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EFFECTS OF INLET VELOCITY AND THERMAL CONDUCTIVITY RATIO ON PERFORMANCE OF A SOLAR VOLUMETRIC RECEIVER

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Abstract

This work presents numerical results for the thermal performance of a Solar Volumetric Receiver (SVR). The Thermal Non-Equilibrium Model and Rosseland approximation were used. Radiation boundary condition was implemented at the absorber inlet. The numerical technique employed for discretizing the governing equations was the control volume method with a boundary-fitted non-orthogonal coordinate system. The SIMPLE algorithm was used to handle the pressure-velocity coupling. Effects of inlet velocity (u_{in}) and thermal conductivity ratio (k_s / k_f) in the solid and fluid temperature distributions of the absorber were investigated. Reduction of temperatures as porosity increase or thermal conductivity decrease was observed, in addition to an increase in entry length for lower porosities or higher thermal conductivity ratio. Increase in inlet solid temperature as permeability increases was accompanied by a longer entry length and reduced final equilibrium temperature.

Keywords: *Thermal Non-equilibrium, Solar Volumetric Receiver, Porous Media, Solar Energy*

1. INTRODUÇÃO

Solar energy, considered as a source of renewable energy and of abundant nature, presents itself as an interesting option in the generation of electric energy (Kreider, 1982). Thus, at present there are several technologies of solar concentrators of power (Concentrating Solar Power - CSP). Among the most promising ones, we can highlight the Central Receiver System (CRS) (Behar *et al.* 2013). However, more research and development (R & D) should be undertaken to reduce costs associated with innovation technology in subsystems or components, and also to consolidate itself as one of the best choices among existing CSP technologies (Roldán *et al.*, 2016).

Solar Receiver (SR) is one of the main components of a CRS that can represent 15% of the total investment cost of a CRS plant (Liao *et al.*, 2014). The SR can be classified, mainly according to their geometric configuration, type of material of the absorber (metallic or ceramic), among others (Garcia *et al.*, 2016; Heller *et al.*, 2006). The Solar Receiver Volumetric (SRV) is a type of SR, usually located at the top of a tower of the CRS, which takes advantage of solar radiation concentrated at high temperatures, generated from a system or set of mirrors or heliostats.

The distribution of solid temperatures and working fluid were obtained through different theoretical models proposed by different researchers (Becker *et al.*, 2006; Fend *et al.*, 2004; Bai, 2010), taking into account conduction, convection and radiation couplings. If some considerations were made on the models, such as: wall thickness significantly smaller than the length of the absorber, insulation on the sidewalls of the absorber, radiation fluxes of homogeneous incidence. The models can be reduced to unidimensional models, representing adequately the thermal performance in an absorber. Sano *et al.* (2012) analyzed the complex heat transfer that occurs basically in a SiC absorbing. For this, it associates the term of radiation, convection and conduction, using the local non-equilibrium model with porous media and the Rosseland aproximation to calculate the radiative heat transfer through the solar receiver.

Motivated by the foregoing, in this study we also used the local thermal non-equilibrium model with porous media and Rosseland approximation applied to porous Solar Volumetric Receiver. The contribution herein is to extent previous analytical, numerical and experimental analyses of SVRs

(Behar *et al.*, 2013; Kribus *et al.*, 2014; Sano *et al.*, 2012; Smirnova *et al.*, 2010), mostly done for a particular set of parameters, considering now the effects of inlet velocity, porosity, permeability and thermal conductivity ratio of the absorber, in addition to using a proper radiation boundary condition at the solar receiver inlet. Results herein might contribute to design and analysis of modern and energy efficient solar energy power plants.

Mathematical Model

The mathematical model here employed has been already fully described in the open literature. It is here extended to simulate radiation, laminar convection flow in a Solar Receiver Volumetric. As the macroscopic model is already available elsewhere (De Lemos, 2012; Coutinho, 2012), governing equations will be just presented and are summarized as follows:

Mass Continuity

The macroscopic mass continuity for an incompressible fluid flowing through a porous medium, such as is given by,

$$\nabla \cdot \bar{\mathbf{u}}_D = 0 \tag{1}$$

where $\bar{\mathbf{u}}_D$ is the average surface velocity (also known as seepage, superficial or Darcy Velocity).

