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Investigating non-Newtonian nanofluid flow in a narrow annulus based on second law of thermodynamics

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A B S T R A C T

The present research attempts to study the convective heat transfer and analysis of the second law of thermodynamics for the non-Newtonian nanofluid flow containing TiO_2 nanoparticles within a narrow annulus. The base fluid is solution of 0.5 wt% Carboxymethyl Cellulose (CMC) in water. The employed nanofluid is of the pseudoplastic behavior, and power law model is utilized for apparent viscosity. The convective heat transfer coefficient increases by increasing Reynolds number and nanoparticle concentration. In higher concentrations, due to intensified shear-thinning behavior, and consequently, flatter velocity profile, convective heat transfer increases with a greater rate by an increase in concentration. Thermal, frictional and total entropy generation rates, both local and integrated, are assessed at different Reynolds numbers, concentrations and heat fluxes. The results show that increasing the concentration and Reynolds number leads to a decrease in thermal entropy generation rate and an increase in frictional entropy generation rate. The profile of thermal entropy generation rate at the annulus cross section is flatter at higher Reynolds numbers; while the same occurs for frictional entropy generation rate at lower Reynolds numbers. The lower the Reynolds number, the more evident the effect of heat flux change on total entropy generation rate. At low heat fluxes, the total entropy generation rate increases by increasing the concentration. However, at high heat fluxes, the total entropy generation rate decreases by concentration increment that can be beneficial from the second law viewpoint. Moreover, the effect of changing the value of heat flux on Bejan number is greater at higher concentrations.

1. Introduction

Nanofluids, i.e. suspensions containing ultrafine nanoparticles (1–100 nm), exhibit fascinating behaviors including improved thermal conductivity and increased heat transfer coefficient in comparison with pure fluids. Nanofluids have attracted great attention in recent years due to their applications ranging from thermal management in miniature electronic equipment such as nano-electromechanical systems (NEMS) and micro-electromechanical systems (MEMS) to more advanced energy conversion devices such as heat pipes and solar collectors.

Many studies, both numerical and experimental, have been conducted in the recent decade due to the great potential of nanofluids in various thermal systems. Most studies indicate significant improvements in thermal characteristics of base fluids through addition of nanoparticles. Some researchers have reviewed the studies conducted in this area [1–6]. Yu et al. [7] reviewed essential aspects of the turbulent convective heat transfer of nanofluids relevant to their applications, in detail based on both theoretical investigations and experimental studies. They concluded that with more than a decade of research and development of nanofluid technologies, the main focus of nanofluid studies has gradually shifted from experimental thermophysical property characterizations to practical heat transfer coefficient determinations. Kamyar et al. [8] and Bahiraei [9] reviewed and summarized the numerical investigations conducted in this area including conventional and novel numerical methods. It was concluded that from a numerical point of view, nanofluids lead to a significant improvement in the heat transfer performance, which is in a good agreement with experimental studies.

The majority of studies found in literature have been conducted on Newtonian nanofluids, and non-Newtonian nanofluids have almost been overlooked. The flows of non-Newtonian fluids have a key role in many industrial and engineering processes, for instance, paper production, petroleum drilling, pharmaceuticals, plastic sheet formation, glass blowing, extrusion of polymeric fluids and melts, biological solutions, paints, glues, and so forth. Moreover, they are employed in electronic modules or compact heat exchangers as cooling enhancing mediums. Therefore, an investigation of behavior of non-Newtonian nanofluids for the possibility of heat transfer enhancement in various processes of these industries is critical.

Hojjat et al. [10,11] experimentally evaluated the forced convective heat transfer of a non-Newtonian nanofluid flow through a tube under laminar and turbulent flow regimes. In their investigations, nanofluids were made by dispersion of Al_2O_3, CuO, and TiO_2 nanoparticles in an

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aqueous solution of 0.5 wt% of CMC. Their results revealed that heat transfer coefficients of nanofluids are greater than those of the base fluid.

Esmaeilnejad et al. [12] investigated the convection heat transfer and laminar flow of nanofluids with a non-Newtonian base fluid in a rectangular microchannel numerically using the two-phase mixture model. The power law model was used for non-Newtonian nanofluids. Their results showed significant improvement of heat transfer through applying nanoparticles particularly in the entrance region. In addition, higher heat transfer enhancement was observed by increasing the volume fraction.

Baheri Islami et al. [13] examined heat transfer and fluid flow of a non-Newtonian nanofluid in a two dimensional parallel plate microchannel without and with micromixers. The nanofluid was composed of CuO nanoparticles and the non-Newtonian base fluid of 0.5 wt% aqueous solution of CMC. Two baffles on the bottom and top walls worked as micromixer. It was concluded that the presence of baffles and also increasing the *Re* number and nanoparticle concentration increase the local and average heat transfer and friction coefficients.

The majority of studies conducted on nanofluids have focused on the investigation of the fundamental heat transfer phenomena or applications, and are based on the first law of thermodynamics, which is not sufficient to explain about the energy efficacy of these types of systems. Hence, it is necessary to develop examinations based on the second law of thermodynamics as well.

