International Communications in Heat and Mass Transfer 82 (2017) 29–39

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Heat transfer augmentation in concentric elliptic annular by ethylene glycol based nanofluids

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ARTICLE INFO

Available online 5 February 2017

Keywords:
Numerical investigations
Mixed convection
Heat transfer enhancement
Annulus
Nanofluids

ABSTRACT

In this article, laminar mixed convective heat transfer at different nanofluids flow in an elliptic annulus with constant heat flux boundary condition has been numerically investigated. The three dimensional governing equations (continuity, momentum and energy) are solved using the finite volume method (FVM). The investigation covers Reynolds number and nanoparticle volume fraction in the ranges of 200–1000 and 0–4% respectively. In the present work, four different types of nanofluids are examined in which Al_2O_3, CuO, SiO_2 and ZnO are suspended in the base fluid of ethylene glycol (EG) with different nanoparticle sizes 20, 40, 60 and 80 nm. The results show that SiO_2-EG nanofluid has the highest Nusselt number, followed by Al_2O_3-EG, ZnO-EG, CuO-EG, and lastly pure ethylene glycol. The Nusselt number increased as the nanoparticle volume fraction and Reynolds number increased; however, it decreased as the nanoparticle diameter increased. It is found that the glycerine-SiO_2 shows the best heat transfer enhancement compared with other tested base fluids. Comparisons of the present results with those available in the literature are presented and discussed.

1. Introduction

Nowadays after a century of struggling for enhancing industrial heat transfer by fluid mechanics, the low thermal conductivity of conventional fluids such as water, oil, and Ethylene-Glycol (EG) for transferring the heat has been one of the great challenges on the heat transfer science. One of the ways to overcome this problem is to replace conventional fluids with some advanced fluids with higher thermal conductivities [1–7].

Due to the importance of heat exchangers in many engineering applications, the subject of potential heat transfer enhancement in these devices has received substantial attention in research and practice. In the field of heat exchanger performance, it is known that utilization of the elliptic annulus can potentially lead to better heat transfer performance due to enhanced mixing of the fluid by the elliptic annulus. However, even more improvements in heat exchanger performance are sought after in order to meet the industry requirements and demands for higher heat transfer performance. Research on the methods for heat transfer enhancement in heat exchangers has received great attention in order to cater to the growing needs of higher efficiencies in these devices. For this purpose, in recent years, it has been shown that adding nanoparticles to the traditional heat transfer fluids (such as water, oil and ethylene glycol), can lead to improvement in their thermal conductivity. These so called 'nanofluids' can be applied in heat exchangers to enhance the heat transfer, leading to higher heat exchanger efficiency [8–24].

Heat transfer is categorized into numerous mechanisms, such as conduction, convection, and radiation. Convection is one of the chief methods of heat transfer that can be qualified in terms of being natural, forced, gravitational, granular, or thermomagnetic. Combined convection heat transfer exists when natural convection currents are the same order of magnitude as forced flow velocities [25]. The term 'mixed convection' means that the flow occurs when both natural (free) and forced convection mechanisms concurrently and significantly contribute to the heat transfer. The relative contribution of each mechanism depends on the flow regime (laminar or turbulent), magnitude of the temperature driving force for heat transfer, magnitude of Reynolds number, and orientation (vertical, horizontal, angled) [26].

Mixed convection heat transfer and fluid flow in an annulus is a significant phenomenon in engineering systems as it as, a common and essential geometry for fluid flow and heat transfer devices. It has a lot of engineering applications such as in double pipe heat exchanger, gas turbines, nuclear reactors, turbo machinery, thermal storage systems,

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.02.008
0735-1933/

Nomenclature

A	surface area,(m^2)
L	length of annulus, (m)
M	molecular weight, (mol)
Re	Reynolds number, ($Re = u_{av} D_h/\nu$)
g	acceleration due to gravity (m/s^2)
dp	diameter of nanofluid particles, (nm)
D_{in}	inner diameter, (m)
D_H	hydraulic diameter, (m) ; ($D_h = 4A/P$)
R_o	outer radius, (m)
Ra	Rayleigh number, ($Ra = Gr.Pr$)
T_{in}	inner cylinder temperature, (K)
K	thermal conductivity, (W/m. K)
N	Avogadro number
Al_2O_3	aluminum oxide
CuO	copper oxide
Gr	Grashoff number, ($Gr = \beta\ g\ L^3(T_i\text{-}T_o) / \nu^2$)
t	time, (*s*)
P	pressure, (Pa)
f	friction factor, ($f = (2\Delta PDh) /(L\rho u_{av}^2)$)
HRR	hydraulic radius ratio
Nu	Nusselt number, ($Nu = h\ D_h/k$)
H	heat transfer coefficient, (W/m^2 K)
D_o	outer diameter, (m)
R_{in}	inner radius, (m)
Pr	Prandtl number, ($Pr = C_p\ \mu/k$)
v	inlet velocity,(m/s)
C_p	specific heat, (KJ/kg.K)
q	cylinder heat flux, (W/m^2)
ΔP	dimensionless pressure drop
SiO_2	silicon oxide
ZnO	zinc oxide
EG	ethylene glycol