Momentum Equation

The Eq. (2) shows, the macroscopic momentum Equation (Navier-Stokes) for an incompressible fluid with constant properties flowing through a porous medium can be written as:

$$\nabla \cdot \left(\rho_f \frac{\bar{\mathbf{u}}_D \bar{\mathbf{u}}_D}{\phi} \right) = -\nabla \left(\phi \langle \bar{p} \rangle^i \right) + \mu \nabla^2 \bar{\mathbf{u}}_D + \nabla \cdot \left(-\rho_f \phi \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i \right) - \left[\frac{\mu \phi}{K} \bar{\mathbf{u}}_D + \frac{c_F \phi \rho_f |\bar{\mathbf{u}}_D| \bar{\mathbf{u}}_D}{\sqrt{K}} \right] \tag{3}$$

where the last two terms in Eq. (3) represent the Darcy and Forchheimer contributions. The symbol K is the porous medium permeability, $c_F = 0.55$ is the form drag coefficient, $\langle p \rangle^i$ is the intrinsic average pressure of the fluid phase, μ represents the fluid viscosity and ϕ is the porosity of the porous medium. The permeability K of the porous matrix is determined using the Equation **(4)**,

$$K = \frac{\phi^3 D^2}{144(1-\phi)} \tag{4}$$

Two-Energy Equation Model

When average temperatures in distinct phases are substantially different from each other, for example in solar receiver device, energy storage units, combustion processes, etc. Macroscopic energy equations are obtained for both fluid and solid phases by applying time and volume average operators to the instantaneous local Eq. **(5)** we name this approach Local Thermal Non Equilibrium (LTNE). After including the fluid and the solid phase energy balance **(6)**. One gets the following Equations:

$$\text{Fluid:} \quad \nabla \cdot (\rho_f \, c_{pf} \, \mathbf{u}_D \langle \overline{T_f} \rangle^i) = \nabla \cdot \left\{ \mathbf{K}_{eff,f} \cdot \nabla \langle \overline{T}_f \rangle^i \right\} + h_i a_i \left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i \right) \tag{5}$$

$$\text{Solid:} \quad 0 = \nabla \cdot \left\{ \mathbf{K}_{eff,s} \cdot \nabla \langle \overline{T_s} \rangle^i \right\} - h_i a_i \left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i \right) \tag{6}$$

where, $a_i = A_i / \Delta V$ is the interfacial area per unit volume, h_i is the film coefficient for interfacial transport, $\mathbf{K}_{eff,f}$ and $\mathbf{K}_{eff,s}$ are the effective conductivity tensors for fluid and solid, respectively, given by:

$$\mathbf{K}_{eff,f} = \left\{ \overbrace{\phi k_f}^{conduction} \right\} \mathbf{I} + \underbrace{\mathbf{K}_{f,s}}_{local\ conduction} + \underbrace{\mathbf{K}_{disp}}_{dispersion} \tag{7}$$

$$\mathbf{K}_{eff,s} = \left\{ \overbrace{(1-\phi)[k_s}^{conduction} + \overbrace{\frac{16\sigma(\langle T_s \rangle^i)^3}{3\beta_r}}^{radiation}] \right\} \mathbf{I} + \underbrace{\mathbf{K}_{s,f}}_{local\ conduction} \tag{8}$$

In Equations (5) to (8), $\mathbf{I}$ is the unit tensor, β_r is the extinction coefficient, $\sigma = 5.66961 \times 10^{-8}$ W/m^{2}K^4 is the Stephan-Boltzman constant.

Hendricks and Howell (1996), proposed a relation between β_r and the properties of a reticulated porous media, given by Eq. (8).

$$\beta_r = \frac{4.4(1-\phi)}{D} \tag{9}$$

In Eq. (7) and (8), all mechanisms contributing to heat transfer within the medium, together with the radiation term (Rosseland approximation), are here included in order to compare their effect on temperature distribution. Further, such distinct contributions of various mechanisms were modeled by applying gradient type diffusion expressions, in the form:

Thermal dispersion: $-(\rho c_p)_f \left(\phi \ \langle {}^i\mathbf{u}^i T_f \rangle^i \right) = \mathbf{K}_{disp} \cdot \nabla \langle T_f \rangle^i$ (10)

Local conduction: $$\begin{cases} \dfrac{1}{\Delta V} \displaystyle\int_{A_i} \mathbf{n}_i \, k_f T_f \, dA = \mathbf{K}_{f,s} \cdot \nabla \langle T_s \rangle^i \\ \dfrac{1}{\Delta V} \displaystyle\int_{A_i} \mathbf{n}_i \, k_s T_s \, dA = \mathbf{K}_{s,f} \cdot \nabla \langle T_f \rangle^i \end{cases} \quad (11)$$

