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TRANSIENT BEHAVIOUR OF VOLUMETRIC SOLAR RECEIVERS

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Abstract. The transient behaviors of the volumetric solar air receiver are crucial for understanding and optimizing the receiver characteristics. The present work numerically analyzes the transient behaviors of the volumetric solar air receiver under various working conditions. Effects of inlet velocity, and thermal conductivity ratio k_s / k_f on equilibrium temperature was investigated. Higher inlet velocities attain quicker stabilization times and decreases equilibrium temperature, T_{eq}. In addition, increasing k_s / k_f increases stabilization time as well as equilibrium temperatures. The results are useful in designing of volumetric solar air receivers and the thermal efficiency increases for lower inlet velocities and higher thermal conductivity ratios, whereas η is reduced for more permeable structures and higher porosities. Thermal efficiency (η) increases for lower inlet velocities and higher thermal conductivity ratios.

Keywords: Volumetric solar air receiver; Transient modeling; Thermal non-equilibrium model;

Introduction

Solar thermal power, also known as concentrated solar power (CSP) or solar thermal electricity (STE), is a renewable energy sector with great potential, as it directly harnesses the abundant amount of solar energy incident on planet earth. CSP plants capture the sun's direct normal irradiation (DNI), concentrate it onto a receiving surface, and transform the absorbed heat into mechanical work and subsequently, into electric energy by using state-of-the-art thermodynamic power cycles [1].

Across all the concentrated solar power (CSP) technologies, the central receiver power plant with the volumetric solar air receiver and a gas turbine has three advantages: (1) This technology requires less water to generate electricity than other technologies; (2) the high temperature of the thermodynamic cycles, results in a high efficiency for generating electricity; (3) the air is inherently a non-problematic heat transfer fluid due to its inert nature within the temperature ranges used. The first point is particularly advantageous as most solar energy abundant regions are located in arid, semi-arid zones and are therefore lack water. Consequently, this technology of generating electricity with solar energy is very promising [2].

Renewable energy sources, such as solar energy, is today considered a viable option for coping with the ever-greater demand for generation of electrical energy [3]. Among the most promising system to harvest solar power, one can mentioned Central Receiver System (CRS) [4], which is a category of the so-called Concentrated Solar Power systems (CSP) [5]. A Solar Receiver (SR) is a component of a CRS plant [6-11]. The Solar Volumetric Receiver (SVR) is a type of SR that takes advantage of solar radiation concentrated at high temperatures, generated from a system or set of mirrors or heliostats [12-14]

The literature reports several studies regarding SVRs [15-19], including analytical, experimental and numerical investigations including thermal and hydrodynamic behavior of SVRs. [20], [21] and [22], carried out a series of experiments on solar collectors in order to obtain characteristic curves of the pressure drop as a function of pore diameter and or porosity. Other works [15, 19, 20] investigated analytically and experimentally the phenomenon of "thermal blockage", which happens due to flow instabilities inside the absorbers.

[16] analyzed the influence of permeability, inertia coefficient and thermal conductivity on flow instabilities in some absorbers. Solids and fluid temperatures were obtained through different theoretical models proposed by different researchers [16,18, 23, 24], taking into account conduction, convection and radiation couplings. [25] and [26] showed analytical solutions without the radiation mechanism. [27] analyzed heat transfer in a SiC absorber.

In an earlier paper, [28] extended previous analytical, numerical and experimental analyses of SVRs [4-24, 27, 29], which were mostly done for a particular set of parameters. In [28], the effects of inlet velocity, porosity, permeability and thermal conductivity ratio of the thermal behavior of the absorber, in addition to using a proper radiation boundary condition at the solar receiver inlet, were investigated.

However, most results shown in the literature, including simulations by [28], considered steady-state solutions and transient thermal behavior of SRVs was not considered.

Motivated by the lack of information on transient behavior on SVRs, the present contribution extends the analysis in [28] considering now the transitory behavior of volumetric absorbers. By that, a broader range of problems can be analyzed, ultimately contributing to the design of modern and more efficient solar power plants.

