavior of an isolated tube.

- In order to analyze the significance of mutual irradiation of adjacent tubes a numerical study is carried out using COMSOL Multiphysics.

Analytical Model

Mackowski (2011) 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.



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

$$\frac{1}{2(g_1{}'(1)+\mathrm{Bi}_1 g_1(1))}g_1(\bar{r})\cos(\varphi)+$$

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

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

$$\bar{r} = \frac{r}{r_1}$$

$$a = \frac{r_2}{r_1}$$

$$Bi_1 = \frac{h_1 r_1}{k}$$

$$Bi_2 = \frac{h_2 r_2}{k}$$

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

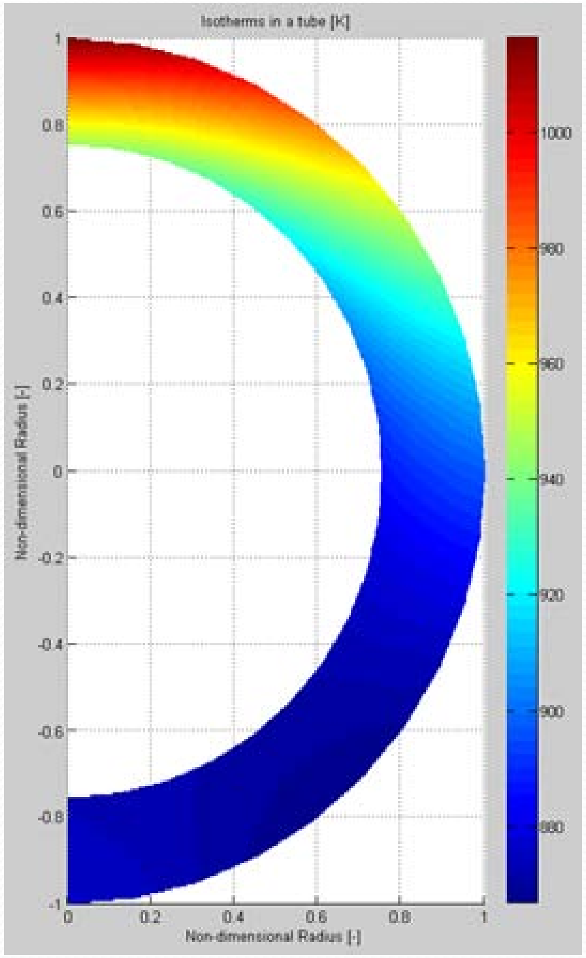
$$g_n(\bar{r}) = (\bar{r})^n + a^{2n}\frac{n-Bi_2}{n+Bi_2}(\bar{r})^{-n}$$

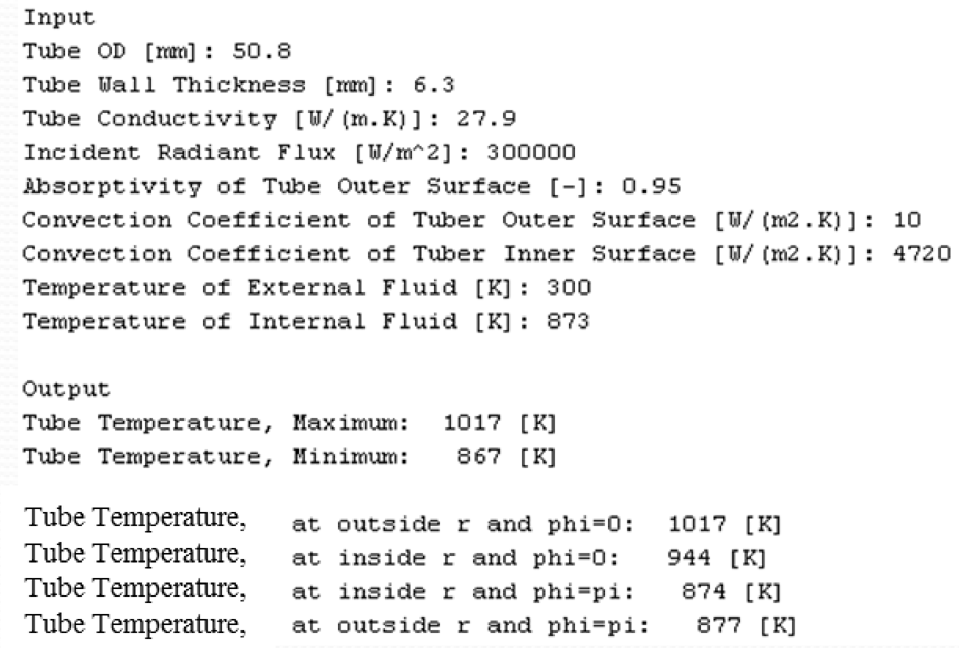
$$g_n'(1) = n\left(1-a^{2n}\frac{n-Bi_2}{n+Bi_2}\right)$$