In Eq. (5) and (6), the heat transferred between the two phases was modeled by means of a film coefficient h_i. A numerical correlation for the interfacial convective heat transfer coefficient was proposed by Kuwahara el al. (2001) for laminar flow as:

$$\frac{h_i D}{k_f} = \left(1 + \frac{4(1-\phi)}{\phi}\right) + \frac{1}{2}(1-\phi)^{1/2} \operatorname{Re}_D \operatorname{Pr}^{1/3}, \text{ valid for } 0.2 < \phi < 0.9 \quad (12)$$

where Pr in the Prandtl number and Re_D is the Reynolds number based on D and the macroscopically velocity $\bar{\mathbf{u}}_D$, given by,

$$\operatorname{Re}_D = \frac{\rho_f \left|\bar{\mathbf{u}}_D\right| D}{\mu} \quad (13)$$

2. COMPUTATIONAL PROCEDURE

In the present simulation, the solar volumetric receiver It was represented by a scheme, as shown in the Figure 1*a*. The above equation set was discretized for a two-dimensional computational domain using the discretization molecule shown in Figure 1*b*.

A hybrid numerical scheme was used for interpolating the convection fluxes. The interpolated schemes are Upwind Differencing Scheme (UDS) and Central Differencing Scheme (CDS).

The SIMPLE algorithm proposed by Patankar and Spalding (1972) is applied for handling the pressure-velocity coupling. At inlet of the absorber, as depicted in Figure 1*c*, the radiation inlet was assumed to be equal the conduction flux reaching the inlet the absorber. Investigated Axial Developments of Solid – Air Temperature Distribution (Heat Transfer) and for the validation parameters were used of Sano *et al.* (2012) and Smirnova *et al.* (2010) respectively. The effects of inlet velocity and thermal conductivity ratio k_s/k_f were evaluated.

Effect of inlet velocity u_{in}

Three cases with different inlet velocity *a)* u_{in}=0.7 m/s, *b)* u_{in}=1.0 m/s, *c)* u_{in}=1.2 m/s for the ratio k_s/k_f varying from 1150, 2300, 3500, 4600, 5600.

Effect of thermal conductivity ratio k_s/k_f

The velocities were varying of 0.7 to 1.2 m/s, the porosity and particle diameter were kept constant in ϕ=0.3 and D_p=9.5x10^{-4} m, already the thermal conductivity ratio was set to k_s/k_f =5600.

3. RESULTS AND DISCUSSION

3.1 Mesh independency studies

In order to investigate independency of mesh size on the results, calculations made use of three different two-dimensional grids of sizes 26x110, 52X202 and 114x450 nodes, respectively. After running the three cases corresponding, the grid refinement shows that the results are independent of grid system. As such, and for conciliating adequate numerical accuracy and reasonable computational cost, all results presented herein were run with a mesh of size 52x202.The convergence criterion for all variable was set to 10^{-9}.

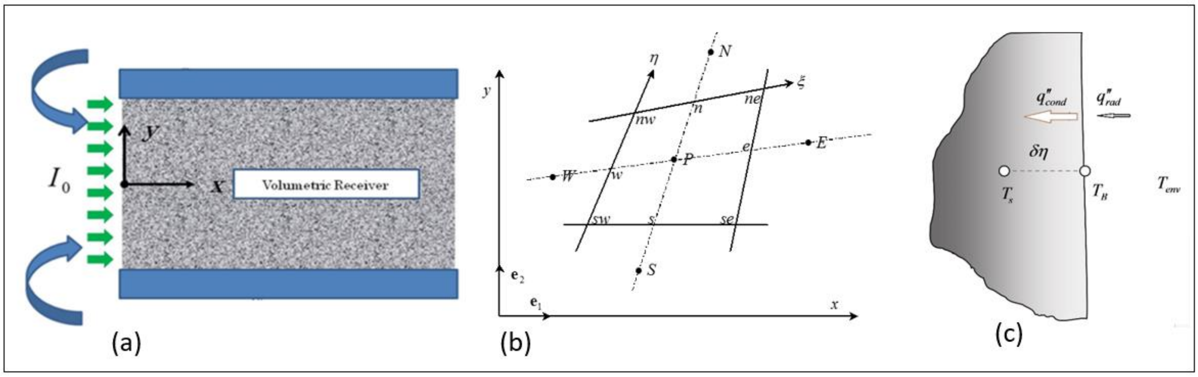


Figure 1 – Problem under consideration and numerical treatment: *a)* Schematic of the solar receiver volumetric, *b)* computational molecule, *c)* radiation boundary condition.