Governing Equations

The mathematical model here employed has been already fully described in the open literature. It is here extended to simulate radiation, laminar forced convection flow in a model Solar Volumetric Receiver. As the macroscopic model is already available elsewhere [30], including natural convection [31], double-diffusion [32], impinging jets [33], as well as reactive systems [34, 35], transport equations will be just presented are [28].

Geometry Investigated

Before presenting the mathematical model, a word about the geometry investigated is timely. Here, the solar volumetric receiver is represented by a scheme depicted in Figure 1. The receiver is assumed to be 1 m long and fully isolated on its surroundings, yielding, by that, a one dimensional situation where the air and solid temperatures vary from the left inlet towards inside the SVR. At entrance, solar energy provides a radiation flux that equals the conduction flux entering the solid material. Cool air is sucked form the environment, being heated up as it gets in contact with the heated solid phase.

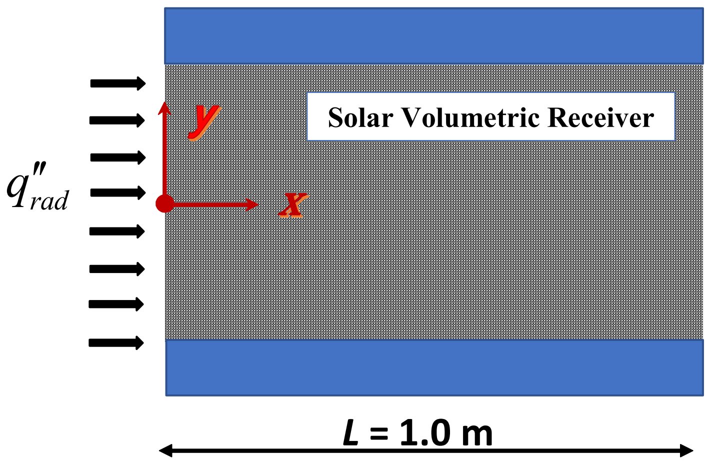

Figure 1. Solar volumetric receiver

The equations used for macroscopic mass continuity for an incompressible fluid flowing through a porous medium and the transient macroscopic momentum equation (Navier-Stokes) for an incompressible fluid with constant properties flowing through a porous medium just presented are [28].

Thermal Non-Equilibrium 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 the volume average operator to the local equations [36]. We name this approach Local Thermal Non Equilibrium (LTNE). After considering the fluid and the solid phase energy balance, one gets the following equations [36],

$$\text{Fluid: } \frac{\partial}{\partial t}\phi\rho_f\, c_{pf}\,\langle T_f\rangle^i + \nabla\cdot(\rho_f\, c_{pf}\,\mathbf{u}_D\langle T_f\rangle^i) = \nabla\cdot\left\{\mathbf{K}_{eff,f}\cdot\nabla\langle T_f\rangle^i\right\} + h_i a_i\left(\langle T_s\rangle^i - \langle T_f\rangle^i\right) \tag{1}$$

$$\text{Solid: } \frac{\partial}{\partial t}(1-\phi)\,\rho_s\, c_{ps}\,\langle T_s\rangle^i = \nabla\cdot\left\{\mathbf{K}_{eff,s}\cdot\nabla\langle T_s\rangle^i\right\} - h_i a_i\left(\langle T_s\rangle^i - \langle T_f\rangle^i\right) \tag{2}$$

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:

$$\mathbf{K}_{eff,f} = \left\{\overbrace{\phi k_f}^{conduction}\right\}\mathbf{I} + \underbrace{\mathbf{K}_{f,s}}_{local\ conduction} + \underbrace{\mathbf{K}_{disp}}_{dispersion} \tag{3}$$

$$\mathbf{K}_{eff,s} = \left\{\overbrace{(1-\phi)[k_s}^{conduction} + \overbrace{\frac{16\sigma(\langle T_s\rangle^i)^3}{3\beta_r}}^{radiation}]\right\}\mathbf{I} + \underbrace{\mathbf{K}_{s,f}}_{local\ conduction} \tag{4}$$