Operating parameters

Superheated steam	
Operating outlet temperature	≤ 600 C (873 K)
Operating Inlet temperature	355 C (628 K)
Operating pressure	≤ 17.5 MPa(g)
Tube bulk velocity	10 to 25 m/s
Tube	
Material	SA213 T91
Conductivity	27.9 W/(m·K) at 500 C
Absorptance	0.95
Emittance	0.09
Outside diameter	50.8 mm
Wall thickness[5]	6.3 mm
Length	≤ 50 m
Ambient	
Air temperature	≤ 50 C (323 K)
Wind Speed	0 to 25 m/s
Concentrated Solar Irradiation	
Solar flux	≤ 300 kW/m^2

Surface Plot of Tube Temperature





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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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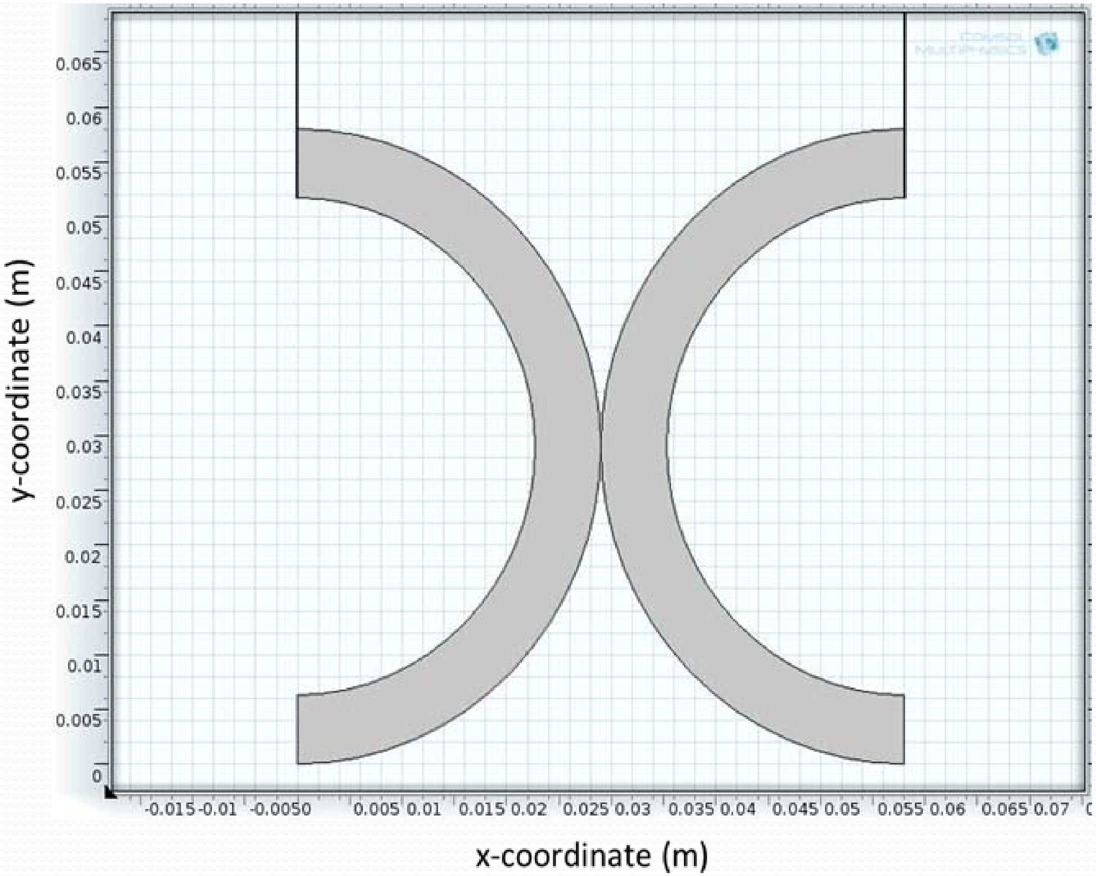
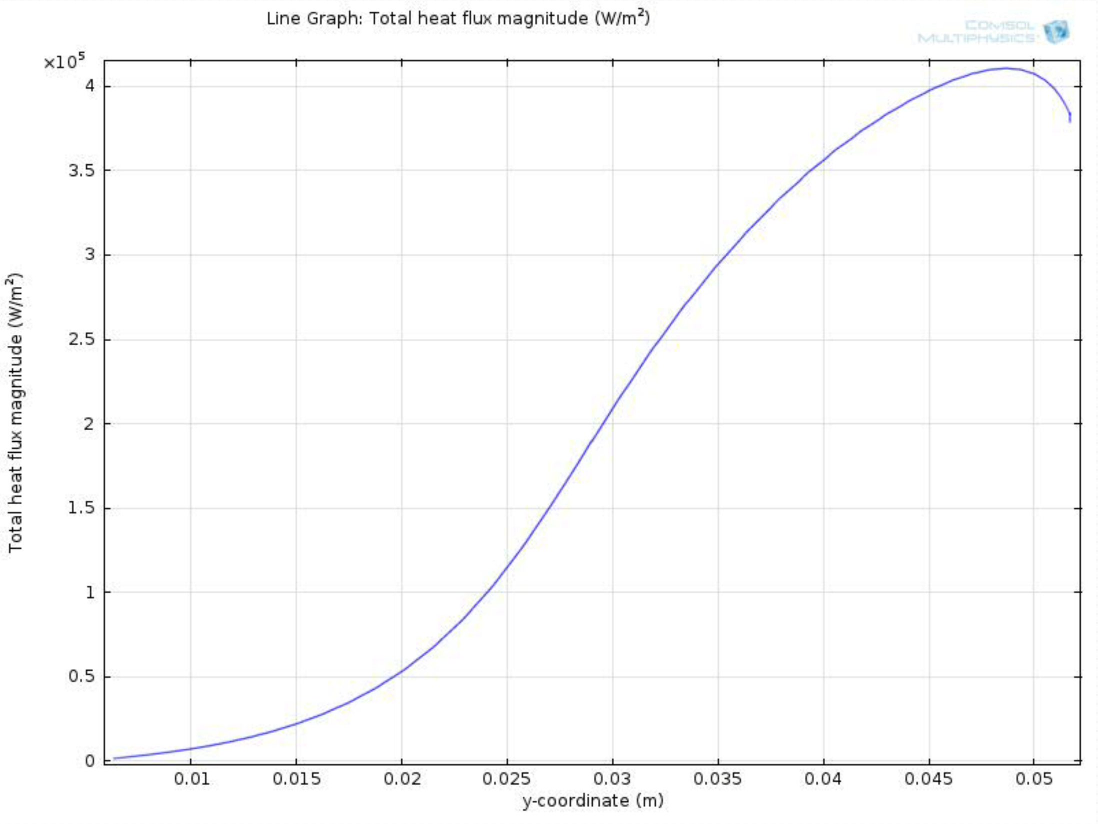
2D Model of Superheater Tubes