3.2 Code Validation

As mentioned, the procedure for code validation and simulations employed here are the same used elsewhere, or say, computations are compared with reported analytical Sano *et al.* (2012) and numerical data Smirnova *et al*. (2010), respectively, as shown in Figure 2. As can be seen in the figure, results herein agree well with reported analytical and numerical simulations, ultimately indicating the correctness and accuracy of the developed code.

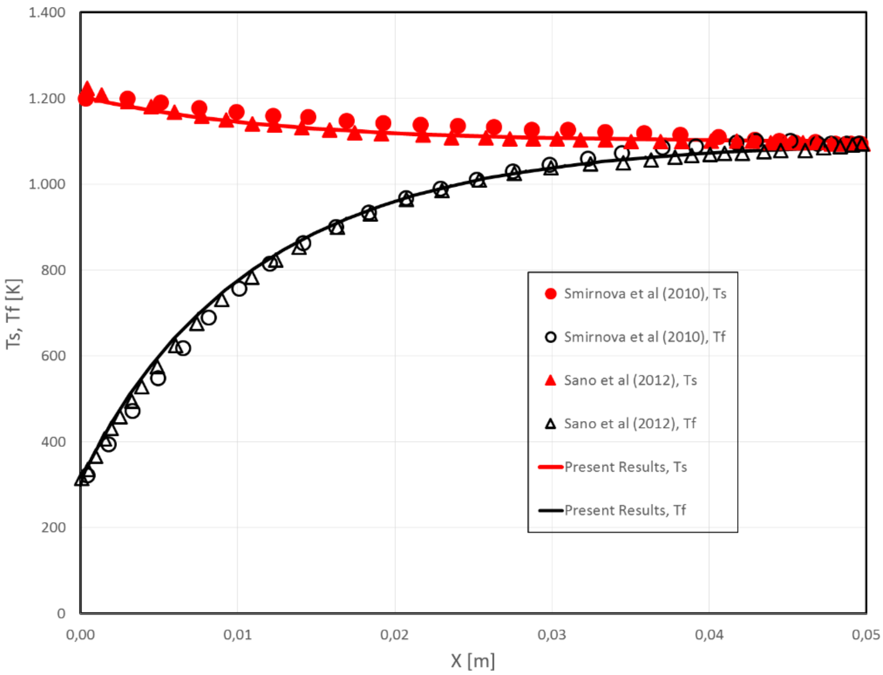


Figure 2 – Comparisons between obtained numerical results with those reported by Sano *et al.* (2012) and Smirnova *et al.*(2010) for the fluid (T_f) and solid (T_s) temperature distributions.

3.3 Effect of inlet velocity u_{in}

As we can see on Figure 3, an increase in inlet velocity causes the decrease of axial development of the air and solid temperatures profiles (two phases) inside of absorber. The velocities were varying of 0.7 to 1.2 m/s, the porosity and particle diameter were kept constant in ϕ=0.3 and D_p=9.5x10^{-4} m, already the thermal conductivity ratio was set to k_s / k_f =5600.

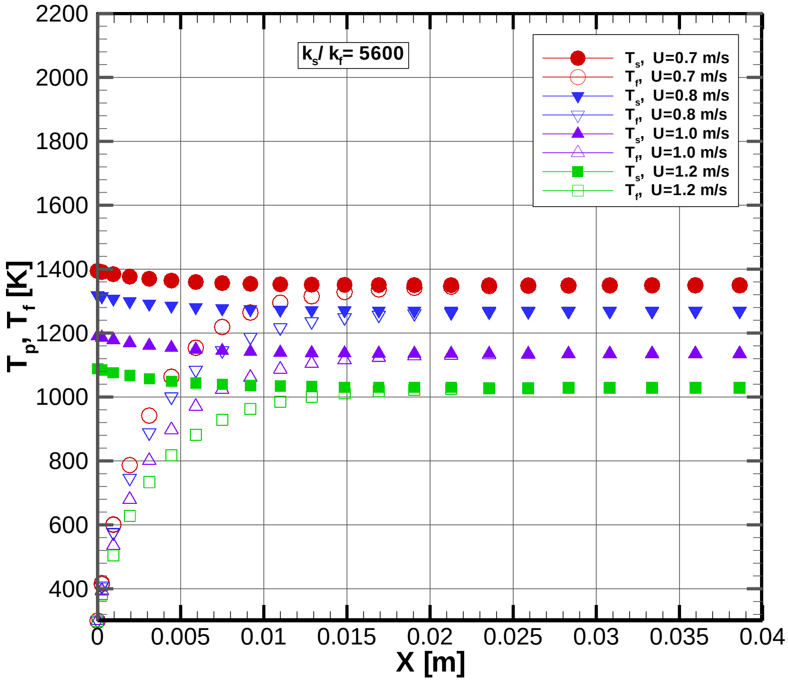
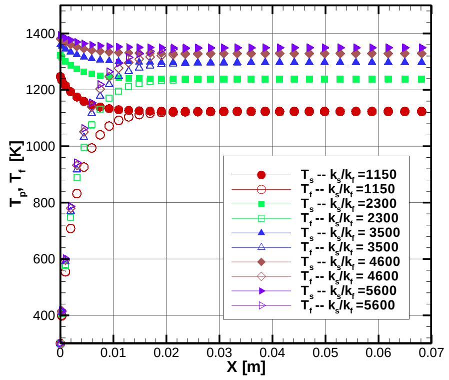


