HEAT TRANSFER IN CHANNELS USING NANOFLUIDS, POROUS MEDIA AND THE TWO ENERGY EQUATION MODEL

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Abstract. *Seeking a better performance in heat transfer systems, new technologies have been developed, such as the use of porous media and nanofluids. The reason is that, the porous media increases the contact area between the fluid and solid, and the nanoparticles increases the thermal conductivity of the working fluid. Therefore, this article aims at understanding the influence of nanofluids on the heat transfer by natural convection in ducts containing porous medium, using two energy equations model (2EEM). As it was expected, the heat increase linearly with the volumetric fraction of nanoparticles. Comparing the heat transfer values of the pure base and porous media, adding nanofluids, it can be 18% higher for a volumetric fraction of 2% of nanoparticles. The results are in full agreement with trends and data of forced convection in porous media saturated with ordinary fluids.*

Keywords: *Nanofluids, Heat Transfer, 2EEM.*

1. INTRODUCTION

Heat transfer is important in a large range of engineering areas and is a dominant feature in practically all the devices of energy generation. Since among the forms of generation of energy, as approximately 70% of the energy generation processes involve heat exchanger processes (Wen, et al., 2009). Thus, proper use of heat transfer is vital to optimize the performance of these systems. Considering the rapid increase in energy demand in the world, intensifying the processes of thermal exchange and reducing energy losses due to inefficiency is an important task (Wen, et al., 2009).

The heat transfer by convection is enhanced by passively changing the flow geometry, increasing the available area of heat exchange, the boundary conditions or increasing the thermal conductivity of the working fluid. Therefore, in order to increase the thermal exchange efficiency, it is necessary to increase the contact surface between the solid and the working fluid or increase the thermal conductivity of the working fluid (Wang & Mujumdar, 2007).

Seeking a better performance in these systems, new technologies have been developed, such as the use of porous media. Such media consists in a solid matrix composed of pores, typically filled with fluid, which increases the area of contact between the fluid and the solid surface. In this type of structure, heat is transferred by conduction in the solid and by natural convection in the fluid. In addition, another technology that has been receiving attention, due to its diverse applications to engineering, are the nanofluids. This new class of fluids is characterized by having metals dissolved in a base fluid, typically used in heat transfer processes (water, oil, ethylene glycol). The presence of nano particles in the fluid increases the thermal conductivity of the base solution. Thus, the combination of both technologies can considerably enhance the final efficiency of the heat transfer systems (Da Fonseca, 2007).

The thermal conductivity of fluids plays a key role in the industry. Processes requiring heat exchangers used for cooling and heating are highly dependent on heat transfer fluids. However, the fluids traditionally used (water, alcohol, ethylene glycol) have low thermal conductivity when compared to metallic solids. In order to increase heat transfer rates without increasing equipment size, metallic solids can be dissolved in the liquids to increase the thermal conductivity of the mixture (Da Fonseca, 2007).

However, solutions with micro or mili solid particles have low solution stability and tend to sediment, creating a new resistance to heat transfer, which can cause erosion of the equipment or clog small-scale channels. On the other hand, nano particles with an average size smaller than 50nm have a larger contact surface than the micro or mili particles and greater solution stability. Thus, the thermophysical properties of the working fluid still can be improved in a porous media heat transfer, since the nano particles will not obstruct the pores (Wang & Mujumdar, 2007). Applying porous media and nanofluids in the same thermal system, it is possible to ally high heat transfer surface area to volume ratio with an improved thermal conductivity of the working fluid. Due to this reason, it is expected that the combination of porous media with nanofluids can enhance the heat transfer (Kasaeian, et al., 2017).

Although there are a number of studies in the literature that consider heat transfer using nanofluids, most are concentrated in closed cavities and few studies consider the porous media. When compared to studies in forced convection of nanofluids, there is only a limited range of studies considering the natural convection in heat transfer (Kasaeian, et al., 2017). Considering the experiments presented in the literature, the heat transfer behavior in nanofluids is complex and should not be based just on the effective thermal conductivity. Many other factors are crucial and play an important role on the heat transport, such as particle sizes, morphology, and their distribution in the liquid (Wen & Ding, 2005). Considering these aforementioned aspects, this study aims to understand the influence of nanofluids on natural convection phenomena inside ducts containing a porous medium. For the proposed analysis, two energy equations model is applied (Carvalho & De-Lemos, 2009).

