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Investigation of Heat Transfer of Non-Newtonian Pseudo-Plastic Fluids in Porous Heat Exchangers

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ABSTRACT: In this paper, the natural heat transfer of Rayleigh-Benard's non-Newtonian Pseudo-Plastics fluid in a tube heat exchanger with its left wall lined with a porous layer of a thickness l is considered numerically for an unstable state of laminar. The lower wall of the heat exchanger is at constant temperature T_h and the upper wall at T_c temperature (T_h>T_c). The walls are left and right insulated. The dimensionless governing equations are solved by the finite element method and the accuracy of the results is compared with previous studies. The results show that, in a large Rayleigh number, the average Nusselt number increases due to the fact that the natural heat transfer is more than conduction heat transfer. Also, in small Darcy numbers, the flow permeability is very low which causes reduce natural heat transfer convection. The results show that by decreasing the Power-law index, the non-dimensional temperature is reduced and the lowest non-dimensional temperature is obtained for the lowest Power-law index. On the other hand, with the increase of the Power-law index in a constant Rayleigh number and the passage of time, the increase of natural heat transfer occurs in the tube. Also, the Rayleigh number decreases with the increase of the Power-law index to start the natural convection in the heat exchanger.

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1. INTRODUCTION

The heat transfer from non-Newtonian fluids to pipes is important in the chemical, petrochemical, polymer, food, pharmaceutical, industries, etc. The purpose of the heat transfer of non-Newtonian fluids is to design heat exchangers. Due to the fact that in many chemical processes, especially in the field of polymeric materials and non-Newtonian fluid, it is necessary to study the thermal behavior and how the heat transfer coefficient of these fluids is changed. In the case of heat transfer of non-Newtonian fluids in Laminar flow in tubes, investigation studies have been carried out by Bird and Lyche [1]. In their review, it has been shown that the temperature curve changes in the tube relative to the tube radius (r/R) with a faster increase in the Power-Law model. Popovska and Wilkinson [2] have experimented on Pseudo-Plastics. Experimental studies on the heat transfer of viscous fluids during a laminar flow into a circular tube can be seen in many published papers [3]. Al-Sumaily and et al. [4] investigated the effects of porosity particle size on the heat transfer from a circular cylinder, assuming a thermal imbalance numerically. Sun and et al. [5] studied the heat transfer of Rayleigh-Barnard's non-Newtonian fluid of Al_2O_3 water, numerically, following a power law in a square enclosure.

2. METHODOLOGY

2.1. Modeling

Fig. 1 demonstrates a schema of the physical model for natural convection of the Rayleigh-Benard heat transfer process in the pipe.

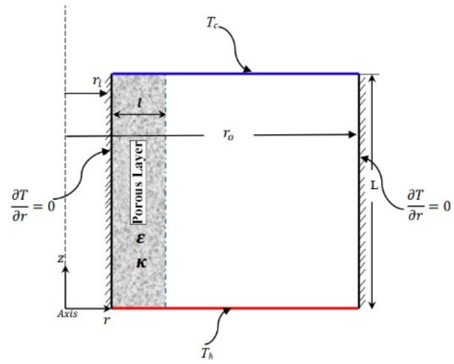

Fig. 1. Schematic view of the model in 2D

The model is two coaxial pipes With radius r_i,r_o and height L. The boundary conditions in this study included constant temperatures of the bottom and upper walls, represented by T_h and T_c, respectively, such that T_h>T_c, as well as two base walls of the annuluses with adiabatic conditions $\partial T/\partial z$ =0. In this study, radiation effects were assumed to be negligible. The Problem is considered as axisymmetric and unsteady and heat transfer by natural convection, with a laminar flow.

2.2. Governing equations

The governing equations on unsteady and laminar flow of base fluid in the two-dimensional cylindrical coordinates (r,z), by using the Boussinesq approximation, are expressed

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in the following. The continuity equation is as below,

$$\rho\nabla^{*}.(\vec{u})=0 \tag{1}$$

where $\vec{u}$ is the vector of velocity. The momentum equation is

$$\rho\frac{1}{\varepsilon}\frac{\partial\vec{u}}{\partial t}+\frac{1}{\varepsilon^{2}}\rho.(\vec{u}.\nabla^{*})\vec{u}=\nabla^{*}.\left[-pI+\frac{\mu}{\varepsilon}\left(\nabla\vec{u}+(\nabla\vec{u})^{T}\right)\right]$$
$$-\frac{\mu}{K}\vec{u}+\rho\vec{g}\beta\Delta T \tag{2}$$

In order to consider non-Newtonian behavior of the fluid, the Power-law is used, based on this model can be written: [6]

$$\mu(\dot{\gamma})=m\mu_{a}\rightarrow\begin{cases}\mu_{a}=(\dot{\gamma})^{n-1}\\ \dot{\gamma}=\max\left(\sqrt{[D']:[D']},\dot{\gamma}_{\min}\right)\\ D'=\frac{1}{2}\left(\nabla\vec{u}+(\nabla\vec{u})^{T}\right)\end{cases} \tag{3}$$

where n is called power-law index the deviation of n from unity indicates the degree of deviation from Newtonian behavior, that is n<1 for pseudo-plastic. The energy equation is expressed in the form of Eq. (4)

$$(\rho c_{p})_{eff}\frac{\partial T}{\partial t}+(\rho c_{p})\vec{u}.\nabla^{*}T=\nabla^{*}.(k_{eff}\nabla^{*}T) \tag{4}$$

