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HEAT TRANSFER STUDY IN A CSP VOLUMETRIC RECEIVER FOR DIFFERENT POROSITIES

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Abstract. This is a numerical study on heat transfer in a volumetric receiver applied in solar plants based on concentrating solar radiation. The mathematical model and the numerical techniques are presented. The result is for a dimensional study with a high temperature imposed on the porous media surface. It is observed that the porous media strongly plays its role as to increase the contact area of air to be heated and the solid conductive material with prescribed temperature on one surface as to approximate effects of incident radiation on such surface Radiation is not considered in this work.

Keywords: Concentrating Solar Plant, Volumetric Receiver, Heat transfer, Porous media.

1. INTRODUCTION

Clean and renewable energy generation is among the most discussed topics by the scientific community, due to the drawbacks of traditional source (fossil fuel) and the world energy consumption increase. Central tower power plants with volumetric concentrator have shown high performance in the production of clean and cheap energy (Ho and Iverson, 2014).

Volumetric receivers are cavity receivers that have a porous structure within them, capable of absorbing and transforming solar radiation into thermal energy, which will be absorbed by a fluid through forced convection, as it passes through the pores of a porous matrix, inside the volumetric receiver (Zhirong Liao, 2016). Albanakis (2009) studied types of porous materials, which have better performances in thermal energy convection to the system fluid. Avila-Martin (2011) reviewed types of volumetric receivers, indicating the receiver from REFOS program as the most efficient. A study by Behar (2013) analyzed researches related to solar thermal power plants with central receiver, indicating that systems with volumetric receiver technology have great energy potential.

The receivers located in the tower are exposed to the great sun exposure and as high temperatures, should receive quite high requirements Thus, the present study aimed to analyze the heat transfer occurring inside the receiver.

2. RECEIVER DESIGN AND PROBLEM FORMULATION

The geometry of the volumetric receiver and its dimensions were defined based on the REFOS air receiver, developed by the German Aerospace Center (DLR) in 1996 to be used in the movement of gas turbines in a combined cycle (Buck, 2002). At this receiver, the air is forced through the porous matrix, based on Alumina (Al2O3).

The problem to be studied is the effect of porosity and permeability by (fixed) radiation and forced convection at the receiver. The flow regime was considering steady laminar forced convection, because it is an initial study. Porosity and permeability variations were performed so that could be analyzed possible variations in the temperature, velocity and pressure gradients. The permeability variation values used were: 0.00001; 0.001; 0.1 and 0.5. And the porosity values were based on Akiyoshi (2014). These values exist in the market for different types of alumina.

2.1 Design

The computational domain consists of four subdomains. These subdomains are the air domain, represented by region 1(air entrance), region 2(air exit) and the inner region 3 (between porous media and glass window), and the porous media domain (region 4) sown in the Fig. 1 - B. There are 6 contact surfaces (boundaries), represented by the Fig. 1- A.
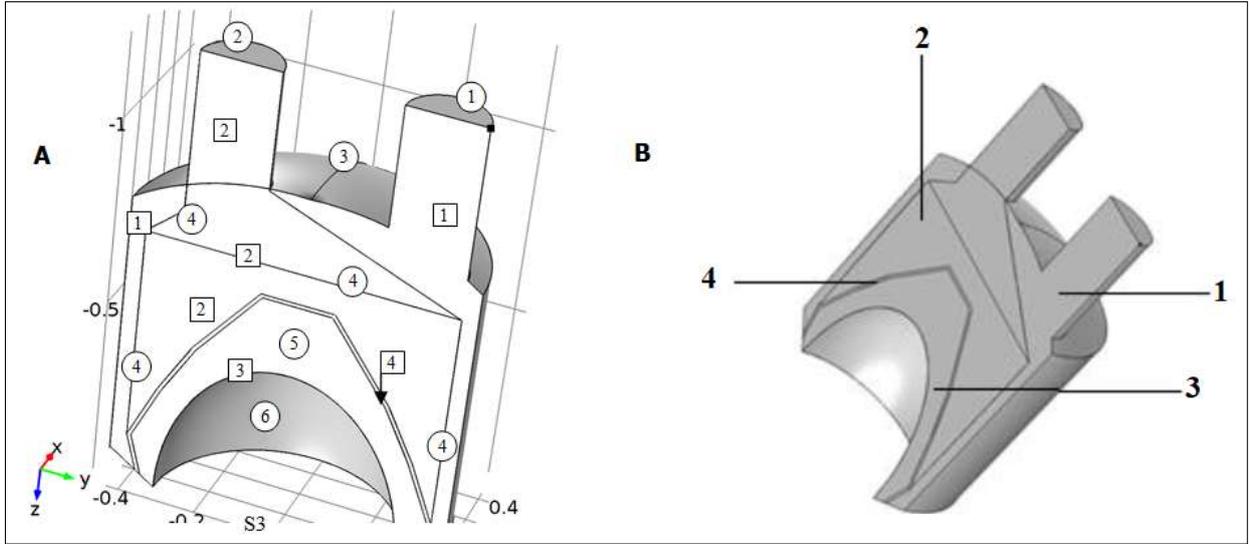
Figure 1. Geometry and boundary conditions.

Where:
  Surface 1: inlet: Temperature (T_0): 293.15 K; pressure (p_0) = 15 bar.
  Surface 2: outlet: developed flow conditions.
  Surface 3, 4 and 6: outer walls: no-slip condition, thermal isolation.
  Surface 5: temperature (T_{matrix}): 800 K.