2. COMPUTATIONAL PROCEDURES

Studies have been developed to predict the behavior of thermal conductivity in nanofluids, from simple correlations (Maxwell, 1881) to complex and detailed models. However, the model that best describes the nanofluid behavior must consider that the metallic particles not only alter the thermal conductivity but also viscosity, density, and consequently, the heat transfer capacity as described in. In this study, the model proposed by Heyhat et al. (2012) is the chosen model used to compute the nanofluids thermo-physical properties.

In reason to describe the behavior of the fluid inside the porous media, the Local Thermal Equilibrium (LTE) cannot be applied, thus the model namely two-energy-equation (2EEM) is used to handle the problem under studying. The macroscopic flow equations are obtained by instant local equations of continuity and momentum and applied to 2EEM, differentiating the solid material and the fluid. The macroscopic flow model and the two energy equation models are described in (Carvalho & De-Lemos, 2009), and are summarized as follows:

The permeability (K) of the porous matrix is determined using the Equation (1),

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

Where, ϕ is porosity and d_p porous diameter. For steady-state conditions, we consider the fluid and the solid phase energy balance Equations (2) and (3):

Fluid:
$$\nabla \cdot (\rho_f \, c_{pf} \, \mathbf{u}_D \langle \overline{T_f} \rangle^i) = \nabla \cdot \left\{ \mathbf{K}_{eff,f} \cdot \nabla \langle \overline{T}_f \rangle^i \right\} + h_i a_i \left(\langle \overline{T}_s \rangle^i - \langle \overline{T}_f \rangle^i \right) \tag{2}$$

Solid:
$$0 = \nabla \cdot \left\{ \mathbf{K}_{eff,s} \cdot \nabla \langle \overline{T_s} \rangle^i \right\} - h_i a_i \left(\langle \overline{T}_s \rangle^i - \langle \overline{T}_f \rangle^i \right) \tag{3}$$

where, $a_i = A_i / \Delta V$ is the interfacial area per unit volume, h_i is the film coefficient for interfacial transport, $\langle T_f \rangle$ fluid temperature, $\langle T_s \rangle$ solid temperature, $\mathbf{u}_D$ Darcy velocity vector, ρ density, $\mathbf{K}_{eff,f}$ and $\mathbf{K}_{eff,s}$ are the effective conductivity tensors for fluid and solid, Equations (4) and (5) respectively, given by:

$$\mathbf{K}_{eff,f} = \left\{ \underbrace{\phi k_f}_{conduction} \right\} \mathbf{I} + \underbrace{\mathbf{K}_{f,s}}_{local\ conduction} + \underbrace{\mathbf{K}_{disp}}_{dispersion} \tag{4}$$

$$\mathbf{K}_{eff,s} = [(1-\phi)k_s]\,\mathbf{I} + \mathbf{K}_{s,f} \tag{5}$$

In Equations (4) and (5), $\mathbf{I}$ is the unit tensor and k_f/k_s the fluid and solid conductivity. The Reynolds and Nusselt number are the dimensionless numbers employed along this work to evaluate the thermal gradient in the dominion studied. Where, Nusselt number at the wall defined by,

$$Nu_w = \frac{Q_w D}{k_{ef}\Delta T} \tag{6}$$

where, ΔT is the reference temperature difference of 100ºC, Effective conductivity (k_{ef}) is defined by $k_{ef} = \phi + (1-\phi)k_f/k_s$, D the tube diameter, overall heat rate (kW) along the entire upper wall and the Reynolds Number is defined by,

$$Re = \frac{\rho D U_{in}}{\mu} \tag{7}$$

where, ρ is density, μ dynamic viscosity and U_{in} the mean inlet velocity of the fluid.

This set of partial differential equations were solved based on the finite volume method. For the mesh independence study, 100x100 and 200x200 grid sizes were applied, and a variation of the heat transfer rate smaller than 1% was found between meshes. Therefore, this study will apply the 100x100 grid as a manner to save computational time. The convergence criteria for all variables were set to 10^{-9}. The SIMPLE method of Patankar (1980) was used to the handle the pressure-velocity coupling and applied for relaxing the systems of algebraic equations. The procedure for code validation and simulations employed here are the same used by (Carvalho & De-Lemos, 2009), or say, computations results are compared with analytical data shown in (Heyhat, et al., 2012).

