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Numerical simulation of entropy generation due to unsteady natural convection in a semi-annular enclosure filled with nanofluid

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ABSTRACT

A numerical study has been carried out to investigate the natural convection and entropy generation for different nanofluids within an inclined half-annulus heated from above. The conservation equations in cylindrical coordinates are solved using an in-house FORTRAN code based on the finite volume method coupled with multigrid acceleration. Water-based nanofluid containing various types of nanoparticles (Au, Ag, Cu and CuO) are used to examine the fluid flow and potential heat transfer enhancement in the annulus. The effective thermal conductivity and viscosity of nanofluids are calculated using the Maxwell–Garnetts (MG) and Brinkman models, respectively. The results demonstrate clearly that the average entropy generation due to heat transfer (<STG>) is strengthened by increasing Φ and *Ra*. Furthermore, for small inclination angles $\gamma = 0^\circ$ and 45° (<SVG>) and (<STG>) values are reduced as RR is augmented, whereas, their values were observed to strengthen when RR increases for large tilt angles $\gamma = 90^\circ$, 135° and 180°. So, several important issues are highlighted that deserve greater attention.

1. Introduction

Heat transfer in the annulus between two horizontal concentric cylinders occurs in many engineering applications such as solar collector, cooling of electronic components, heat exchanger, nuclear reactors. It is for this reason that the heat transfer in horizontal semi-annular cavity presents the interest of many researchers aiming to deepen their knowledge of this area to enhance the heat transfer in the mentioned industrial applications. In this context, a comprehensive literature survey of on this subject was presented by a series of papers of the same authors Kuehn et al. [1–3], experimental and numerical studies of steady-state natural convection heat transfer in horizontal concentric annuli were presented, in which the effects of Rayleigh and Prandtl numbers and aspect ratio were parametrically explored and correlating equations were proposed as well. Thereafter, as the computing power was boosted significantly, a great number of numerical efforts were made on this subject. A brief review of selected recent papers was presented by Xu et al. [4]. However, although natural convection heat transfer in a horizontal concentric annulus has long been investigated for steady conditions, the knowledge regarding the transient features, which are of great practical interest, is rather limited [5–7].

The importance of the raised theme, namely, the heat exchange in many engineering applications such as those aforementioned, motivates researchers to find effective techniques for enhancing the heat transfer. Among the techniques are the control strategies i.e. using porous media, placement of obstacle and fins and using vortex generators (passive control); suction and/or blowing of the fluid and the application of local or external forcing (active control). In spite of their efficacy for many situations, these techniques have no effect on other applications. The best solution found is the nanofluids, colloidal solutions formed by metals, metal oxides, carbon nanotubes or silica carbides nanoparticles which have higher thermal conductivity suspended in a base fluid such as pure water, ethylene glycol, oils [8,9]. Lately, Bezi et al. [10,11] investigated the enhancement of heat transfer in natural convection flow and heat transfer in a horizontal and an inclined annulus partially heated from above and filled with nanofluids by using an in house FORTRAN code. It is observed that the type of nanoparticles is a key factor in the heat transfer invigoration. When different base fluids are scrutinized, the highest values of the average Nusselt number are obtained for the combinations $Au \setminus SEA50$ and $Al_2O_3 \setminus SEA50$. Studying the Two-phase mixture numerical simulation of natural convection of nanofluid flow in a cavity partially filled with porous media to enhance heat transfer is another topic in the recent

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research papers. Toosi et al. [12] has investigated the mixture density and viscosity which are defined by Corcione's model and Darcy-Brinkman-Forchheimer relation is employed for fluid flow simulation in porous media. Authors concluded that the single use of nanofluid in a clear cavity showed that for $Ra = 10^3$ increasing the nanofluid volume fraction will increase *Nu*. While for other *Ra* numbers an optimal concentration exists in order to maximize the average *Nu*.

The Lattice Boltzmann method which is a popular alternative to conventional Navier-Stokes (NS) methods to study incompressible fluid dynamics has a significant role to play in this field. Therefore, An in-house parallel LBM code was developed by Ghasemi et al. [13] to study natural convection of nanofluid flow in an enclosure filled by porous media, when different linear temperature distributions exposed on the boundaries. They concluded that increasing nanoparticle concentration had led to higher *Nu* values, while an optimum *Ra* exists to maximize heat transfer enhancement due to addition of nanoparticles. In other contribution, Ghasemi et al. [14] studied numerically the MHD natural convection of Cu-water nanofluid in a square porous enclosure using the same code, taking into account viscous dissipation effects, and the base fluid viscosity is defined as a function of temperature. It has been proved that the implementation of nanofluid with porous media could not be recommended generally. Depending on the *Ra*, *Ha* and K^* numbers, use of nanofluid might be beneficial or detrimental. Only for $Ra = 10^3$ it can be generally recommended to use nanofluid with porous foam.

