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Entropy generation due to flow and heat transfer in nanofluids

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ABSTRACT

Present study provides a theoretical investigation of the entropy generation analysis due to flow and heat transfer in nanofluids. For this purpose, the most common alumina–water nanofluids are considered as the model fluid. Since entropy is sensitive to diameter, three different diameters of tube in their different regimes have been taken. Those are microchannel (0.1 mm), minichannel (1 mm) and conventional channel (10 mm). To consider the effect of conductivity and viscosity, two different models have been used to represent theoretical and experimental values. It has been found that the reduced equation with the help of order of magnitude analysis predicts microchannel and conventional channel entropy generation behaviour of nanofluids very well. The alumina–water with high viscosity nanofluids are better coolant for use in minichannels and conventional channels with laminar flow and microchannels and minichannel with turbulent flow. It is not advisable to use alumina–water nanofluids with high viscosity in microchannels with laminar flow or minichannels and conventional channels with turbulent flow. Also there is need to develop low viscosity alumina–water nanofluids for use in microchannel with laminar flow. It is observed that at lower tube diameter, flow friction irreversibility is more significant and at higher tube diameter thermal irreversibility is more. Finally, for both laminar and turbulent flow, there is an optimum diameter at which the entropy generation rate is the minimum for a given nanofluid.

1. Introduction

The continuous growth of electronic industry requires better cooling methods and asks for improved heat transfer characteristics. In recent times nanofluids (NFs) have emerged as a promising medium which can be used to enhance heat transfer due to unique characteristics of these fluids. NFs are engineered dilute colloidal dispersions of nano-sized (less than 100 nm) particles in a base-fluid [1]. Anomalous heat transfer and thermal conductivity enhancement of these fluids were observed by many researchers in the past and has been discussed by Das et al. in their review [2]. This increase in heat transfer characteristics was argued to be brought about by thermal conductivity enhancement associated with some particle migration. Using these fluids effectively as a coolant requires their viscosity increase to be nominal. Viscosity studies of NFs were reviewed by Murshed et al. [3]. They found that NFs across the board exhibit much higher viscosity values than that of the theoretical predictions for suspensions. This opposing behaviour of viscosity and conductivity of NFs indicates that the advantage of using NFs over base fluid for tube flow cannot be established merely on the basis of a single thermo-physical property namely thermal conductivity. This needs a proper experimental and theoretical investigation of NF in convective flow.

A number of studies have been carried out on convective heat transfer of NFs in tube flow and was reviewed by Wang and Mujumdar [4]. It was found that heat transfer characteristics of NFs are in general better than that of base fluids. For microchannel convective heat transfer studies, Lee and Mudawar [5] and Jung et al. [6] showed that the heat transfer coefficient and pressure drop both increase for NF flow. Even though all these experimental studies describe the higher heat transfer coefficients for NFs and claim the advantage of NFs over the base fluid, there are very few theoretical studies which discuss about the overall effectiveness of NFs over base fluids and confirm these claims. Prasher et al. [7] were the first to analyze the NF flow theoretically. They compared the pressure drop of NFs with base fluid by considering equal heat transfer coefficients for both fluids and finally showed that if the NFs have to be better than base fluid, its increase in viscosity should be less than four times the increase in conductivity. Or in other words, $C_\mu < 4C_k$, where, C_μ is the viscosity coefficient and C_k is the conductivity coefficient.

Similarly Garg et al. [8] presented the figure of merit to compare the performance of NFs with base fluids. They defined it as

$$\eta = \frac{(\text{heat removed})_{NF}/(\text{pumping power})_{NF}}{(\text{heat removed})_{BF}/(\text{pumping power})_{BF}}$$

where NF stands for nanofluids and BF for base fluids.

This is a better method for comparison of two fluids since it shows how much heat transfer is achieved at the expense of the

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Nomenclature

C_k	thermal conductivity coefficient
C_μ	viscosity coefficient
$\dot{S}'_{gen}$	entropy generation per unit length, W/m K
f	friction factor
q''	heat flux per unit length, W/m
$\dot{m}$	mass flow rate, kg/s
C_p	specific heat, J/kg K
D	diameter of tube, m
k	thermal conductivity, W/m K
n	shape constant
NF_s	nanofluids