Greek symbols

ρ	Density of the fluid, (kg/m^3)
μ	dynamic viscosity, (N.m/s)
υ	kinematic viscosity, (m^2/s)
β	thermal expansion coefficient, (1/K)
κ	Boltzmann constant
Φ	nanoparticles volume fraction (%)

Subscripts

bf	base fluid
nf	nanofluid
np	nanoparticle
H	hydraulic
eff	effective
Av	average
S	solid
O	outlet

aircraft fuselage insulation to underground electrical transmission cables, solar energy systems, boilers, cooling of electronic devices, compact heat exchangers, cooling core of nuclear reactors, cooling systems, gas-cooled electrical cables, thermal insulation, electrical gas insulated transmission lines ventilation and air conditioning system [27].

The heat transfer enhancement technology has been improved and widely used in heat exchanger applications. One of the widely used heat transfer enhancement technique is inserting different shaped elements with different geometries in channel flow [28–30]. Akbarinia and Behzadmehr [31] numerically investigated the fully developed laminar mixed convection of Al_2O_3–water nanofluid flowing through a horizontal curved tube. In their studies, three-dimensional elliptic governing equations were used. The effects of the buoyancy force, centrifugal force and particle concentration on the heat transfer performance were presented. The results showed that the particle concentration has no direct effect on the secondary flow, axial velocity and skin friction coefficient. However, when the buoyancy force is more important than the centrifugal force, the effect of particle concentration on the entire fluid temperature can affect the hydrodynamic parameters. Moreover, the results also indicated that the buoyancy force decreases the Nusselt number whereas the particle concentration has a positive effect on the heat transfer enhancement and on the skin friction reduction. Ben Mansour et al. [32] experimentally investigated the thermally developing laminar mixed convection flow of water and Al_2O_3 mixture inside an inclined tube with a uniform wall heat flux. They observed that a higher particle volume concentration clearly induces a decrease of the Nusselt number for the horizontal inclination. On the other hand, for the vertical one, the Nusselt number remains nearly constant with an increase of particle volume concentration from 0 to 4%. The apparent contradictory behavior observed between experimental data and analytical/numerical results regarding the heat transfer enhancement of nanofluids prompted them to raise serious concerns regarding the applicability of using the single phase and homogeneous fluid model for nanofluids under natural convection effect.

Conceptually, investigation of the heat transfer enhancement in annuluses is essential. Some researchers have been considering application of the nanofluids in annulus [33–35]. Abu-Nada [33] has studied single phase Al_2O_3–water nanofluid flow in an annulus. Different viscosity and thermal conductivity models are used to evaluate heat transfer enhancement in the annulus by his work. Bianco et al. [34] investigated the heat transfer performance of an Al_2O_3–water nanofluid flowing through a circular tube under a laminar flow regime numerically. A single-phase model and two-phase model were used to determine the heat transfer coefficient of the nanofluid. The results demonstrated that the heat transfer performance increases with increasing Reynolds number as well as particle volume concentration. Moreover, differences in the average heat transfer coefficient between the single-phase and two-phase models were observed as approximately 11%. Abu-Nada et al. [35] have studied various nanofluids consisting base water and different nanoparticles such as Cu, Ag, Al_2O_3 and TiO_2 in horizontal annulus with single phase approaches.

Many attempts in this field have been completed to formulate appropriate effective thermal conductivity and dynamic viscosity of nanofluid [36–38]. Teng et al. [39] have measured the effects of

Table 1
The thermophysical properties of different nanoparticles and different base fluids at $T = 300$ K.

Thermophysical properties Ref.	Al_2O_3 [48]	CuO [48]	SiO_2 [49]	ZnO [49]	Glycerine [50]	Engine oil [50]	EG [50]
$\rho\ (kg/m^3)$	3970	6500	2200	5600	1259.9	884.1	1114.4
$Cp\ (J/kg\cdot K)$	765	535.6	703	495.2	2427	1909	2415
$k\ (W/m\cdot K)$	40	20	1.2	13	0.286	0.145	0.252
$\mu\ (Ns/m^2)$	–	–	–	–	0.799	0.486	0.0157
$\beta\ (1/K)$	5.8×10^{-6}	4.3×10^{-6}	5.5×10^{-6}	4.31×10^{-6}	4.8×10^{-4}	7×10^{-4}	6.5×10^{-6}