In Equations (1) to (4), $\mathbf{I}$ 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)[37], proposed a relation between β_r and the properties of a reticulated porous media, given by,

$$\beta_r = \frac{4.4(1-\phi)}{D} \tag{5}$$

In Equations (3) and (4), 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:

$$\text{Thermal dispersion: } -(\rho c_p)_f\left(\phi\ \langle {}^i\mathbf{u}\,{}^iT_f\rangle^i\right) = \mathbf{K}_{disp}\cdot\nabla\langle T_f\rangle^i \tag{6}$$

$$\text{Local conduction: } \begin{cases} \dfrac{1}{\Delta V}\displaystyle\int_{A_i}\mathbf{n}_i\, k_f T_f\, dA = \mathbf{K}_{f,s}\cdot\nabla\langle T_s\rangle^i \\ \dfrac{1}{\Delta V}\displaystyle\int_{A_i}\mathbf{n}_i\, k_s T_s\, dA = \mathbf{K}_{s,f}\cdot\nabla\langle T_f\rangle^i \end{cases} \tag{7}$$

In Equations (1) and (2), 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 [38] for laminar flow as:

$$\frac{h_i D}{k_f} = \left(1 + \frac{4(1-\phi)}{\phi}\right) + \frac{1}{2}(1-\phi)^{1/2}\,\mathrm{Re}_D\,\mathrm{Pr}^{1/3}, \text{ valid for } 0.2 < \phi < 0.9 \qquad (8)$$

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

$$\mathrm{Re}_D = \frac{\rho_f |\mathbf{u}_D| D_p}{\mu}$$

Discretization details

Governing equations were discretized in a two-dimensional computational domain. Due to isolation boundary conditions in Figure 1, a one-dimensional situation was recovered, as mentioned. A hybrid numerical scheme was used for interpolating the convection fluxes. The SIMPLE algorithm [39] was applied for handling the pressure-velocity coupling. Discretization of the transient term in the governing was accomplished by using a backward Euler or implicit formulation [40]. At inlet of the absorber, as depicted in Figure 2, the solar irradiation flux at the inlet was assumed to be equal the conduction flux penetrating the solid matrix of the absorber. Air is assumed to be a transparent gas that is heated up buy the contact with the porous absorber.

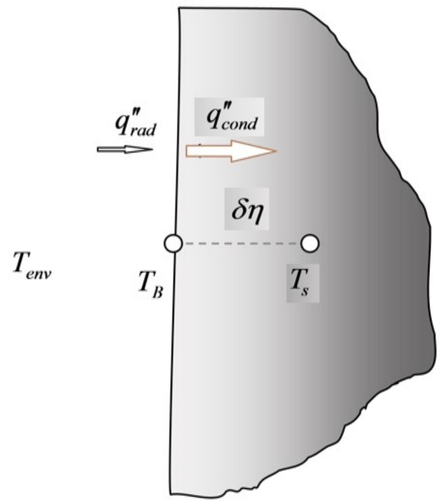

Figure 2 inlet boundary condition with radiation.

RESULTS AND DISCUSSION

Mesh independency and Code Validation

As presented in , Rivas et al. (2019) [28], calculations were made using three different two-dimensional grids of sizes 26x110, 52X202 and 114x450 nodes, which were equally spaced. A fourth grid of size 12x102, concentrating point at the absorber entrance, was tested. This coarser grid gave nearly the same results as fines grids and, for conciliating adequate numerical accuracy and reasonable computational cost, all results presented herein were run with a mesh size of 12x102, which is coarser than the grid used in [28]. Convergence criterion for all variables brought down residues to 10^{-9}. To validate the code, computations were compared with reported analytical [27] and numerical data [29]. For the sake of completeness, we reproduce here those results indicating the correctness and accuracy of the developed code. Results for transient analysis will be shown next.