3. RESULTS AND DISCUSSION

The arrangement evaluated, consists in a tube one meter long, 10mm internal diameter, with constant wall temperature of 373K. The fluid enters the channel at 300K, as it can be seen in Figure 1.
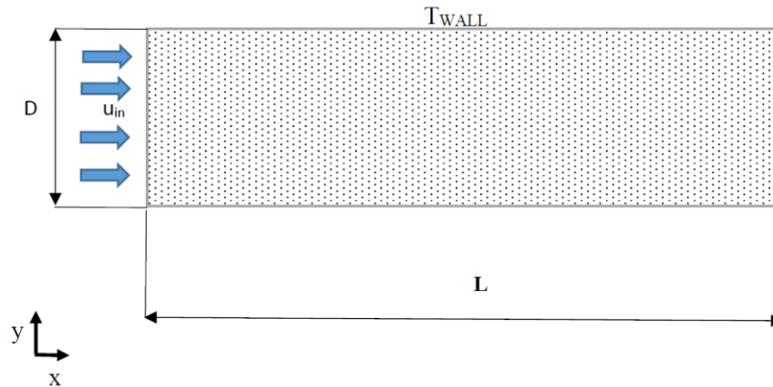

Figure 1 – Sketch evaluated

The evaluated nanofluid has properties, shown in Table 1, which are the same properties used by (Heyhat, et al., 2012).

Table 1 – Nanoparticles Properties

dp (nm)	ρ (kg/m³)	k (W/m.K)	Cp (J/kg.K)
40	3900	42.34	880

Figure 2 shows the percentage increase in the heat transfer rate with the use of nanofluids for different volumetric fractions (φ_n) of the nanoparticles, defined by,

$$\eta = \frac{Q_w - Q_w^o}{Q_w^o} \times 100 \qquad\qquad (6)$$

where Q_w^o is the overall heat rate (kW) along the entire upper wall for the pure base fluid Q_w and the overall heat rate (kW) along the entire upper wall for the nanofluid. As can be observed in Figure 2, the increase in the rate of heat transfer is linear, which is in agreement with reference (Heyhat, et al., 2012).
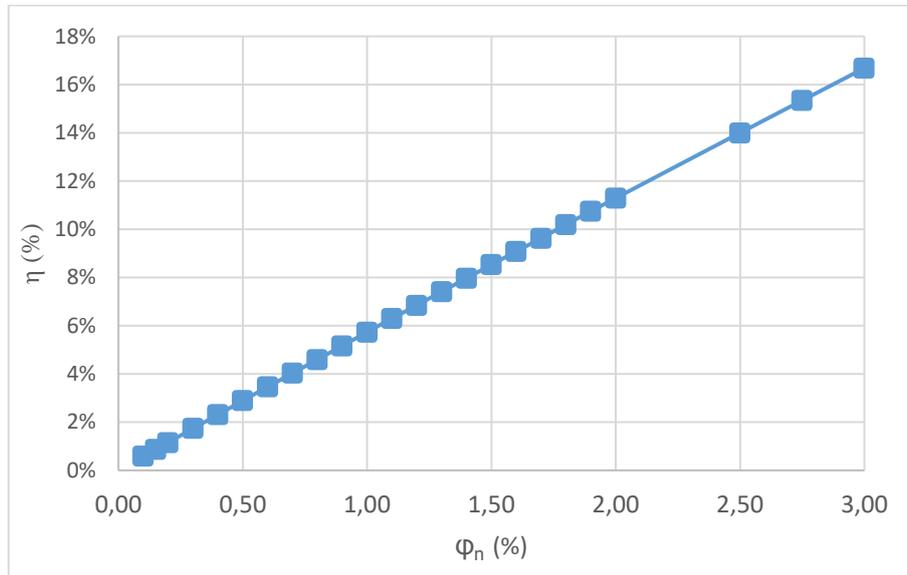

Figure 2– Increase of heat rate transfer η as function of volumetric fraction φ_n

