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Numerical investigation of entropy generation to predict irreversibilities in nanofluid flow within a microchannel: Effects of Brownian diffusion, shear rate and viscosity gradient

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HIGHLIGHTS

- Irreversibilities in nanofluid flow are evaluated considering particle migration.
- Effects of viscosity gradient, shear rate, and Brownian diffusion are considered.
- Brownian impact reduces at higher concentrations compared with other factors.
- Total entropy generation in the microchannel decreases by particles enlargement.
- An ANN model for entropy generation rates is developed using the numerical data.

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ABSTRACT

In the present contribution, irreversibilities caused by heat transfer and friction for the water-TiO_2 nanofluid flow in a circular microchannel are investigated by evaluating entropy generation rates. The effects of viscosity gradient, non-uniform shear rate and Brownian diffusion on particle migration are taken into account in order to examine the effect of nanoparticle arrangement on entropy generation rates. The results show that nanoparticle migration alters concentration distribution and consequently, changes entropy generation rates. Nanoparticle migration increases concentration of the particles in central regions, and this migration is more noticeable for higher mean concentrations and larger particles. Thermal entropy generation rate intensifies with increasing wall heat flux and particle size while decreases with increasing concentration. Frictional entropy generation rate increases by concentration increment and decreases by particles enlargement, while it changes trivially by increasing wall heat flux. Frictional entropy generation rate is larger than thermal entropy generation rate in the microchannel under study and therefore, total entropy generation mostly stems from friction. Thus, total entropy generation rate decreases by particles enlargement, which is a positive result according to second law of thermodynamics. Eventually, a model for entropy generation rates is developed using the numerical data by means of Artificial Neural Network (ANN).

1. Introduction

With the advancement of fabrication technologies, microchannel structures have been developed in the last two decades. Microchannel structures enable liquid to flow through channels of a hydraulic diameter of 100–1000 μm and the heat transfer surface area can be dramatically increased. Heat sinks with microchannels are suitable for high flux heat dissipation in a broad range of high performance electronics (Klein et al., 2005; Ramos-Alvarado et al., 2011).

A modern method for heat transfer enhancement is suspending solid nanoparticles inside a base liquid, which resulting suspension is called nanofluid. Research on nanofluids shows that this new class of suspensions has excellent thermal characteristics, such that nanofluids can be used to increase heat transfer with high rates (Yang et al., 2015, 2016; Bahiraei, 2016; Mahian et al., 2013c; Sheikholeslami and Bhatti, 2017). Hence, some researchers have examined the effect of using nanofluids in miniaturized configurations such as micro-scale geometries.

Anbumeenakshi and Thansekhar (2017) investigated experimentally the combined effect of nanofluid and non-uniform heating on the cooling performance of a microchannel heat sink. The microchannel heat sink had 30 rectangular channels with a

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Nomenclature

A	area (m^2)
Be	Bejan number
c_p	specific heat (J/kg K)
D_b	Brownian diffusion coefficient (m^2/s)
d_p	diameter of nanoparticles (m)
g	gradient
h	convective heat transfer coefficient (W/m^2 K)
J	total particle flux (m/s)
J_μ	particle flux due to viscosity gradient (m/s)
J_c	particle flux due to non-uniform shear rate (m/s)
J_b	particle flux due to Brownian motion (m/s)
K_c	constant
K_μ	constant
k	thermal conductivity (W/mK)
k_B	Boltzmann's constant (J/K)
P	pressure (Pa)
q	wall heat flux (W/m^2)
R	radius of tube (m)
Re	Reynolds number
r	radial coordinate
$\dot{S}'''_f$	local frictional entropy generation rate (W/m^3 K)
$\dot{S}'''_h$	local thermal entropy generation rate (W/m^3 K)
$\dot{S}'''_t$	volumetric total entropy generation rate (W/m^3 K)
T	temperature (K)
$\mathbf{v}$	velocity (m/s)

Greek letters

α	learning rate
$\dot{\gamma}$	shear rate (1/s)
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)
φ	volume concentration
φ_m	mean volume concentration