2.2 Governing conservation equations

On the surfaces interfacing two different domains, appropriate boundary conditions are imposed in relation to one another. The governing equations for such a problem are:

1. For the fluid domain (squares 1, 2 and 3):
    Continuity equation:

$$\nabla.\left(\rho \mathbf{u}\right)=0 \tag{1}$$

Momentum equation:

$$\rho\left(\boldsymbol{u}.\nabla\right)\boldsymbol{u}=\nabla.\left[-p\boldsymbol{I}+\mu\left(\nabla\boldsymbol{u}\right)+\left(\nabla\boldsymbol{u}\right)^{T}-\frac{2}{3}\mu\left(\nabla\boldsymbol{u}\right)\boldsymbol{I}\right] \tag{2}$$

Energy equation:

$$\rho C_{p}\boldsymbol{u}\nabla T=\nabla.\left(k\nabla T\right) \tag{3}$$

where $\boldsymbol{u}$ is the fluid velocity vector, ρ is the fluid density, $\boldsymbol{I}$ is the identity vector, μ is the dynamic viscosity, Cp is the specific heat, k is the fluid thermal conductivity, p is the pressure and T the is the temperature.

2. For the porous matrix (square 4):
    Brinkman's equations:

$$\frac{\rho}{\varepsilon_{p}}\left(\left(\boldsymbol{u}.\nabla\right)\frac{\boldsymbol{u}}{\varepsilon_{p}}\right)=\nabla.\left[-p\boldsymbol{I}+\frac{\mu}{\varepsilon_{p}}\left(\nabla\boldsymbol{u}+\left(\nabla\boldsymbol{u}\right)^{T}\right)-\frac{2\mu}{3\varepsilon_{p}}\left(\nabla.\boldsymbol{u}\right)\boldsymbol{I}\right]-\left(\mu K^{-1}+\beta_{F}\left|\boldsymbol{u}\right|+\frac{Q_{br}}{\varepsilon_{p}^{2}}\right)\boldsymbol{u} \tag{4}$$

$$\rho\nabla.\boldsymbol{u}=Q_{br} \tag{5}$$

Where ε_p is porosity and K is the permeability.

3. Heat transfer in porous media equations (square 4):

$$\rho C_p \boldsymbol{u} \nabla T = \nabla.\left(k_{eq} \nabla T\right) \tag{6}$$

$$k_{eq} = \theta_p\, k_p + \left(1-\theta_p\right)k \tag{7}$$

where θ_p is the volume fraction, k_p is the effective thermal conductivity fluid of the fluid-sloid mixture.

3. VALIDATION

The principal validation problem was the porous media that was contrasted with the model of Hossain and Wilson (2002). It is a porous medium square cavity with air in natural convection. Tc is the temperature on the cold surfaces and Th represents the higher temperature (Fig. 2). There is a region on the bottom right vertical wall where the temperature varies linearly. Temperature and velocities behaviors were analyzed and there is compatibility. This validation can be found in the COMSOL documentations.
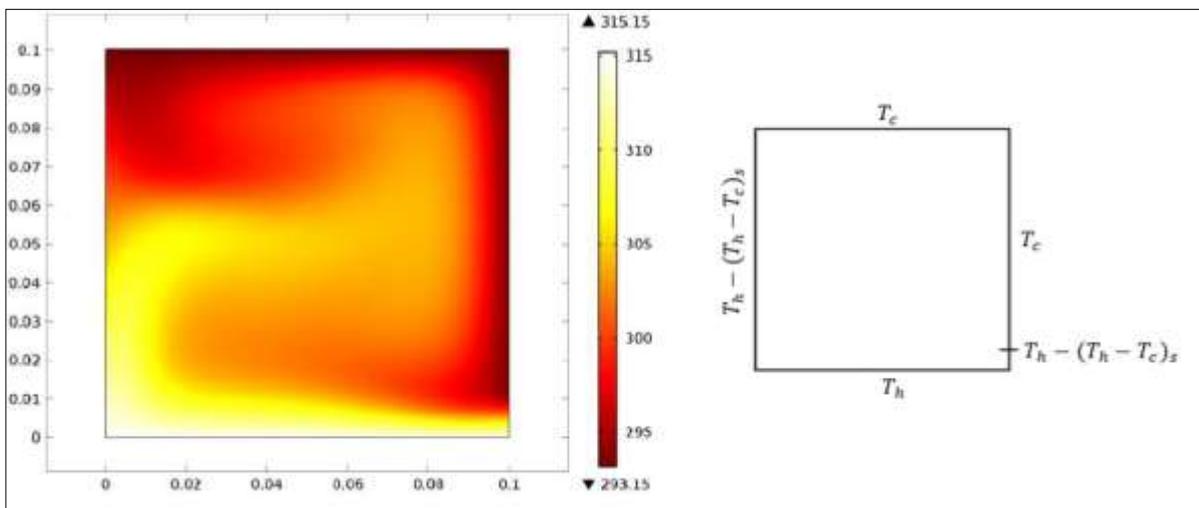

Figure 2. Geometry, boundary conditions and the isotherms for Rayleigh number equal to 10^5.