<u>Assumptions</u>

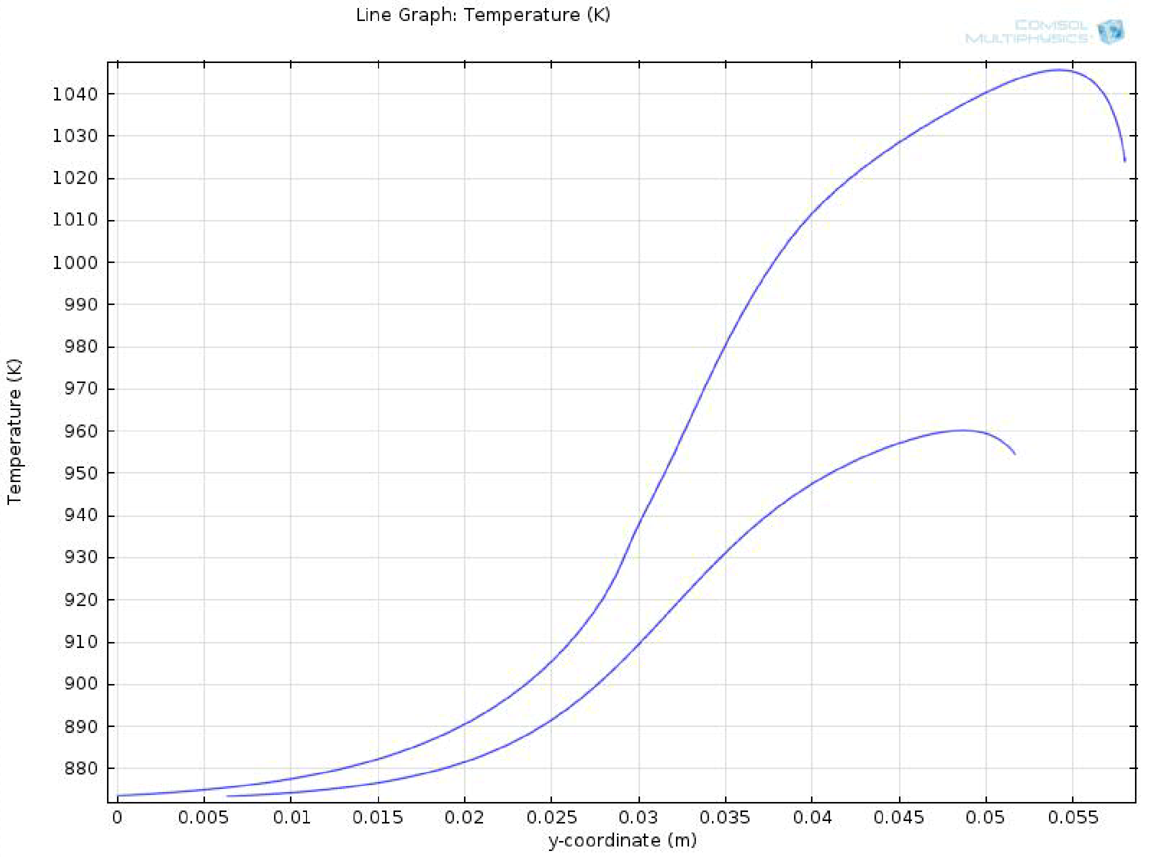
- Radiation source: Black Body
- Negligible outer convective heat transfer
- Surface emissivity: 0.09

Results – Heat Flux Distribution



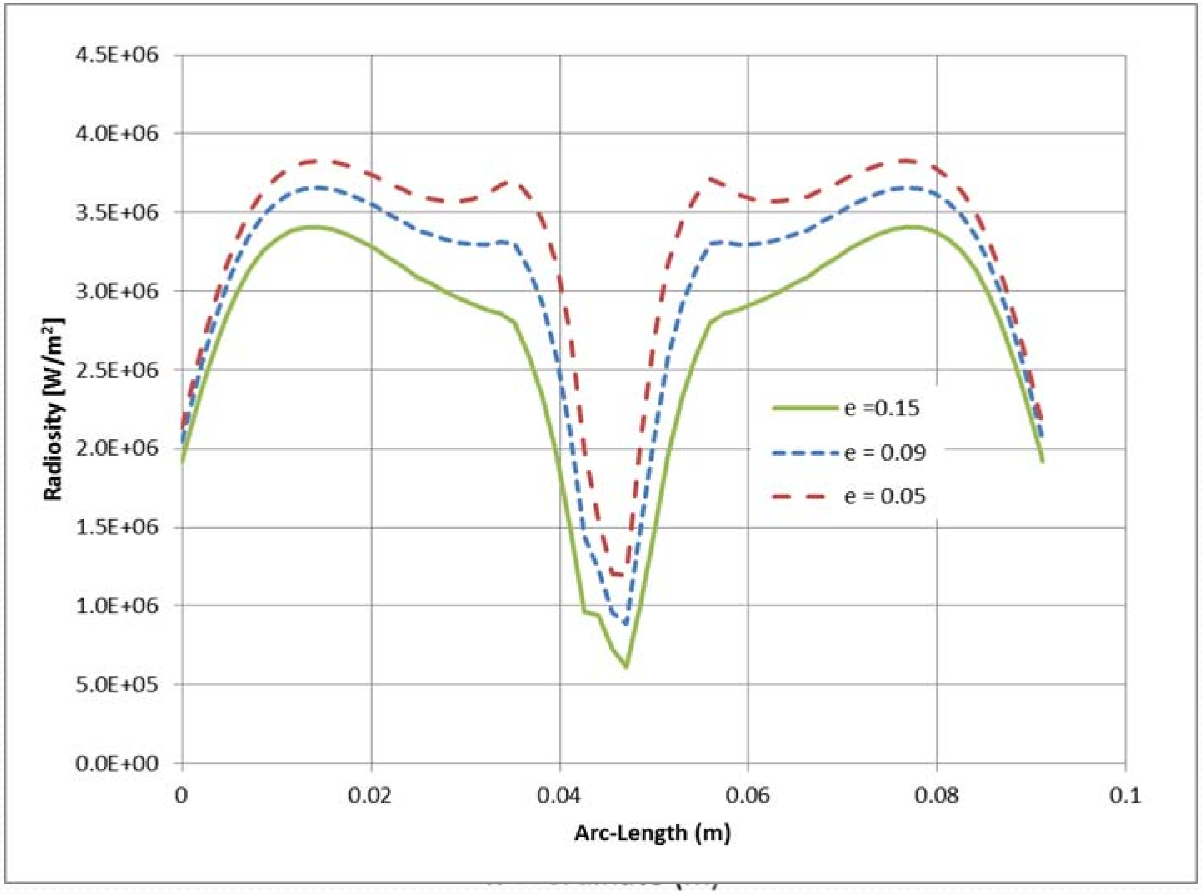
- Heat flux distribution at the inner surface of 6.3 mm thick tube (base case)
- Heat flux at the bottom half of the tube is quite low, but it increases significantly in the upper half, reaching ~4 x 10^5 W/m^2

