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Entropy generation in a variable viscosity channel flow of nanofluids with convective cooling

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ABSTRACT

The present work investigates the combined effects of thermophoresis, Brownian motion and variable viscosity on entropy generation in an unsteady flow of water-based nanofluids confined between two parallel plates with convective heat exchange with the ambient surrounding at the walls. Both first and second laws of thermodynamics are applied to analyse the problem. The nonlinear governing equations of continuity, momentum, energy, and nanoparticles concentration are tackled numerically using a semi-discretisation finite-difference method together with a Runge–Kutta–Fehlberg integration scheme. Numerical results for velocity, temperature, and nanoparticles concentration profiles are obtained and utilised to compute the skin friction, the Nusselt number, the entropy generation rate, the irreversibility ratio, and the Bejan number. Pertinent results are displayed graphically and discussed quantitatively.

1. Introduction

Heat-transfer enhancement in engineering and industrial systems is one of the hottest topics in research today. With the growing demand for efficient cooling systems, more effective coolants are required to keep the temperature of heat-generating engines and engineering devices such as electronic components below safe limits. In recent time, the use of nanofluids has provided an innovative technique to enhance heat transfer. Nanotechnology has been widely used in engineering and industry, since nanometer-sized materials possess unique physical and chemical properties. The addition of nanoscale particles into the conventional fluids like water, engine oil, ethylene glycol, etc., is known as nanofluid and was firstly introduced by Choi [1]. Moreover, the effective thermal conductivity of conventional fluids increases remarkably with the addition of metallic nanoparticles with high thermal conductivity. Nanofluids may be considered as single phase flows in low solid concentration because of very small sized solid particles. There are many experimental and theoretical studies on the flow of nanofluids in different geometries [2–9]. A numerical study of buoyancy-driven flow and heat transfer of an alumina (Al_2O_3)–water-based nanofluid in a rectangular cavity was done by Hwang et al. [10]. The nanofluid in the enclosure was assumed to be in a single phase. It was found that for any given Grashof number, the average Nusselt number increased with the solid volume concentration parameter. Nield and Kuznetsov [11] investigated numerically the Cheng–Minkowycz problem for a natural convective boundary-layer flow in a porous medium saturated by a nanofluid. Oztop and Abu-Nada [12] considered natural convection in partially heated enclosures having different aspect ratios and filled with a nanofluid. They found that the heat transfer was more pronounced at low aspect ratios and high volume fractions of nanoparticles.

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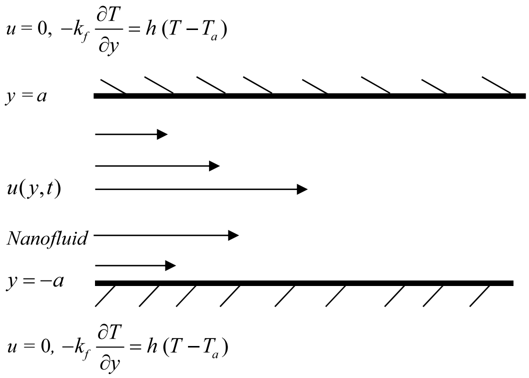

Fig. 1. (Colour online.) Schematic diagram of the problem under consideration.

Ibrahim and Makinde [13] studied the effect of double stratification on the boundary-layer flow and the heat transfer of nanofluid over a vertical plate. The buoyancy effects on the stagnation point flow and heat transfer of a nanofluid past a convectively heated stretching/shrinking sheet with or without magnetic field were considered by Makinde et al. [14] and Makinde [15]. Wang and Mujumdar [16] presented a comprehensive review of heat transfer characteristics of nanofluids. Detailed reports on convective transport in nanofluids can be found in Buongiorno [17], Mutuku-Njane and Makinde [18], Tiwari and Das [19], etc.

Meanwhile, in the nanofluids flows, the improvement of the heat transfer properties causes a reduction in entropy generation. The foundation of knowledge of entropy production goes back to Clausius and Kelvin's studies on the irreversible aspects of the second law of thermodynamics. Since then the theories based on these foundations have rapidly developed, see Bejan [20,21]. However, the entropy production resulting from heat and mass transfer coupled with viscous dissipation in nanofluids has remained untreated by classical thermodynamics, which motivates many researchers to conduct analyses of fundamental and applied engineering problems based on second law analysis with respect to nanofluid. Based on the concept of efficient energy use and the minimal entropy generation principle, optimal designs of thermodynamic systems have been widely proposed base on the second law of thermodynamics [22]. It is possible to improve the efficiency and overall performance of all kinds of flows and thermal systems through entropy minimisation techniques. The analysis of energy utilisation and entropy generation has become one of the primary objectives in designing a thermal system. This has become the main concern in many fields such as heat exchangers, turbo machinery, electronic cooling, porous media and combustion. Several studies have thoroughly dealt with conventional fluid flow irreversibility due to viscous effect and heat transfer by conduction [23–26]. Makinde et al. [27] performed numerous investigations to calculate entropy production and irreversibility due to flow and heat transfer of nanofluids over a moving flat surface. They found that the entropy generation in the flow system can be minimised by appropriate combination of parameter values together with nanoparticles volume fraction.

In the present study, we analyse the combined effects of thermophoresis, Brownian motion, and variable viscosity on the entropy generation rate in an unsteady channel flow of water-based nanofluid under the influence of convective heat exchange with the ambient surroundings. Such flows are very important in engine cooling, solar water heating, cooling of electronics, cooling of transformer oil, improving diesel generator efficiency, cooling of heat exchanging devices, improving heat-transfer efficiency of chillers, domestic refrigerator and freezers, cooling in machining and in nuclear reactor. In the following sections, the problem is formulated, numerically analysed, and solved. Pertinent results are displayed graphically and discussed.

2. Mathematical model

Consider the unsteady flow of an incompressible variable viscosity nanofluid in a channel between two parallel plates under the combined action of a constant pressure gradient and convective heat exchange with the ambient surrounding. It is assumed that the channel width is $2a$ and the flow is symmetrical with no slip at the walls as depicted in Fig. 1.

$$u = 0, \qquad -k_{\mathrm{f}}\frac{\partial T}{\partial y} = h(T - T_{\mathrm{a}})$$

Using the Buongiorno nanofluid model [17] with the Brownian motion, thermophoresis and nanoparticle volume fraction distributions, the governing equations for continuity, momentum, energy and nanoparticle concentration are:

$$\frac{\partial u}{\partial x} = 0 \tag{1}$$

$$\rho_{\mathrm{f}}\frac{\partial u}{\partial \bar{t}} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial y}\left(\mu_f(T)\frac{\partial u}{\partial y}\right) \tag{2}$$