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Entropy generation analysis of laminar flow of a nanofluid in a circular tube immersed in an isothermal external fluid

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ABSTRACT

This paper is an analytical study of entropy generation in the laminar flow of nanofluids in a circular tube. The tube is immersed in an isothermal external fluid – which is the most general thermal boundary condition but has not been studied in much detail in literature. Two nanofluids, namely – water–Al_2O_3 and ethylene glycol–Al_2O_3 have been chosen for this study. The effects of the external Biot number, non-dimensional temperature difference and volume fraction on the entropy generation characteristics of the flow have been shown through graphs and the physical reasoning behind the observed trends has been discussed threadbare. It is shown that the addition of nanoparticles is beneficial only at smaller Reynolds number and for less viscous base fluids. Most importantly, it is proved that the entropy generated in the case of a tube immersed in an isothermal external fluid is bounded by those for uniform heat flux and uniform wall temperature boundary conditions.

1. Introduction

Enhancement of heat transfer rate in a heat exchanger tube without changing its physical dimensions is an enduring challenge in thermal sciences and engineering. To meet this challenge, several methods are being researched in industry and in academia. These include and are not limited to- making fins on the internal surfaces of tubes, insertion of twisted tapes, introduction of nanoparticles and others.

The word "nanofluid" was coined by Choi [1]. Nanofluid is a suspension of nanoparticles in a base fluid. The principal way in which nanofluids increase the performance of a thermal system is by enhancing the thermal conductivity of the fluid. To that end, a body of work is devoted to investigation of the thermophysical properties of nanofluids as functions of their size and concentration [2–5]. A study by Xuan and Li [6] measured the thermal conductivity of copper based nanofluid. Lee et al. [7] measured the thermal conductivities of oxide nanofluids experimentally. Das et al. [8] included the effect of temperature on the thermal conductivity of water based nanofluids. There have been other models of thermophysical properties presented by researchers like Masoumi et al. [9], Corcione [10] and Khanafer and Vafai [11].

Apart from the modeling of thermophysical properties, there has been considerable research to understand the effect of nanofluids on the heat transfer rate itself. This research has been performed in both experimental and numerical domains. Pak and Cho [12] proposed a correlation for Nusselt number for turbulent convection of nanofluids. Similar correlation was proposed for copper based nanofluids by Xuan and Li [13]. As far as numerical investigation is considered, Maiga et al. [14] studied the laminar and turbulent heat transfer of nanofluids using the commercially available code FLUENT. Bahiraei and Hangi [15] numerically investigated the hydrothermal characteristics of nanofluid in a C shaped chaotic channel using both single-phase and two-phase methods. Bahiraei [16] used the two-phase Euler–Lagrange method to find the phenomenological constants needed to calculate the diffusion fluxes in nanofluid laminar flow in a circular pipe.

A very recent line of research in this domain pertains to magnetic nanofluids – which comprise of non-magnetic base fluid and magnetic nanoparticles. Here, mass transfer and heat transfer can be controlled by applying magnetic fields. Some of the relevant research work in this area can be accessed in Refs. [17,18].

A prominent disadvantage concerning the use of nanofluids is that due to the concomitant increase in viscosity, the pressure drop (and thereby, the pumping power required) is higher. This means that the heat transfer engineer/researcher should continuously evaluate the advantage of high heat transfer rate vis-à-vis the penalty of high pumping power requirement. An effective tool for this evaluation is the entropy generation analysis. Entropy generated due to heat transfer decreases while the entropy generated due to pressure difference increases with introduction of

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Nomenclature

A	cross-sectional area (m^2)
Be	Bejan number
Bi	Biot number $h_e r/k$
C_p	specific heat capacity (J/kg K)
D	cross sectional diameter (m)
Ec	Eckert number (defined in Eq. (30))
f	friction factor
FF	entropy generated due to fluid friction
h	internal heat transfer coefficient $\dot{q}''/(T_w - T)$ (W/m^2K)
$\hat{h}$	overall heat transfer coefficient $\dot{q}''/(T_e - T)$ (W/m^2K)
h_e	external heat transfer coefficient $\dot{q}''/(T_e - T_w)$ (W/m^2K)
k	thermal conductivity (W/m K)
L	duct length (m)
$\dot{m}$	mass flow rate (kg/s)
$N_{s,a}$	entropy generation augmentation number
Nu	internal Nusselt number hD/k
$\widehat{Nu}$	overall Nusselt number $\hat{h}D/k$
P	pressure (Pa)
Pr	Prandtl number
$\dot{q}''$	local heat flux (W/m^2)
$\dot{q}'$	heat rate per unit length (W/m)
$\dot{Q}$	heat rate (W)
r	radius of tube (m)
Re	Reynolds number
s	specific entropy (J/kg K)
$\dot{S}$	entropy rate (W/K)
St	Stanton number (defined in Eq. (13))
T	temperature (K)
U	average fluid velocity (m/s)