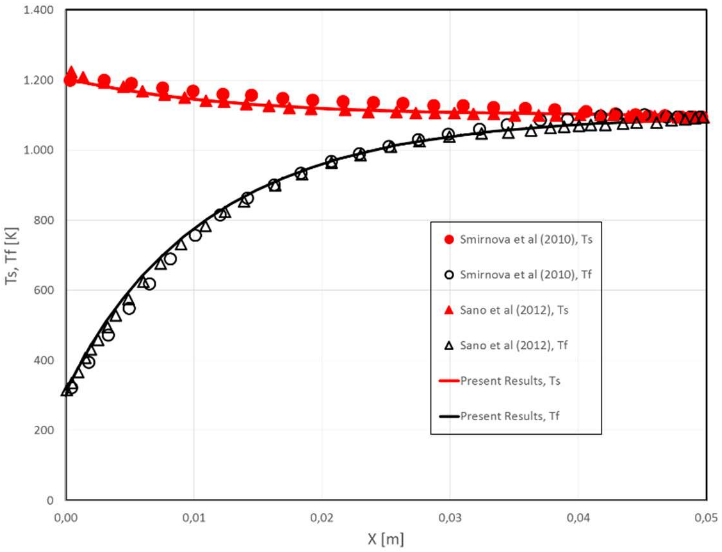

Figure 3. Comparison with results by Sano et al. (2012) [27] and Smirnova et al. (2010) [29] for T_f and T_s.

Effect of inlet velocity u_{in}

Results for equilibrium temperature T_{eq} as a function of inlet velocities u_{in}, varying from 0.7 to 1.2 m/s, are shown in Figure 4. Equations (1) and (2) are solved with the accumulation term and using the parameters. Porosity and Darcy number were kept constant as ϕ=0.3 and Da=0.3453 10^{-9}, respectively, in addition of the thermal conductivity ratio, k_s / k_f =5600. As we can see in the figure, higher velocities attain thermal stabilization quicker as more intensive heat transfer between phases take place. Also coherent with results in [28] is that an increase in inlet velocity causes the decrease of equilibrium temperature.

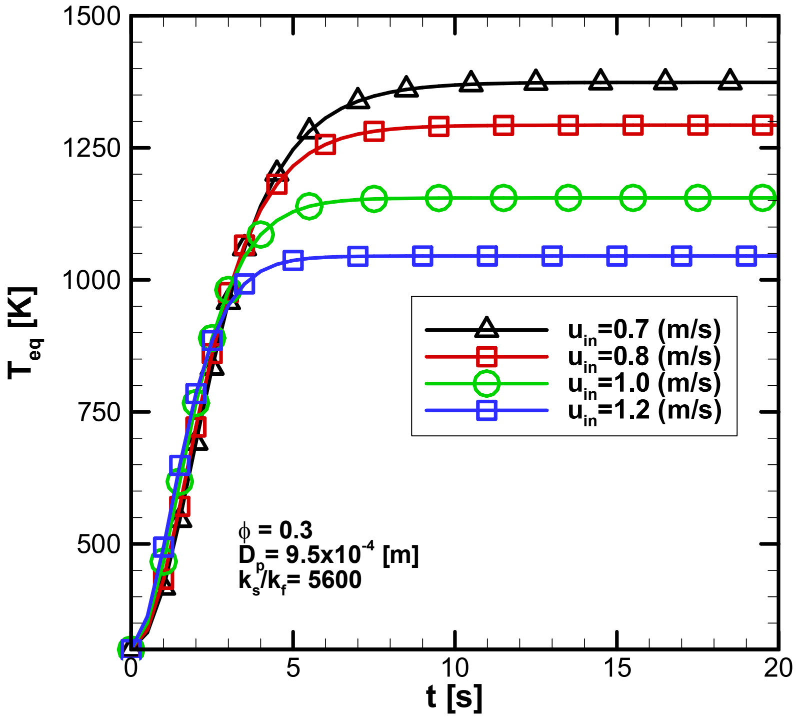

Figure 4. Effect of inlet velocity u_{in} on temporal variation of equilibrium temperature Teq for x/L=0.6, Ø=0.3, Da= 0.3453 10-9, k_s/k_f=5600.

Effect of thermal conductivity ratio k_s / k_f

The effect of k_s / k_f is presented next. Results were simulated with different inlet velocity u_{in}, namely =0.7 m/s, Da = 0.3453×10^{-10}, k_s / k_f varying from 1150 to 5600 and for ϕ in the range 0.3 to 0.9, covering then a wide range of solar receiver configurations and materials. One can see in Figure 5*a* that increasing k_s / k_f implies in an increase in the distribution of temperatures, with a slight increase in time for reaching the thermal equilibrium state. Further, increasing the size of void space or porosity (Figure 5*b* to *d)*. Also seen is the reduction of temperature variation for distinct values of k_s / k_f for highly permeable media. With less solid material composing the porous matrix, the effect of its thermal conductivity became of a less important.