4. NUMERICAL METHOD

The finite element method is used in the software COMSOL Multiphysics. The Figure 2 shows the mesh with 118744 tetrahedral elements among others.
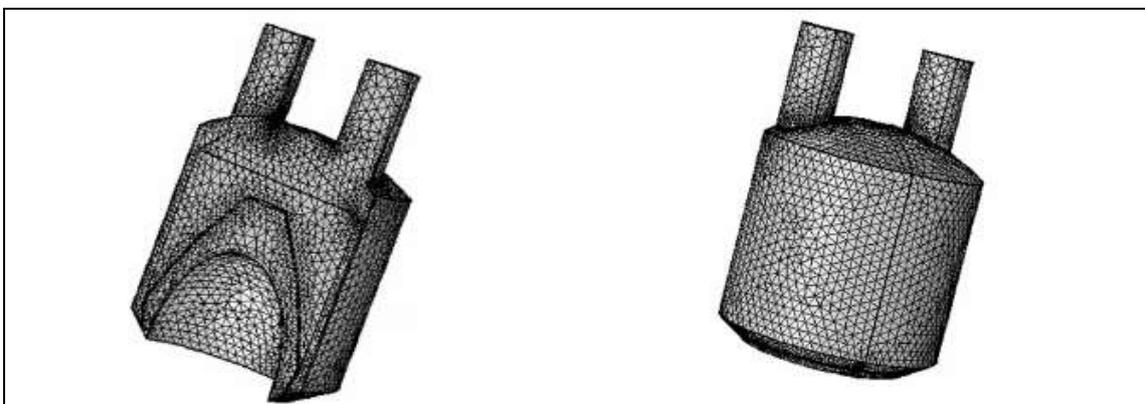

Figure 3. Receiver mesh.

5. RESULTS

As there would be many graphs that should be placed in the present work, the behavior of only one of the variations of porosity with will be demonstrated. The results of temperature, velocity and pressure of the other variations will be shown in table form, for a better understanding. The graphs to be demonstrated below refer to a porosity of 0.1535 and permeability of 0.00001 to temperature (Fig. 4), pressure (Fig. 5) and velocity (Fig. 6) fields.
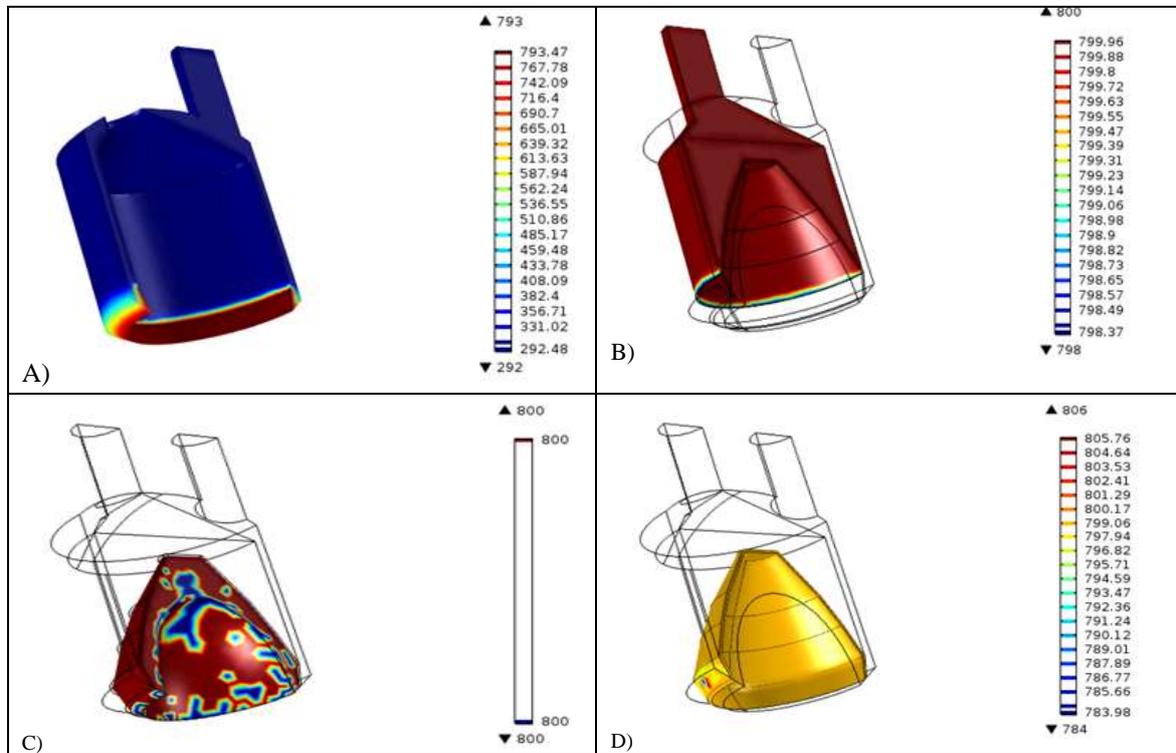

Figure 4. Thermal fields for $V_0 = 0.1$ m/s, $T_0 = 293.15$K, $T_{matrix} = 800$K and $p_0 = 15$ bar.