Greek letters

α	dimensionless parameter (defined in Eq. (28))
τ	dimensionless temperature difference (defined in Eq. (29))
λ	dimensionless length (defined in Eq. (15))
λ_L	dimensionless length (defined in Eq. (17))
ψ	dimensionless entropy generation rate (defined in Eq. (31))
φ	volume fraction of nanoparticles
ΔP	pressure drop (Pa)
ρ	fluid density (kg/m^3)
μ	fluid viscosity (Ns/m^2)
π_1	dimensionless parameter (defined in Eq. (33))
π_2	dimensionless parameter (defined in Eq. (34))

Subscripts

avg	average
bf	base fluid
e	external
i	internal
nf	nanofluid
np	nanoparticle
out	outlet
ref	reference
w	wall

nanoparticles in the fluid. Thus, it is possible – indeed desirable, to gauge the effectiveness of nanofluids by studying their total entropy generation rates. The entropy generation of nanofluids between two co-rotating cylinders was investigated by Mahian et al. [19]. They showed that it is possible to minimize the entropy generated in the nanofluid with respect to the volume fraction of the nanoparticles. Bianco et al. [20] studied the entropy generated in nanofluid under turbulent conditions in a circular tube subject to constant wall heat flux. They showed that the optimum nanoparticle concentration for minimum entropy generation is lower at higher Reynolds number. Leong et al. [21] studied the effect of cross-sectional shape on the entropy generation analyses of nanofluids. They found out that the circular tube generated the least amount of entropy compared to the tubes of other cross-sections. The same research group also studied the entropy generation in a tube with uniform wall temperature for nanofluids derived from alumina and titanium dioxide [22]. They concluded that titanium oxide nanofluids generate less entropy than that generated by alumina based nanofluids.

It is to be noted that all the cases of entropy generation analysis considered in extant literature have been based on one of the two common thermal boundary conditions: UWT (uniform wall temperature) and UHF (uniform heat flux). Sparrow and Patankar in a seminal study in 1977 [23] showed that these two boundary conditions are special cases of a more generic boundary condition, namely – immersion in an isothermal external fluid. When the thermal contact between the isothermal external fluid and the tube wall is superior, UWT boundary condition is obtained. On the other hand, if the external thermal contact is poor, the boundary condition reduces to UHF.

The entropy generation analysis for laminar flow in a circular tube immersed in an isothermal external fluid was performed by the author in an earlier publication [24], but that analysis was only for a single phase fluid. The concept of heat transfer enhancement by the introduction of nanoparticles was outside the scope of that paper – but is included in the current paper.

This paper deals with entropy generation analyses of nanofluid flow in a circular tube immersed in an isothermal external fluid. Two nanofluids: water–Al_2O_3 and ethylene glycol–Al_2O_3 have been chosen for the study. These two nanofluids have been chosen primarily because they are the most commonly used nanofluids in industry and in research. Moreover, the fact that the difference in these two nanofluids is only due to the difference in base fluid – the nanoparticles are the same – makes the assessment more systematic and organized. The novelty of this paper derives from the choice of the thermal boundary condition, namely – immersion in an isothermal external fluid. This is the most common thermal boundary condition seen in nature as well as in industry. For example, the thermal characteristics of a pipe carrying water in ambient surroundings, an oil pipeline in the ocean-bed, and heat exchanger tubes in shell-and-tube heat exchangers will be governed by this thermal boundary condition. It is shown in the results section that both UHF and UWT boundary conditions serve as lower and upper bounds respectively for the isothermal external fluid boundary condition and are thus only special cases of a more generic boundary condition.

2. Problem statement

The schematic of the physical system under consideration is shown in Fig. 1. It consists of a circular tube immersed in an isothermal external fluid, which is at uniform and constant temperature T_e. The diameter of the tube is D. The nanofluid (water–Al_2O_3 or ethylene glycol–Al_2O_3) enters the tube at temperature T_i.