Figure 3 – Effect of inlet velocity u_{in} on air (T_f) and solid (T_p) temperatures inside the absorber for ϕ=0.3, *Da*= 0.3453 10^{-9}, k_s/k_f=5600.

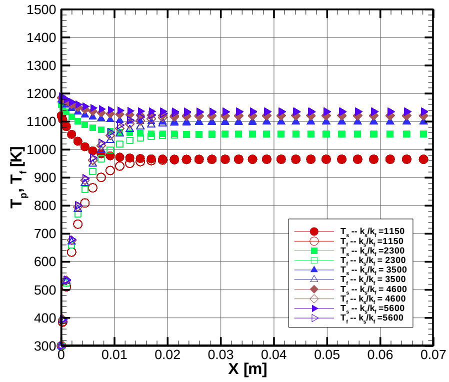
3.4 Effect of thermal conductivity ratio k_s/k_f

The Fig. 4 show results of temperature profiles for three cases with different inlet velocity *a*) u_{in} =0.7 m/s, *b*) u_{in} =1.0 m/s, *c*) u_{in} =1.2 m/s for the ratio k_s/k_f varying from 1150, 2300, 3500, 4600, 5600 covering then a wide range of materials. One can note that increasing k_s/k_f in the absorber material, implies an increase in the distribution of temperatures, for all cases analyzed. Another important observation would be the slight development of the decrease temperature distribution for the increases inlet velocity from 0.7 to 1.2 m/s.

a)



b)



c)

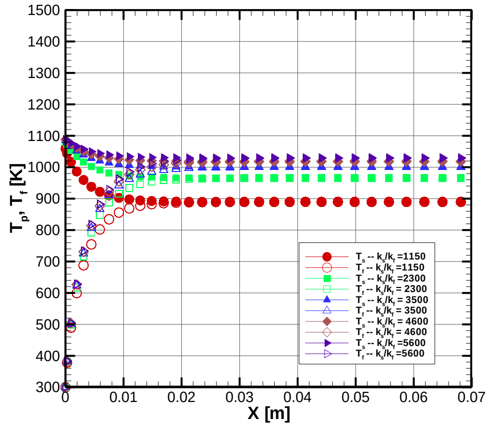


Figure 4 – Effect of thermal conductivity ratio k_s/k_f on air (T_f) and solid (T_p) temperatures: For ϕ=0.3, *Da* = 0.3453 10^{-10}: *a)* u_{in}=0.7 m/s, *b)* u_{in}=1.0 m/s, *c)* u_{in}=1.2 m/s.

4. CONCLUDIG REMARKS

The analysis of a solar volumetric receiver was investigated using the thermal non-equilibrium hypothesis and radiation boundary condition. The results were compared to analytical and numerical data by (Sano *et al.*, 2012; Smirnova *et al.*, 2010) indicating that temperatures values agreed with the comparisons measurements, It is also possible to conclude that the pressure drops in the absorber agree satisfactorily with the experimental data reported by Wu *et al.* (2010). Effects of inlet thermal conductivity ratio k_s / k_f , on the air and solid temperature distribution and pressure drop along the air flow directions, were investigated. Increasing k_s/k_f in the absorber material, Implies an increase in the distribution of temperatures, for all cases analyzed. The maximum temperature of solid phase and equilibrium temperature decrease with the increasing of inlet velocity. Also, the maximum temperature of solid phase increases with the particle diameter increasing.

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AUTHOR'S RESPONSIBILITIES:

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