The domains thermal fields for $V_0 = 0.1$ m/s, $T_0 = 293.15$K, $T_{matrix} = 800$K and $p_0 = 15$ bar are shown in figure 4 represented by A - entrance region, B - exit region, C- inner region, D- the porous region. In A, the temperature varies from 292,48K to 793,47K. The more heated region is placed on the lower region that is in contact with the porous region surface that is at 800 K. Air is significantly heated as it passes through the porous region. In B, the region after the porous matrix, temperature ranges from 798.37K to 799.96K. There was about a 273% temperature increase when comparing to the inlet air temperature of 293.15K. This is due to the porous medium effect that plays a role of augmenting the thermal contact between air and the porous material. Region C, the porous matrix, has a nearly uniform temperature field, presents almost a uniform temperature of 800K. The thickness of this layer is small and the material used, Alumina ceramic, has a high thermal conductivity of approximately 150 W/m*K. The volume of air after the porous matrix (Fig. 4 B) also has a constant temperature distribution due to the fact that the air has already passed through the porous matrix and has undergone heat exchanges with it. This demonstrates the efficiency of the equipment and the importance of the porous matrix.

By analyzing Fig. 5 in the next page, it is possible to perceive the different pressure orders that are present in the four domains. The fact that the inlet pressure is greater than the outlet pressure can be explained by the higher speeds in the inlet region. It is also worth mentioning the intense loss of charge that occurs in the porous matrix, since the fluid has a lower pressure after passing through the pores. However, it is noted that inside the matrix, the pressure is very high, reaching values of $1.01*10^5$Pa.

Figure 6 shows the velocity fields for the four domains. For the porosity conditions of the material presented, it is seen that the exit velocity (Fig. 6-B) is almost 4 times higher than the inlet velocities (Fig. 6-A), even though the inlet to outlet diameters they are the same. In the case analyzed, the air was considered incompressible. Therefore, the regions of higher velocities refer to regions of lower pressures. This can be seen in Fig. 6-B, which extremely low speeds are shown, however, this same region has very high pressures.
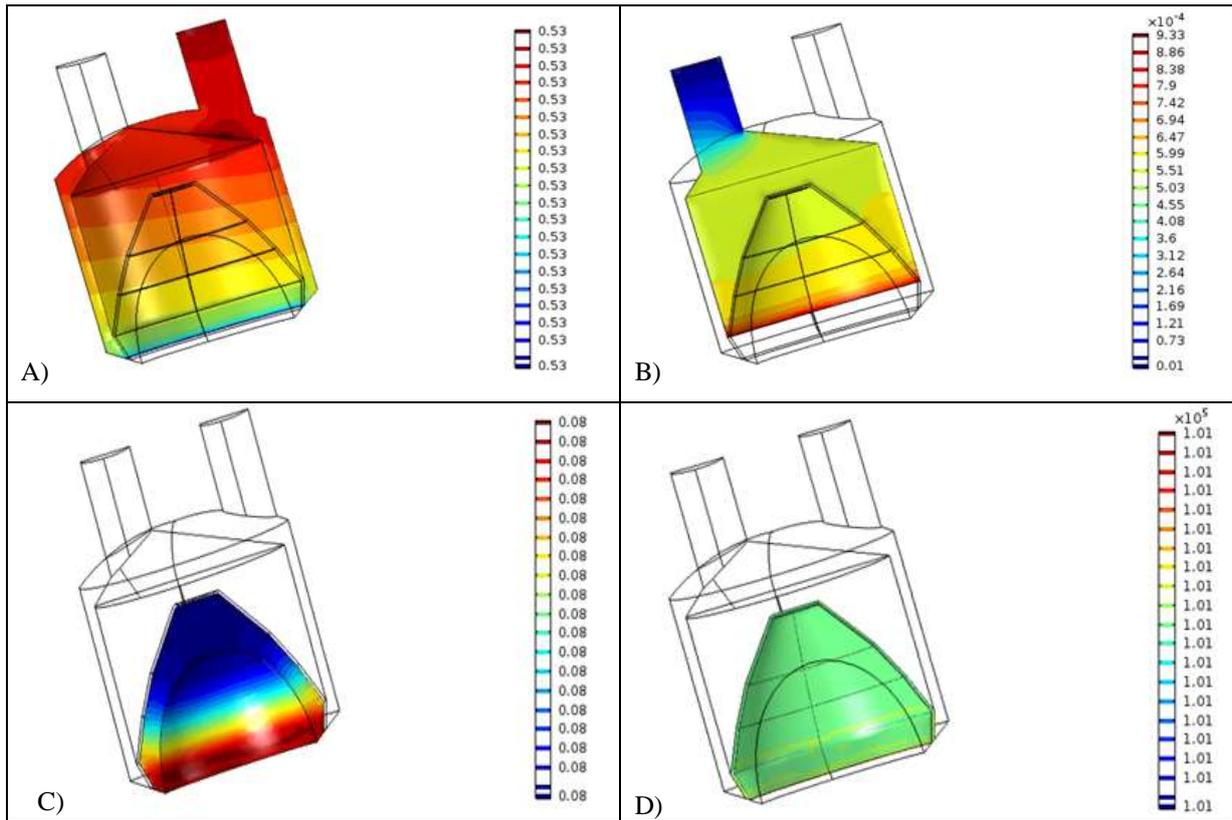
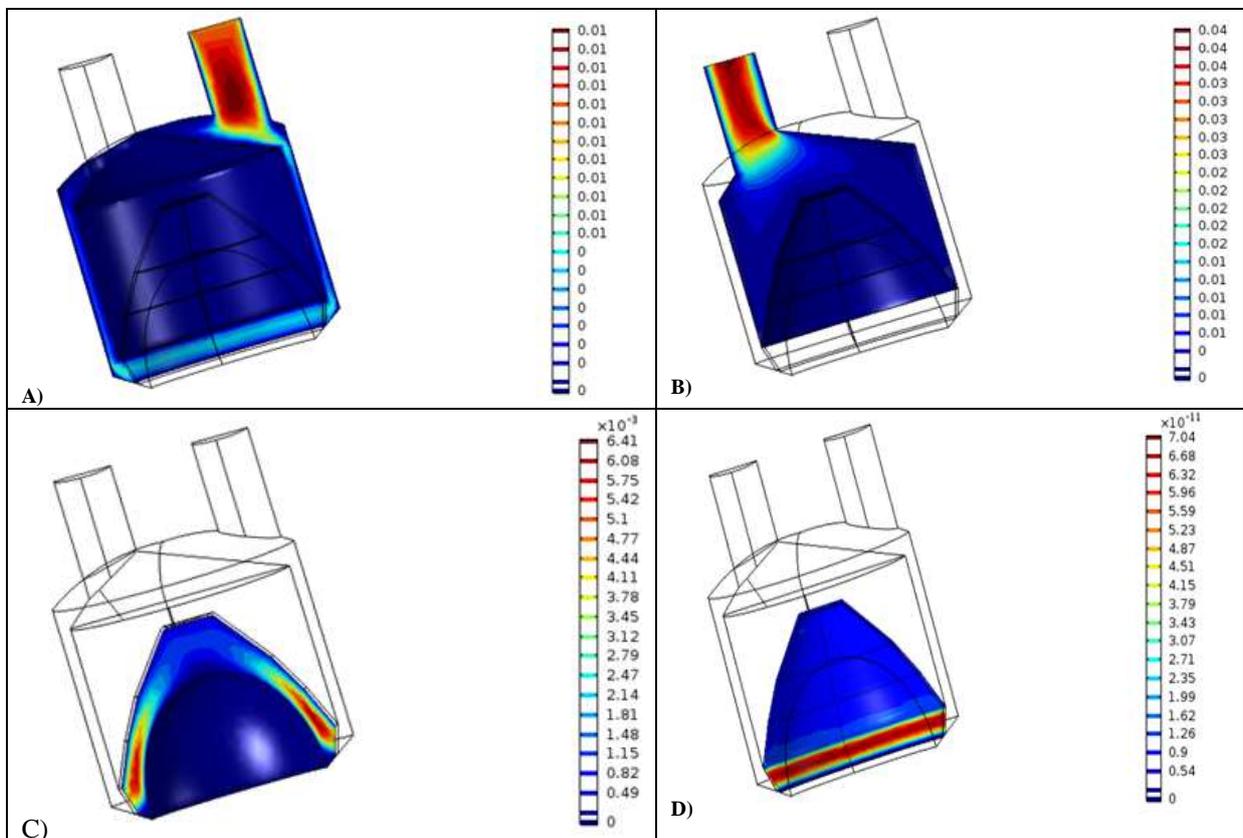Figure 5. Pressure distribution in (Pa) for $V_0 = 0.1$ m/s, $T_0 = 293.15$K, $T_{matrix} = 800$K and $p_0 = 15$.