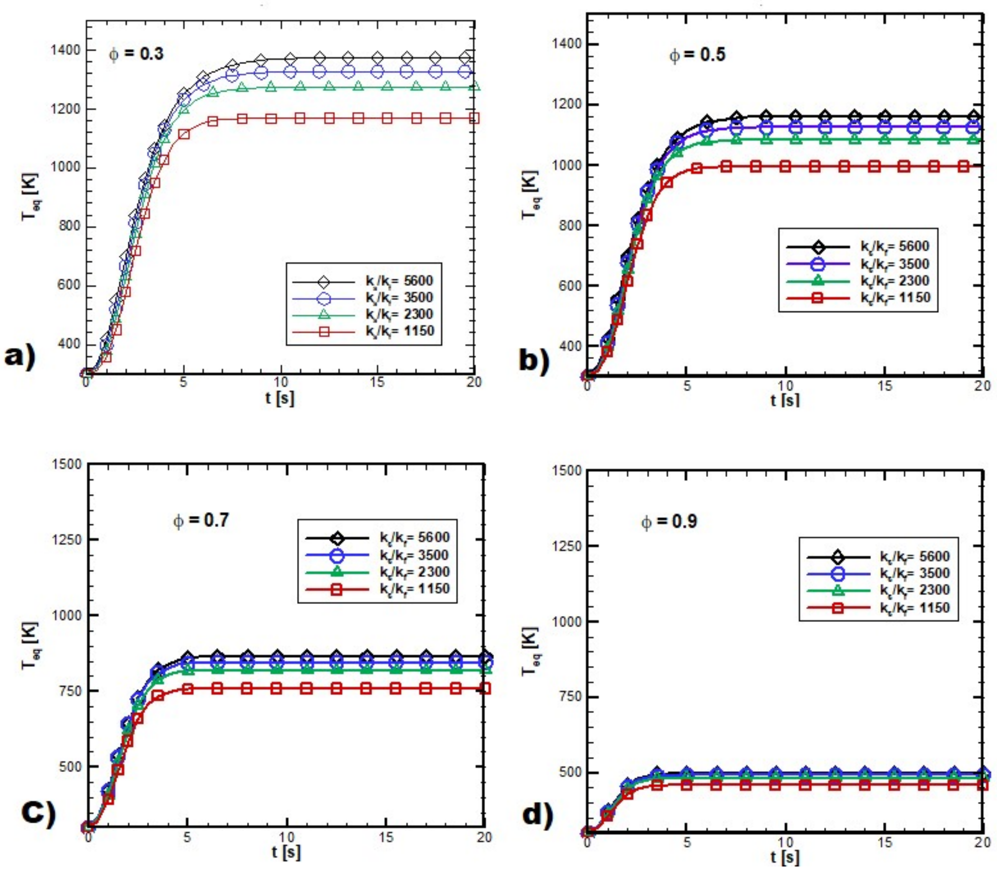

Figure 5. Effect of thermal conductivity ratio on equilibrium temperature Teq, for uin=0.7 m/s, Da = 0.3453×10-10: a) ϕ=0.3, b) ϕ =0.5, c) ϕ =0.7, c) ϕ =0.9.

CONCLUDIG REMARKS

Transient behavior and thermal efficiency of a solar volumetric receiver was investigated using the thermal non-equilibrium hypothesis coupled with inlet radiation boundary condition. Validation was accomplished by comparing present results to analytical and numerical data by [27, 29]. Transient effects of inlet velocity and thermal conductivity ratio k_s / k_f on equilibrium was investigated. Higher inlet velocities attain quicker stabilization times and decreases equilibrium temperature T_{eq}. Increasing k_s / k_f increases stabilization time as well as equilibrium temperatures. Simulations in present work can contribute to more efficient design and analyses of advanced solar power plants that make use of Solar Volumetric Absorbers but however it is necessary to evaluate other parameters as porosity, permeability (*Da*) and thermal conductivity ratio k_s / k_f on equilibrium temperature.

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