Results – Temperature Distribution



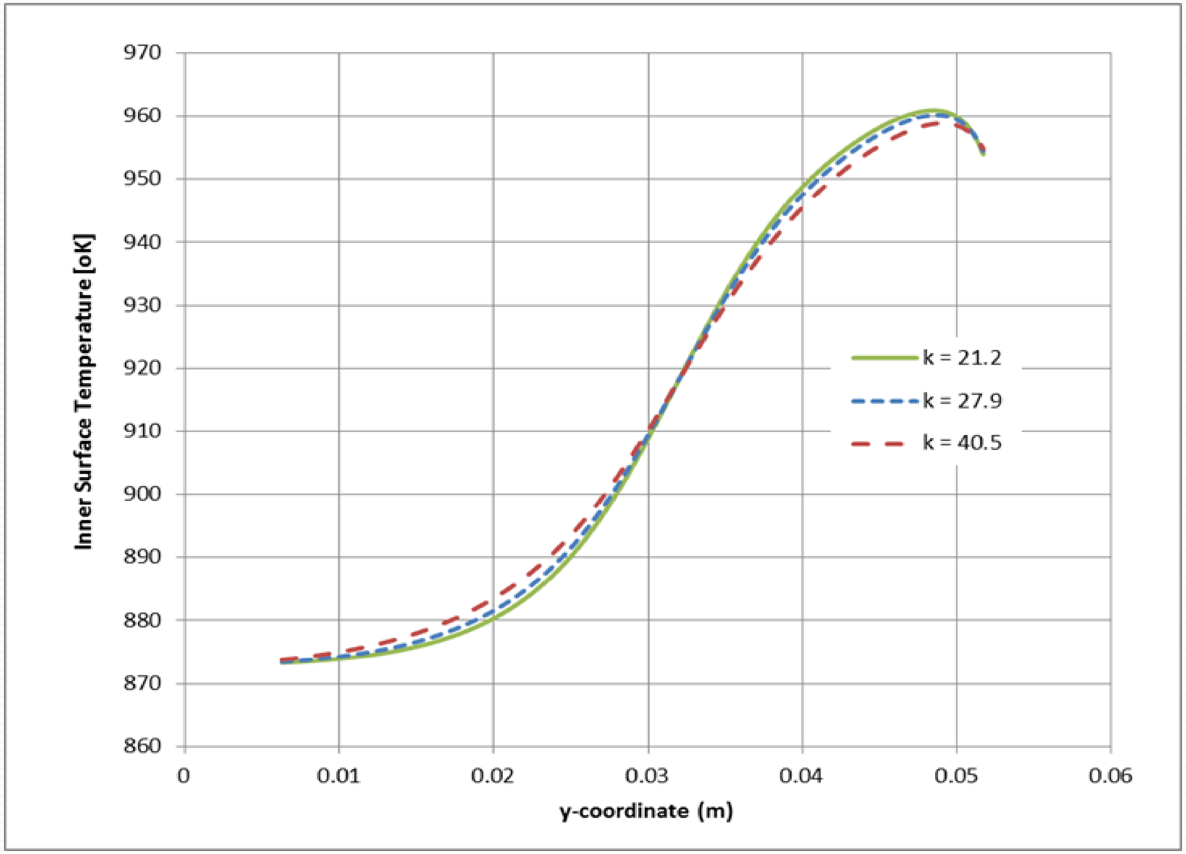
- Outer and inner surface temperatures of 6.3 mm thick tube
- In the bottom half of the tube, the inner surface temperature is quite close to the steam temperature, and both surface temperatures are quite uniform.
- In the upper half of the tube, both surface temperatures and their difference increase significantly.