Figure 6. Velocity fields for $V_0 = 0.1$ m/s, $T_0 = 293.15$K, $T_{matrix} = 800$K and $p_0 = 15$.

Table 8 below lists the values that are generated with variations of porosity, and permeability. When analyzing the table of values generated with these variations, it was observed that there were no large variations, regardless of the porosity and the permeability that was used.

Table 8. Variation of Porosity (ε) and Permeability (Ka) at a velocity of 0.01m/s.

Porosity	Permeability	Average Inlet Pressure (P1)	Average outlet Pressure (P2)	Inlet Temperature (T1)	Outlet Temperature (T2)	Average Inlet Velocitity (V1)	Average Outlet Velocitity (V2)
0,15250	0.00001	4,60140	0,00002	293,15000	800,00000	0,01000	0,02492
	0.0001	0,53207	0,00000	293,15000	800,00000	0,01000	0,02492
	0.001	0,53207	0,00002	293,15000	800,00000	0,01000	0,02492
	0.1	0,53207	0,00002	293,15000	800,00000	0,01000	0,02492
	0.5	0,04948	0,00002	293,15000	800,00000	0,01000	0,02492
0,29380	0.00001	4,60140	0,00002	293,15000	800,00000	0,01000	0,02492
	0.0001	0,53207	0,00000	293,15000	800,00000	0,01000	0,02492
	0.001	0,53207	0,00002	293,15000	800,00000	0,01000	0,02492
	0.1	0,53207	0,00002	293,15000	800,00000	0,01000	0,02492
	0.5	0,04948	0,00002	293,15000	800,00000	0,01000	0,02491
0,57880	0.00001	4,60140	0,00002	293,15000	800,00000	0,01000	0,02491
	0.0001	0,53207	0,00000	293,15000	800,00000	0,01000	0,02492
	0.001	0,53207	0,00002	293,15000	800,00000	0,01000	0,02492
	0.1	0,53207	0,00002	293,15000	800,00000	0,01000	0,02492
	0.5	0,04948	0,00002	293,15000	800,00000	0,01000	0,02492
0.7854	0.00001	4,60140	0,00002	293,15000	800,00000	0,01000	0,02492
	0.0001	0,53207	0,00000	293,15000	800,00000	0,01000	0,02491
	0.001	0,53207	0,00002	293,15000	800,00000	0,01000	0,02492
	0.1	0,53207	0,00002	293,15000	800,00000	0,01000	0,02492
	0.5	0,04948	0,00002	293,15000	800,00000	0,01000	0,02492