Considering the volumetric fraction of 2% nanoparticles, for the pure base fluid and the nanofluid as a function of the Reynolds Number and the Nusselt Number is shown in Figure 3. This particularly nanofluid has a dynamic viscosity of 1.59^{-3}N.s/m, density of 1058 kg/m³ and the velocity range evaluated was from 0.001 to 0.1 m/s.
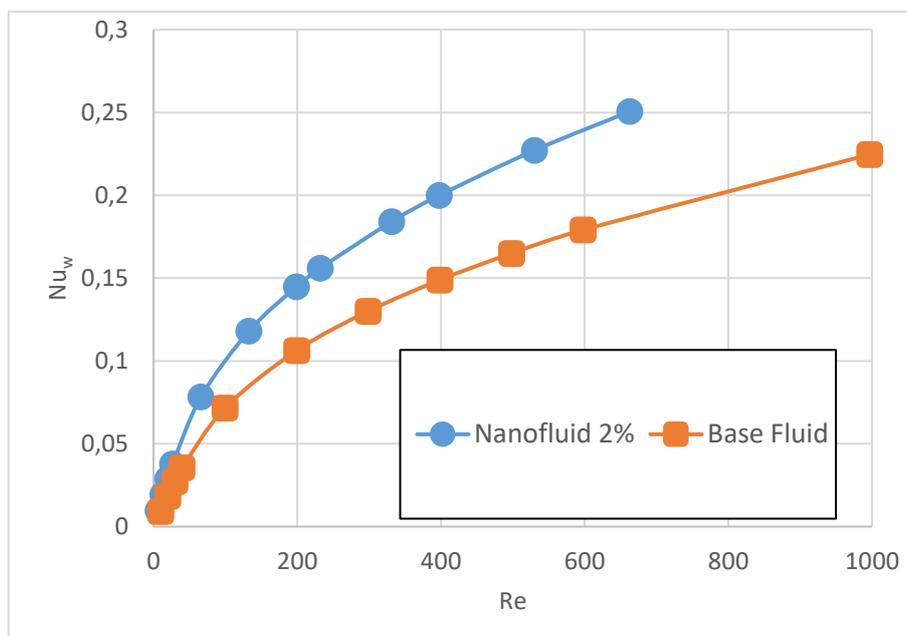

Figure 3 – Nusselt Number Nu_w as a function of the Reynolds Number Re for Nanofluids and the Pure Base

As observed during simulations, the increasing kinematic viscosity due to the presence of nano particles resulted in lower Reynolds numbers, by definition for the same flow rate, when compared to the base fluid. As can be seen in Figure 3, for the same Nu_w the nanofluid has a lower Reynolds number due to the increase on kinematic viscosity. Nevertheless, the laminar regime was mantained for all cases, in the simulated range.

At low Reynolds number Re, the difference of Nu_w between the nanofluid and the base fluid is lower, when compared to higher Re. For low flow velocitites, the heat exchange effectiveness increase and due to this reason the influence of the nano particles is reduced. The difference in the heat transfer rate does not follow linear, because the convective coefficients non-linearly vary with the temperature.

The porous media use in this study has particle diameter (d_p) of each porous region of 9.5 10^{-04}m, ratio of conductivity (k_s/k_f) of 1150 and porosity (ϕ) of 0.5. Figure 4, shows the comparison in the Nusselt number with the Reynolds, for the four cases studied: the pure base, pure base with nanofluids, pure base and porous media and the union of the three cases.
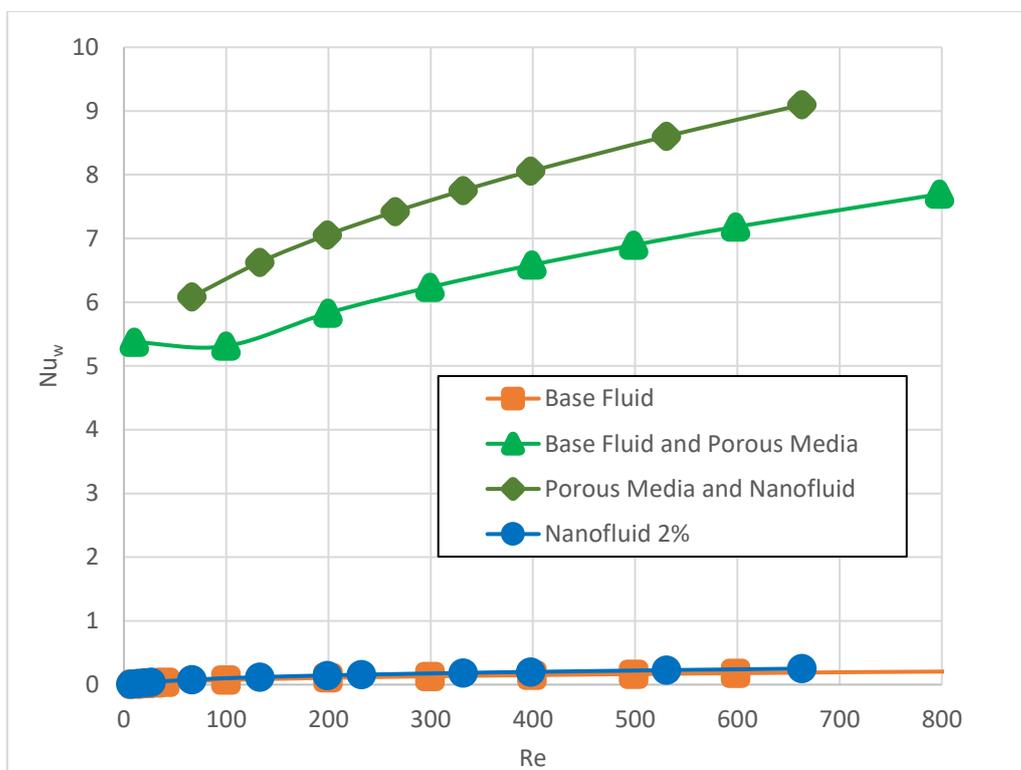