3. RESULTS AND DISCUSSION

The purpose of this paper is to investigate the effect of effective parameters such as Rayleigh number, porosity coefficient of porous media and Darcy number on natural heat transfer. As the first result, the effect of the presence of the porous layer and the absence of a porous layer has been discussed. The velocity vectors are distinguished in the presence of a porous layer with a known thickness of 0.3 (red vectors), which is distinguished from the dark green line compared to the absence of a porous layer (black vectors). As shown in Fig. 2, the vortex vortices formed upward, which causes more heat transfer in the presence of a porous layer than the absence of a porous layer.

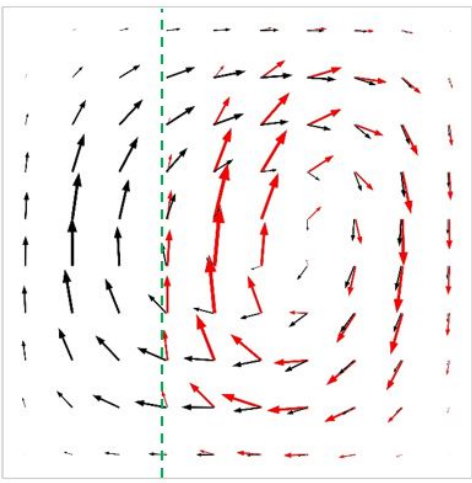

Fig. 2. The effect of the presence or absence of a porous layer on heat transfer

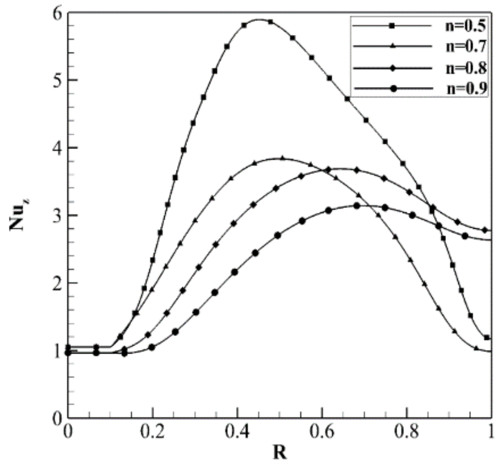

Fig. 3. Nusselt number for the hot wall when *Ra*=10^4, *Da*=10^{-4}, *Ste*=0.012, *1*=0.1 and ε=0.2

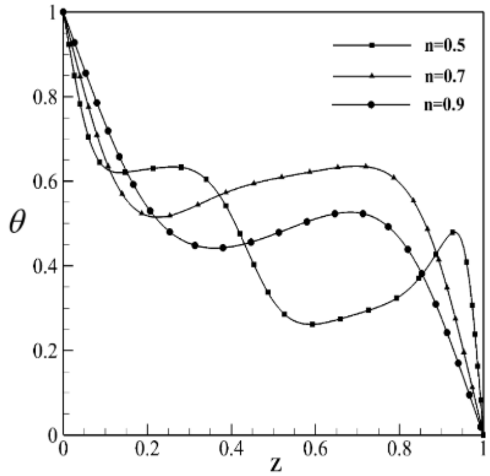

Fig. 4. Temperature variations for different n

The variation of the Nusselt number for the coefficients of the flow index for the hot wall is shown in Fig. 3 when Ra=10^4, Da=10^{-4}, Ste=0.012, 1=0.1 and ε=0.2. According to Fig. 3, at the beginning of the heat transfer process, due to the closeness of the flow to the hot wall, and also because the smaller the power parameter, the faster flow is generated, the Nusselt number increases and then decreases. This reduction in the Nusselt number is due to the fact that the increase of the current index decreases the growth of surface temperature and the temperature difference between the fluid and the surface so that the Nusselt number also decreases. The process of reducing the Nusselt number continues until the floating force overcomes the inertia and the establishment of natural displacement.

According to Fig. 4 By changing the power-law index in a constant $Ra=10^4$, temperature variations are different in relation to the R=0.5 line. In the n=0.5 index, the viscosity of the fluid is high and hence the directional displacement is important; therefore, by decreasing the Power-law index in a constant Rayleigh number, the velocity of the fluid along the cold and hot walls decreases and, as can be seen, the temperature gradient in these regions Decreases. In general, it can be said that by decreasing n, the temperature is reduced and the lowest temperature is obtained for the lowest n.

4. CONCLUSION

The most important results of this research can be presented as follows:

i. By adding a porous layer, due to the rapid growth of the rotary vectors, heat transfer occurs sooner.

ii. Increasing the flow index reduces the surface temperature and temperature difference between fluid and surface, so the Nusselt number also decreases.

iii. By reducing the n, the temperature is reduced and the lowest temperature is obtained for the lowest n.

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