So larger (0.7854) and smaller (0.1525) porosities, lower permeability values (0.00001) and higher permeability (0.1) did not affect the behavior of the temperature, pressure and velocity. Thus, a possible conclusion for this fact is that the velocity of entry into the system (0.01m/s) is considered to be very low. Because the velocity is low, it is understood that the working fluid is able to pass slowly through the porous matrix and perform the heat exchanges.

Therefore, to verify the effect that the flow velocity can cause in the behavior of the system, a study with greater speed, with a value of (0.5 m/s) was performed. In this stage, another analysis was done: which permeability values are more frequent in Alumina. According to Innocentinia (1999), the permeability values do not vary abruptly in a ceramic. The Alumina research demonstrates that the permeability values are almost always low, regardless of the porosity. Thus, a permeability value of $0.0001m^2$ was used for the next studies that used a velocity of 0.5m/s for the porosities: 0.2 and 0.4.

Figure 7 below shows large difference in pressure gradients for porosity of 0.4. These gradients are much larger than those obtained in the previous case (Fig 5). The effect of the input velocity and the porous matrix seem to be determinant for these behaviors to occur more abruptly, with larger gradient values. It is important to note that the pressure of the porous matrix for the present case was 10 times higher than for the previous case, as seen in Figure 5D.
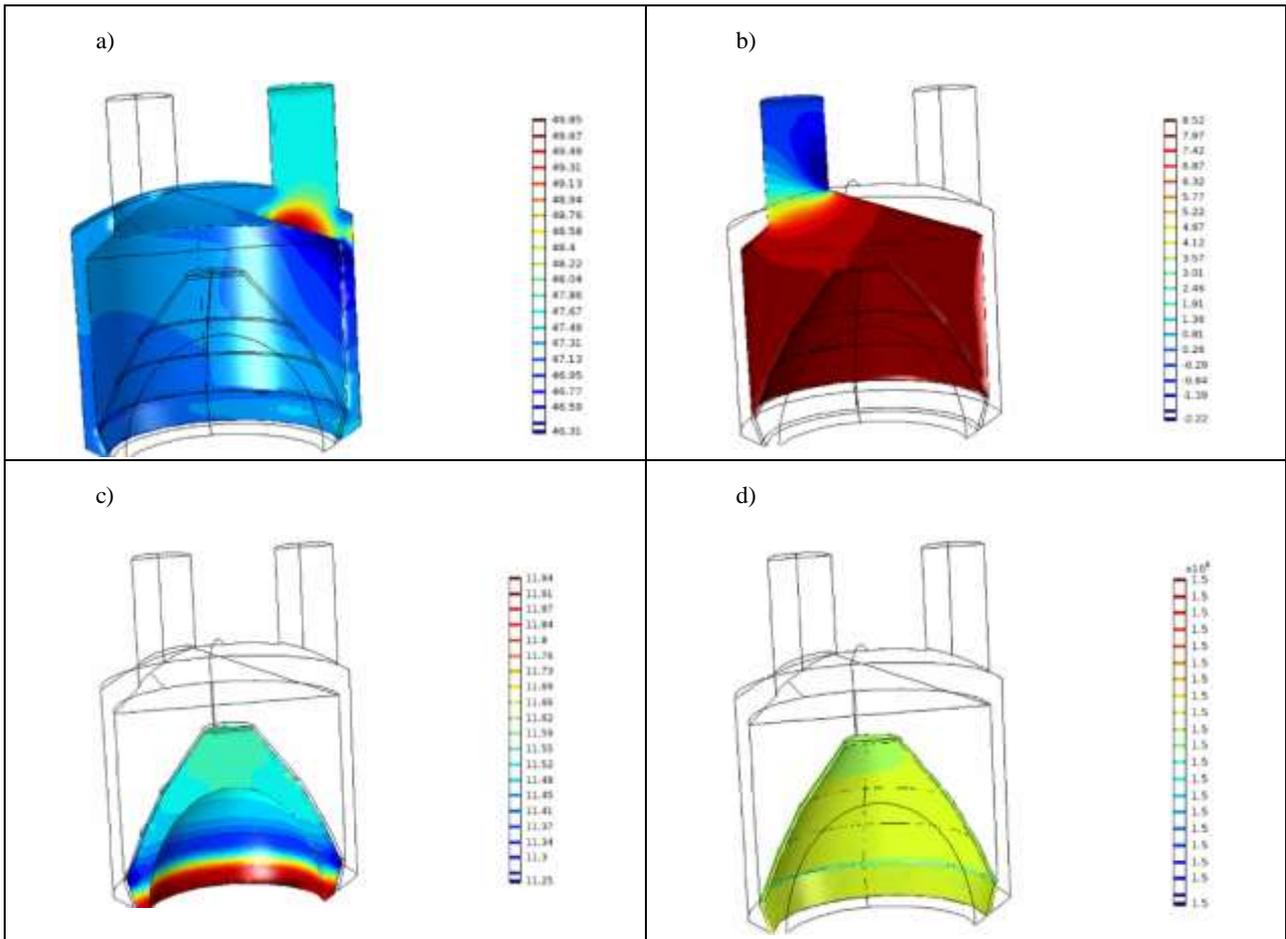
Figure 7. Pressure fields for ε = 0,4 e Ka = 0,0001 m2 para U_0 = 0,5m/s.