As previously mentioned, adding nanoparticles enhances the heat transfer efficiency of fluids, but it also increases the viscosity and consequently the fluid flow pressure loss. Improvement of heat transfer properties decreases the entropy generation and irreversibility, but the increase in pressure drop causes irreversibility and energy loss in systems. Entropy generation rates considering particle migration are studied numerically by Bahiraei et al. [15] in order to produce a biological nanofluid flow in a mini double-pipe heat exchanger. It was noticed that by increasing Reynolds number and mean concentrations, the non-uniformity of particle distribution intensifies. Therefore, particle migration modifies the distribution of thermophysical properties and consequently, affects the entropy generation rates. In addition, as water inlet temperature increases, heat transfer contribution to entropy generation intensifies such that at low Reynolds numbers, the main factor of entropy generation which was friction, changes into the heat transfer. To summarize the important findings in Nanofluids and entropy generation area, Bahiraei [16] attempts in his review paper the studies conducted on nanofluids, considering particle migration, including those conducted via methods such as Eulerian Lagrangian, Buongiorno model. He concluded after referring to several research that entropy generation in nanofluids is affected by velocity and temperature fields. Therefore, as nanoparticle migration in nanofluids causes changes in velocity and temperature profiles, it can affect the entropy generation rate. Entropy generation rates are calculated for the water-CMC/TiO_2 non-Newtonian nanofluid flow in a minichannel having chaotic perturbations as well as a straight minichannel by Bahiraei et al. [17]. Authors pointed out that by increasing the Reynolds number, the total entropy generation decreases at low concentrations, however, an optimal point happens for the total entropy generation at a high concentration. In another contribution, Bahiraei et al. [18] studied Hydrothermal characteristics and entropy generation of a biological nanofluid containing silver nanoparticles in a liquid block heat sink for cooling of an electronic processor. Nanoparticles synthesized through plant extract technique from green tea leaves are employed. It was shown that entropy generation analysis reveals that irreversibility in the whole liquid block decreases with increasing either concentration or Reynolds number, which is a positive result based on second law of thermodynamics. Irreversibilities caused by heat transfer and friction for the water TiO_2 nanofluid flow in a circular microchannel are investigated by Heshmatian et al. [19] through entropy generation rates. It was demonstrated that nanoparticle migration alters concentration distribution and consequently, changes entropy generation rates. Furthermore, Nanoparticle migration increases concentration of the particles in central regions, and this migration is more noticeable for higher mean concentrations and larger particles.

In the same context, entropy generation analysis of nanofluid flow in turbulent and laminar regimes has been accomplished by Moghaddami et al. [20]. This research aims to analyze the effects of Al_2O_3 nanoparticle concentration on the entropy generation of water-Al_2O_3 nanofluid flow through a circular pipe under constant wall heat flux boundary condition in laminar and turbulent regimes. The nanofluid flow is simulated using a CFD (Computational Fluid Dynamics) finite volume code and the k-ε model is applied to simulate the turbulent flow. It was observed that increasing Reynolds number and nanoparticle concentration results in a decrease in heat transfer entropy generation while it increases the friction entropy generation. Steady double-diffusive natural convection of two-phase flow through a square enclosure filled with a fluid-saturated porous medium, in presence of the internal thermal and solutal source was carried out numerically by Siavashi et al. [21]. They investigated the effect of the enclosure inclination angle on heat and mass transfer rates and the flow strength. It can be pointed out that enclosures including two separate internal sources have relatively better heat and mass transfer rates in comparison with the single source enclosures. Moreover, when two vertical rectangular sources are placed inside the cavity, better Nusselt and Sherwood numbers are obtained and the total entropy generation is minimum. Heat transfer and entropy generation of developing laminar forced convection flow of water-Al_2O_3 nanofluid in a concentric annulus with constant heat flux on the walls was investigated numerically by Siavashi et al. [22]. Therefore, two approaches are employed and it is shown that only one of these methods can provide appropriate results for flow inside annuli. Siavashi et al. [22] showed that radius ratio is a very important decision parameter of an annular heat exchanger such that in each Re, there is an optimum radius ratio to maximize *Nu* and minimize entropy generation. Moreover, the effect of nanoparticles concentration on heat transfer enhancement and minimizing entropy generation is stronger at higher Reynolds. Siavashi et al. [23] carried out numerically in another work the effect of porous rib arrays on the heat transfer and entropy generation of laminar nanofluid flow inside annuli using a two-phase mixture model for nanofluid flow simulation. Altogether, it was proved that addition of nanoparticles in most of the cases increases heat transfer and decreases the thermal entropy generation, whereas some exceptions exist for special configurations. Further, the behavior of entropy generation, Nusselt, and performance numbers greatly depends on the Reynolds and Darcy number, and the rib array height and spacing.

From a numerical point of view, primarily owing to the richness of physical phenomena associated with the entropy generation of the non-Newtonian power-law nanofluid. Siavashi et al. [24] proposed convective heat transfer and entropy generation of power-law non-Newtonian nanofluids inside a cylindrical annular enclosure partially filled with porous media using two-phase mixture model for nanofluid. To do, different control parameters were used. Based on these parameters, it can be summarized that for $k_{eff} / k_f = 4$, and shear-thinning fluids with low Darcy ($Da = 10^{-3}$, 10^{-4}) and high Rayleigh ($Ra = 10^6$) numbers, convection is the main mechanism of heat transfer and use of low permeable porous foam weakens the convection field and subsequently reduces the heat transfer rate and the non-porous cavity is suggested. In these