Results – Radiosity Distribution



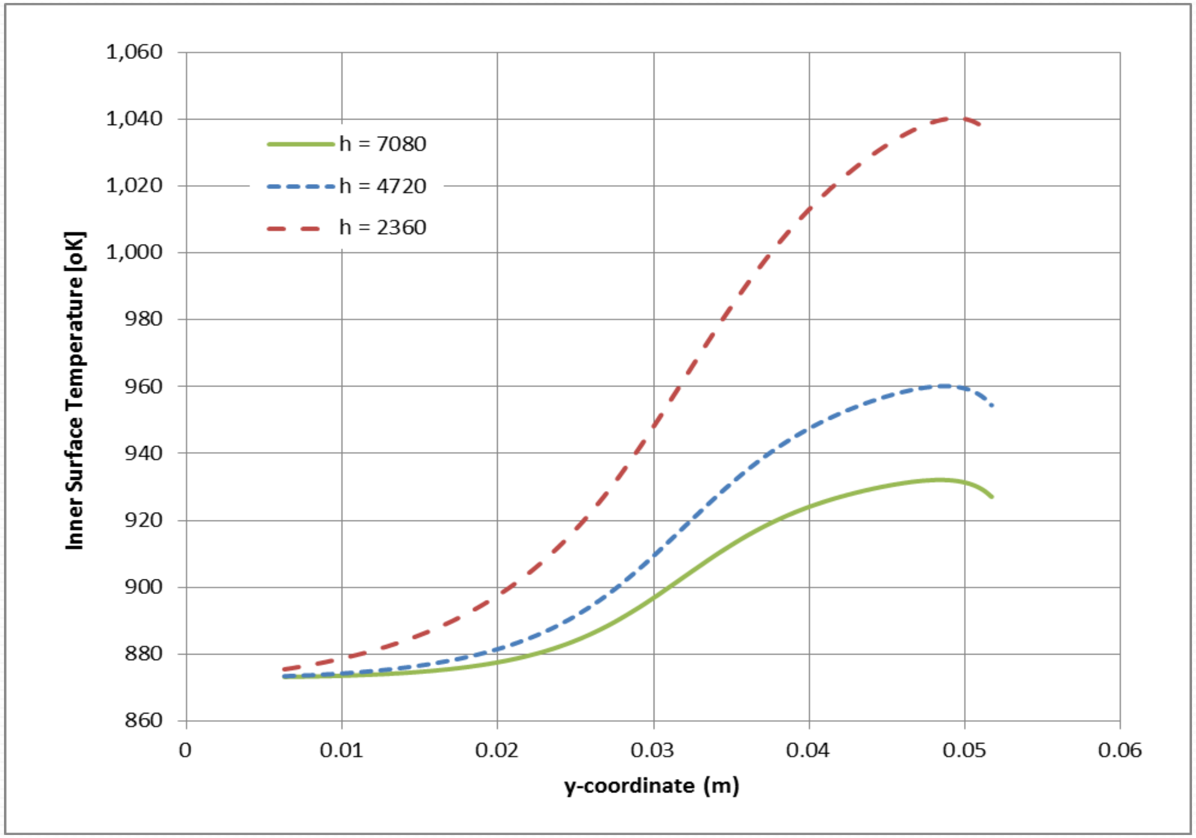
- Effect of emissivity on the radiosity of the outer surfaces (exposed to the radiation)
- A maximum is observed at a distance of about D/4 from the azimuth, while a significant decrease is noted as the point of contact of two adjacent cylinders is approached.
- As the emissivity of the radiating surfaces increases, the radiosity decreases.

Results – Inner Surface Temperature



- Effect of tube thermal conductivity (k in W/(m·K)) on the inner surface temperature
- A slightly more uniform temperature distribution along the tube circumference is observed for the more conductive material.
- 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.

Results – Inner Surface Temperature



- Effect of internal heat transfer coefficient (h_2 in W/(m²·K)) on the inner surface temperature.
- The effect of the internal heat transfer coefficient is more significant than that of the thermal conductivity, with a more uniform temperature for the highest heat transfer coefficient .
- 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.

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.
- The analysis presented can lead to the reduction of the maximum tube temperature and the optimization of a steam generator design.