Subscripts

f	base fluid
p	particles

hydraulic diameter of 0.727 mm. Three separate heaters of identical dimensions were used. The results showed that Al_2O_3/water nanofluid exhibits lower maximum surface temperature and average surface temperature than water. The values of thermal effectiveness obtained for nanofluids encouraged the use of nanofluids in microchannel heat sinks for thermal management of cooling applications. Malvandi and Ganji (2015) investigated convective heat transfer of a nanofluid in microchannels subjected to different heat fluxes. It was revealed that nanoparticles eject themselves from heated walls, construct a depleted region, and accumulate in the core region, but more likely to accumulate near the wall with lower heat flux. Moreover, the non-uniform nanoparticle distribution caused velocities to move toward the wall with a greater heat flux and increased heat transfer rate there. Hedayati and Domairry (2015) evaluated mixed convection of titania/water nanofluid inside a vertical microchannel via Runge–Kutta–Fehl berg method. It was found that the asymmetric boundary condition affects the direction of nanoparticles motion and distorts the symmetry of the velocity and temperature profiles. Nitiapiruk et al. (2013) investigated the performance of a microchannel heat sink using TiO_2/water nanofluids. The effects of uncertainties in thermophysical properties on the Nusselt number and friction factor were evaluated by using three different sets of thermophysical properties. It was concluded that the use of the model which was based on experimental data was very important to estimate the friction factor, while the use of different models to calculate of thermal conductivity had no considerable effect on the Nusselt number.

Most studies on nanofluids have focused on characteristics of the first law of thermodynamics, and few researchers have analyzed the second law of thermodynamics in nanofluids. However, in addition to the first law of thermodynamics, the second law of thermodynamics should be also considered in order to find an optimal system. Indeed, it will be possible to calculate irreversibility factors in a system using entropy generation rates through the second law of thermodynamics. Researchers have investigated irreversibilities of different systems and have proved that entropy generation can be used as an appropriate criterion to determine effectiveness of systems.

Several studies have been conducted on entropy generation in nanofluids. Mahian et al. (2013a) carried out a comprehensive review on this field. The entropy generation analysis of nanofluids has been performed in various systems such as rotating cylinders (Mahian et al., 2012a, 2012b), open cavities (Kolsi et al., 2016), solar collectors (Mahian et al., 2015, 2014a; Salavati Meibodi et al., 2016), magnetohydrodynamic flows (Mahian et al., 2013b), and minichannels (Mahian et al., 2014b, 2014c). Sohel et al. (2013) assessed entropy generation in a circular minichannel using different nanoparticles and base liquids. Particle concentration varied from 2% to 6%. The largest reduction in the rate of entropy generation was observed for the copper-water nanofluid. A very small entropy was generated for water due to higher thermal conductivity of water compared with ethylene glycol. Moreover, frictional entropy generation decreased with increasing concentration. Bahiraei and Mohammadi (2016) studied the second law of thermodynamics and heat transfer characteristics for the water-alumina nanofluid flow in a triangular channel. In their study, the effects of particle concentration, particle size, Reynolds number and wall heat flux were studied and discussed. In a numerical study, Karami et al. (2012) examined the effect of water-alumina nanofluid on entropy generation, pumping power and wall temperature in a circular tube under constant heat flux. They reported that entropy generation and wall temperature decrease while required pumping power increases with increasing concentration.

The results reported in the literature about the flow and heat transfer characteristics of nanofluids are full of contradictions. These contradicting results verify that the interactions between base liquid and nanoparticles can significantly affect the heat transfer rate which are currently less disclosed. Although many possible mechanisms such as ballistic conduction of phonon, Brownian motion, liquid layering, and so forth have been introduced, there is no overall approach to determine the thermal behavior of nanofluids. In the investigations reported thus far, a nanofluid was frequently assumed to be a homogeneous fluid, and its properties were considered to be constant in all points of the system. These assumptions are not realistic, and can lead to misunderstandings in the phenomena related to nanofluids. Taking into account the effects of particle migration is suggested as one efficient method which can be beneficial in better recognition of nanofluids behavior.

So far, few studies have examined particle migration and its effect on nanofluid characteristics. Hwang et al. (2009) considered the effect of thermophoresis on nanoparticle migration. They discussed on the effects of thermal conductivity under static and