Greek symbols

ρ	density
η	figure of merit
φ	volume fraction
μ	viscosity

Subscript

BF	base fluid
NF	nanofluids
p	nanoparticles

same pumping power. In their analysis they showed that if the pipe diameter is not changed, the use of NFs in not justifiable. But for the case where the pipe diameter is increased in proportion to the thermal conductivity of the NFs, the NFs are better coolant compared to the base fluid as long as viscosity coefficient is five times less than conductivity coefficient. Both the above analyses insist on achieving maximum heat transfer at a constant pumping power. Even though this is a popular evaluation method for heat exchanger design and can be applied here, increasing the figure of merit does not necessarily ensure decrease in irreversibility [9]. The performance of any thermodynamic system can be truly judged by thermodynamic performance only. It is shown for an internal convective flow that thermodynamic performance parameter is non-monotonic and maximizing the commonly used figure of merit does not ensure improved thermodynamic performance [10] due to irreversibilities involved. These irreversibilities can be measured by entropy generation rates. Researchers have carried out the irreversibility analysis of different systems and have showed that irreversibility or entropy generation analysis is a powerful tool to decide which installation or process is efficient [12]. Entropy generation in a system is the measure of entropy created by the irreversibilties such as friction, mixing, chemical reaction, heat transfer through a finite temperature difference, etc. [11]. In his studies on entropy generation of fundamental convective heat transfer, Bejan [13,14] derived the equations for entropy generation for forced convective heat transfer for various geometries like round tube, boundary layer over a flat plate and single cylinder in cross-flow. This thermodynamic effectiveness or entropy generation in a system is contributed by two parts, thermal irreversibilities and flow frictional losses. Thermal irreversibilities come through finite temperature difference between the fluid and wall. Flow frictional losses come through viscous or turbulent losses of the fluid. It is shown that for minimum entropy generation it is important to start with simplest features like internal and external surface design. Ratts and Raut [15] extended the entropy generation minimization work and showed an optimum Re for fixed heat transfer rate and mass flow rate. All this literature proves that the theory of entropy generation rate is well understood, and it can be applied to compare system performances.

Based on this overview of literature, the present study aims to provide an entropy generation analysis for convection in NFs and the advantage or disadvantage of NFs over base fluids. Although this analysis can be applied to any NF, for the simplicity and easily available property data only alumina–water NFs is considered. To predict the exergetic behaviour of NFs, the effects of tube diameter, fluid properties and particle concentration on entropy generation rate are studied, based on which recommendations related to usage of NFs in convective thermal transport are made. In best of author's knowledge, the second law analysis of NF flow has not been studied so far.

2. Entropy generation minimization analysis

This section provides the adoption of Bejan's equation and its reduction for different type of flow for NFs. For an internal flow with diameter D, heat flux q'', Bejan [13,14] gave the equation for the rate of entropy generation per unit length as

$$\dot{S}'_{gen} = \frac{q''^2 \pi D^2}{kT^2 \mathrm{Nu}((\mathrm{Re})_D, \mathrm{Pr})} + \frac{8\dot{m}^3}{\pi^2 \rho^2 T} \frac{f((\mathrm{Re})_D)}{D^5}$$
$$\dot{S}'_{gen} = (\dot{S}'_{gen})_{\text{heat transfer}} + (\dot{S}'_{gen})_{\text{fluid friction}} \tag{1}$$

As it can be seen from Eq. (1), the total entropy generation rate is contributed by two parts, thermal and fluid friction. Eq. (1) also shows the importance of Nusselt number Nu and friction factor f, which are different for different geometry and regime of flow, and so also the overall entropy generation rate. On the basis of flow regime, the entropy generation analysis can be broadly divided to laminar and turbulent flow.

2.1. Laminar flow in nanofluids

It is well known from the literature that for a laminar, fully developed condition, the Nu is constant and independent of Re, Pr and axial location. For a uniform surface heat flux, the values of Nu and f are

$$\mathrm{Nu} = \frac{48}{11} \quad \text{and} \quad f = \frac{64}{\mathrm{Re}} \quad \text{where } \mathrm{Re} = \frac{4\dot{m}}{\pi \mu D}$$

putting the above in Eq. (1) and rearranging,

$$\dot{S}'_{gen} = \frac{11}{48} \frac{q''^2 \pi D^2}{T^2} \frac{1}{k} + \frac{128\dot{m}^2}{\pi \rho^2 T D^4} \mu \tag{2}$$

For a fixed geometry, fixed Re, constant mass flow rate, and prescribed uniform heat flux, Eq. (2) can be written as

$$\dot{S}'_{gen} = \frac{C_{1l}}{kT^2} + \frac{C_{2l}\mu}{T\rho^2} \tag{3}$$

where C_{1l} *and* C_{2l} are constant and defined as

$$C_{1l} = \frac{11}{48} q''^2 \pi D^2$$
$$\text{and} \quad C_{2l} = \frac{128\dot{m}^2}{\pi D^4}$$

Defining Eq. (3) for NFs and base fluids and comparing the entropy generation rate of these fluids, the equation obtained is,

$$\frac{\dot{S}'_{genNF}}{\dot{S}'_{gen}} = \frac{k}{k_{NF}} \frac{\rho^2}{\rho_{NF}^2} \frac{T^2}{T_{NF}^2} \left(\frac{C_{1lNF}\rho_{NF}^2 + C_{2lNF}\mu_{NF}k_{NF}T_{NF}}{C_{1l}\rho^2 + C_{2l}\mu kT} \right) \tag{4}$$