Figure 4 - Nusselt Number Nu_w as a function of the Reynolds Number Re for all the cases studied

As it can be seen in Figure 4, the Nusselt Number increases with the addition of a porous media due to increase the heat exchange available area, as expected. The addition of nanofluids in the porous media increases the heat transfer of 18%, in average.

The increase in heat exchange and in Nusselt Number is expressive when the Figures 2 and 4 are observed. However, as it was mentioned, the use of nanoparticles has its counterpoint as enhances viscosity what increases the pressure drop. In Figure 5, it is possible to observe this trend. In this case, with inlet velocity of 0.03m/s, the pressure drops increases 33.5% when using nanofluids.
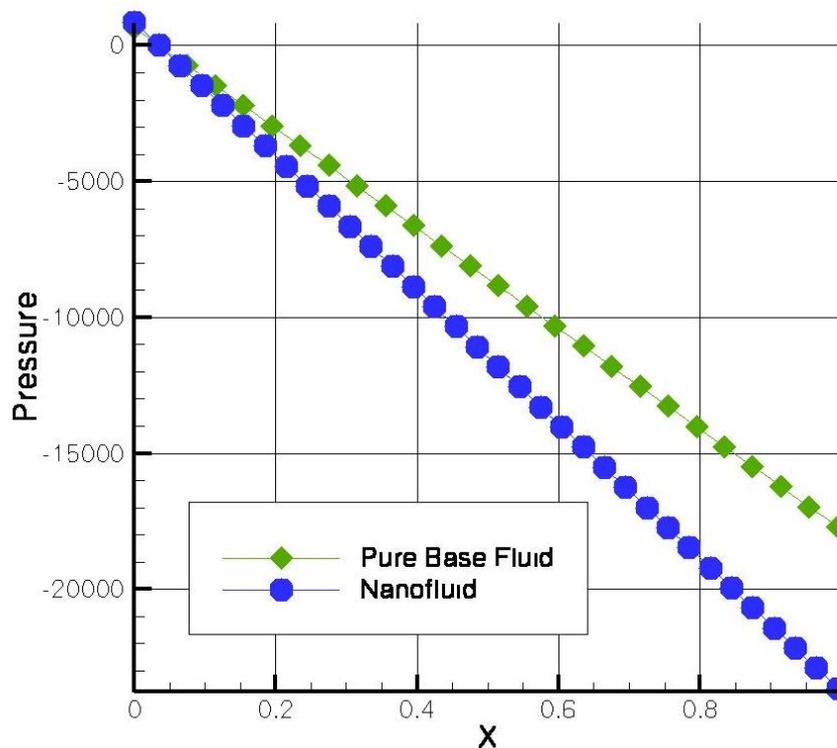
Figure 5 - Pressure Drop along the tube with porous media comparing pure base and nanofluid

Based on the methodology adopted, the presented results have a satisfactory agreement with the references Heyhat, et al. (2012) and Carvalho & De-Lemos (2009). As the presence of nanoparticles in the fluid increases, the thermal conductivity of the base solution and with the porous media the area of thermal exchange between solid and liquid is increased, enhancing the overall heat transfer of the system.

4. CONCLUSION

Forced convection through a cylinder filled with a porous matrix that is saturated with a nanofluid was studied. The two energy equation model was used to simulate the momentum transfer in the porous medium. The impact of the nanofluid compared to a pure fluid in the heat transfer performance of the porous medium was investigated. The present results are in full agreement with trends and data of forced convection in porous media saturated with ordinary fluids and support the idea that the union of porous media and nanofluids can maximize heat transfer.

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