Figure 8 shows there was a greater difference in temperatures before and after the porous matrix, and this fact can be explained by the increase in velocity in the system and also by the porosity being greater than the one used in Fig 4. Another consideration is in relation to the outlet temperature of the receiver (Fig. 8-B), which when compared to Fig. 4-D, it is perceived that it is smaller. This fact can be explained again by the influence of the flow velocity and the porosity that was imposed on Alumina.
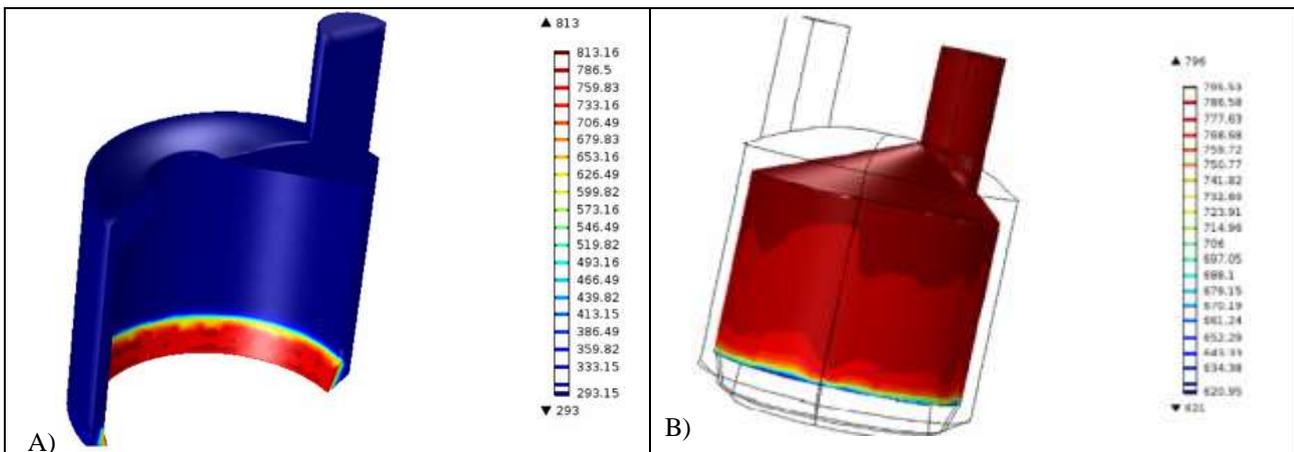

Figure 8. Thermal fields for ε = 0,4 e Ka = 0,0001 m2 para U_0 = 0,5m/s.

Figure 9 shows the temperature fields for porosity of 0.2. There was a larger temperature difference at the receiver base, with temperature values up to 932, 49 K, differently from the other case previously analysed (Fig.8). Comparing

with, it is possible to conclude that the increase in temperature may have been caused by the porosity difference, from 0.4 to 0.2. As the only altered condition was the porosity, the different results that were obtained were attributed to it.
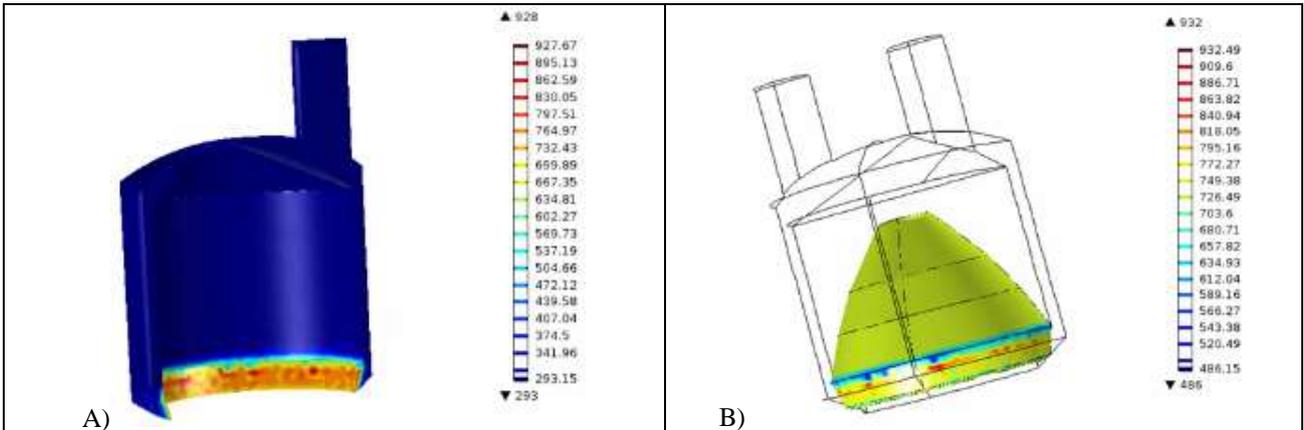

Figure 9. Thermal fields for ε = 0,2 e Ka = 0,0001 m2 para U_0 = 0,5m/s.