Due to the significance of the analysis of the second law of thermodynamics for the study of irreversibility of engineering systems, most of the recent investigations have focused on the issue of entropy minimization in different fields, particularly, in heat and mass transfer processes. Significance of entropy minimization from second law viewpoint is equivalent to the concept of availability, maximization and optimum states in energy production and utilization. The minimum entropy provides possibility of reaching the maximum available work or, in other words, it increases the exergy of system.

According to the relevant literature, it is found that several studies have been conducted in recent years about entropy generation in systems operated with nanofluids [14–16]. Mahian et al. [17] performed a complete review on the studies conducted in this field.

Sohel et al. [18] investigated different types of entropy generation in circular shaped microchannel and minichannel analytically using different types of nanoparticles and base fluids. The volume fraction was changed from 2 to 6%. The Cu–water nanofluid showed the highest decreasing entropy generation rate ratio. The higher thermal conductivity of water caused the generation of a much lower thermal entropy compared to Ethylene Glycol (EG). The friction entropy generation rate decreased significantly by increasing volume fraction. Cu–water and Cu–EG nanofluids gave the maximum decreasing rates of the fluid friction entropy generation at volume fraction of 6%.

Leong et al. [19] assessed the performance of Cu–water nanofluids in three types of shell-and-tube heat exchangers, including helical baffles of 25 and 50°, and segmental, with concentrations below 2%. It was shown that nanofluids at these low concentrations have no significant effect on the total entropy generation. It was concluded that entropy generation was the lowest for the helical heat exchanger of 50°.

Mahian et al. [20] carried out an analytical study of the second law of thermodynamics for the flow and heat transfer of TiO_2/water nanofluid in a vertical annulus with isoflux walls under the influence of magnetohydrodynamic field. The results were presented for different values of volume fraction, Hartmann number and the flow parameter *Gr*/*Re*. The results showed that the use of TiO_2/water nanofluid reduces entropy generation in annulus while an increase in Hartmann number intensifies entropy generation.

Mah et al. [21] investigated analytically the effects of viscous dissipation on entropy production due to Al_2O_3–water nanofluids in a circular microchannel. It was revealed that when the viscous effects are considered in the entropy generation assessment, the entropy generation intensifies with an increase in concentration.

The current paper examines the heat transfer and entropy generation characteristics of a non-Newtonian nanofluid containing TiO_2 nanoparticles in a narrow annulus. The effects of parameters such as particle concentration, Reynolds number, and wall heat flux are evaluated. To our knowledge, this work is the first study which considers the second law analysis for a non-Newtonian nanofluid.

2. Definition of geometry

The geometry under study is a narrow annulus with a length of 3 m, and a radius ratio of $r^* = 0.8$. Radius ratio means the radius of the inner cylinder divided by the radius of the outer cylinder. The diameter of the inner and outer cylinders were considered as 4 and 5 cm, respectively. The problem is two-dimensional, and is modelled as axisymmetric. Therefore, only half of the domain of the problem is investigated (see Fig. 1).

3. Governing equations

The current study evaluates the heat transfer and entropy generation characteristics of a non-Newtonian nanofluid containing TiO_2 nanoparticles. Aqueous solution of CMC with a concentration of 0.5 wt% is employed as the non-Newtonian base fluid. CMC is a derivative of cellulose, and its solution in water is a non-Newtonian pseudo-plastic fluid.

As nanofluids are composed of extremely small particles, it is assumed that nanoparticles and base fluid are in thermal equilibrium and they move with same velocity. In the present work, the non-Newtonian nanofluid is considered incompressible and under such assumptions, the governing equations are written as below:

Conservation of mass:

$$\nabla \cdot \left(\rho_{nf} \mathbf{v}\right) = 0. \tag{1}$$

Conservation of momentum:

$$\nabla \cdot \left(\rho_{nf} \mathbf{v}\mathbf{v}\right) = -\nabla P + \nabla \cdot (\eta \nabla \mathbf{v}). \tag{2}$$

Conservation of energy:

$$\nabla \cdot \left(\rho_{nf} \mathbf{v} c_{p,nf} T\right) = \nabla \cdot \left(k_{nf} \nabla T\right) \tag{3}$$

where ρ, k, c_p and η respectively denote density, thermal conductivity, specific heat and apparent viscosity. Moreover, $\mathbf{v}$, T and P represent velocity, temperature and pressure, respectively and subscript *nf* refers to nanofluid.

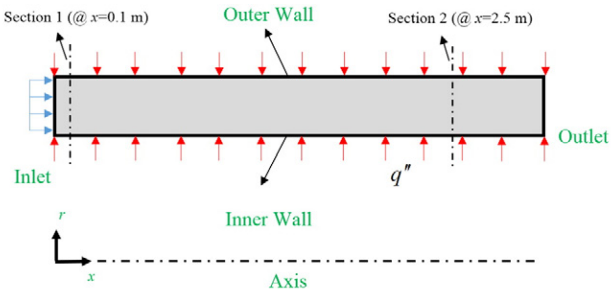

Fig. 1. Configuration under study.