Figure 10 and Fig. 11 demonstrated velocities fields. Thus, by making a comparison, the increase in speed in both cases causes the characteristics of the system to change. For both porosities, in Fig. 10..A and Fig, 11A it is possible to see that the velocity gradient starts high and falls to zero, equally to all previous analyzes. As already said, these explanations are due to the increase of geometric area and also to the increase of pressure.
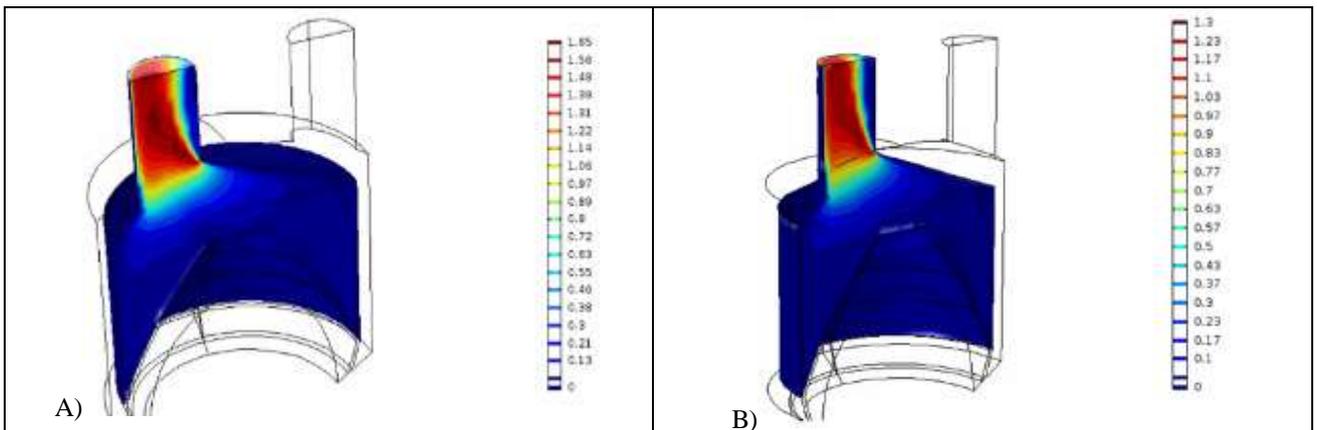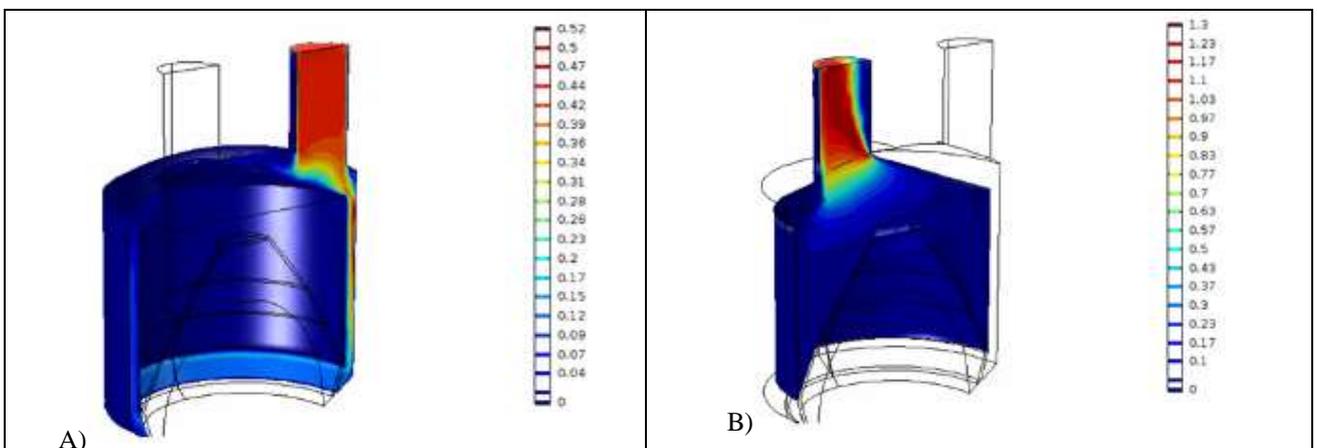

Figure 10. Velocity fields for. ε = 0,4 e Ka = 0,0001 m2 para U_0 = 0,5m/s.

Figure 11. Velocity fields for ε = 0,2 e Ka = 0,0001 m2 para U_0 = 0,5m/s.

Lastly, a necessary comparison is that of figures 10B and 11B, where it is perceived that the output velocities are different, and that of Fig. 11B is smaller than that of Fig. 10B. This observation is important, because possibly this result was obtained due to the porosity being smaller than the case analyzed in Fig. 11.

6. CONCLUSION

Air is significantly heated as it passes through the porous region. The porosity has an important effect on the volumetric receptors. Not only the temperature, but the velocity and pressure gradients are also constantly altered with the porosity changes. Regarding permeability, it was noticed that its variation does not lead to sudden changes in the system.

Another important result was the effect of the flow velocity: for very low velocities, the change of porosity and permeability are not significant for changes in the system, as could be verified with the data that was obtained. In cases where the velocity used was 0.5 m/s, there was a temperature rise at the receiver output of more than 270%, relative to the input. Therefore, it is concluded that the porous matrix is of great importance for the transfer of energy to the system.

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