International Communications in Heat and Mass Transfer 85 (2017) 81–91

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Numerical study of assisting and opposing mixed convective nanofluid flows in an inclined circular pipe

M.T. Al-asadi[a,b,*], H.A. Mohammed[c,**], A.Sh. Kherbeet[d], A.A. Al-aswadi[e]

[a] *Institute of Thermofluids, School of Mechanical Engineering, University of Leeds, UK*
[b] *Refrigeration Department, Eng. Division, South Oil Company, Ministry of Oil, Basra, Iraq*
[c] *Department of Energy Engineering, Technical College of Engineering, Duhok Polytechnic University (DPU), 61 Zakho Road, 1006 Mazi Qr, Duhok-Kurdistan Region, Iraq*
[d] *Department of Mechanical Engineering, KBU International College, 47800 Petaling Jaya, Selangor, Malaysia*
[e] *Department of oil and gas Engineering, International university of technology twintech, Haddeh street, Sana'a, Yemen*

ARTICLE INFO

Keywords:
Assisting flow
Opposing flow
Inclined circular pipe
Nanofluids
Heat transfer enhancement

ABSTRACT

A numerical investigation of mixed convection is carried out to study the heat transfer and fluid flow characteristics in an inclined circular pipe using the finite volume method. The pipe has L/D of 500 and it was subjected to a uniform heat flux boundary condition. Four types of nanofluids (Al_2O_3, CuO, SiO_2, and TiO_2 with H_2O) with nanoparticles concentration in the range of $0 \le \varphi \le 5\%$ and nanoparticles diameter in the range of $20 \le dp \le 60\,nm$ were used. The pipe inclination angle was in the range of $30^\circ \le \theta \le 75^\circ$ using assisting and opposing flow. The influences of Reynolds number in the range of $100 \le \text{Re} \le 2000$, and Grashof numbers in the range of $6.3 \times 10^2 \le Gr \le 8.37 \times 10^3$ were examined. It is found that the velocity and wall shear stress are increased as Re number increases, while the surface temperature decreases. There is no significant effect of increasing *Gr* number on thermal and flow fields. The velocity and wall shear stress are increased and the surface temperature is decreased as φ and *dp* are decreased. It is concluded that the surface temperature is increased as the pipe inclination angle increases from the horizontal position ($\theta = 0^\circ$) to the inclined position ($\theta = 75^\circ$). In addition, it is inferred that the heat transfer is enhanced using SiO_2 nanofluid compared with other nanofluids types. Furtheremore, it is enhanced using assisting flow compared to opposing flow.

(See Table 1.)

1. Introduction

Combined convection heat transfer in pipes is widely encountered because of its practical importance in engineering applications. These include heating or cooling of heat exchangers for viscous liquids, heat exchangers for gas flows, cooling of electronic equipment, cooling the core of nuclear reactor and transmissions using pipelines for industrial applications [1–4]. The most important challenge facing various industries, including manufacturing, solid-state transportation, and microelectronics is to improve the heat transfer. Thus, there is an urgent need for new, improved performance [1].

An experimental investigation was performed by Ghajar [5] to study the flow regime map boundary between mixed convection and forced in a horizontal circular straight tube, It was found that the regime map is applicable to various types of flow. Additionally there is the necessity of utilizing the buoyancy effect by using Reynolds number and GrPr at X/

Table 1
Thermophysical properties of different nanofluids $dp = 20$ nm $\varphi = 2\%$ [23].

Thermophysical properties	CuO	Al_2O_3	SiO_2	TiO_2
Density (kg/m^3)	1107.158	1056.558	1021.158	1062.158
Heat capacity (J/kg.K)	3751.2	3922.4339	4029.225	3899.486
Dynamic viscosity (Ns/m^2)	0.0001608	0.000508	0.0008255	0.0004650
Thermal conductivity (W/m.K)	0.6388	0.6563	0.6162	0.6272
Prandtl number	0.9442	3.0361	5.3978	2.8910
Thermal expansion coefficient (1/K)	0.00018338	0.00019188	0.000198331	0.000190899

---

[*] Correspondence to: M.T. Al-asadi, Institute of Thermofluids, School of Mechanical Engineering, University of Leeds, UK.
[**] Corresponding author.
E-mail addresses: mushtq55@yahoo.com (M.T. Al-asadi), hussein.dash@yahoo.com (H.A. Mohammed).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.04.015

Nomenclature

Al_2O_3	Alumina
B_c	Boltzman constant
CFD	Computational Fluid Dynamic
C_p	Specific heat, J/kg K
CuO	Copper oxide
D	Diameter, m
f	Friction factor
FVM	Finite Volume Method
g	Gravitational the acceleration, m/s^2
h	Heat transfer coefficient, W/m^2 K
H_2O	Water
HMT	Heat and Mass Transfer
k	Thermal conductivity, W/m K
L	Length, m
P	Pressure, N/m^2
$P*$	Pressure field, N/m^2
P_r	Prandtl number
q_w	Uniform heat flux, W/m^2
r	Radial direction
R_a	Rayleigh number
SiO_2	Silicon dioxide
T	Temperature, K
TiO_2	Titanium dioxide
v	Radial velocity component
v_b	Brownian velocity of nanoparticles that temperature
w	Axial velocity component, m/s
x^*	Reduced length

Greek symbols

μ	Viscosity, kg/ms
α	Angular coordinate
Θ	Inclination angle over the horizontal
φ	Volume fraction, %
ρ	Density, kg/m^3
β	Volumetric expansion coefficient

D location.

Heat transfer in a horizontal pipe with a 25 mm diameter and two-phase air-water flow was investigated by Zimmerman et al. [6]. It was calculated that the heat transfer coefficient became more uniform around the pipe for higher air flow-rates, and at the bottom of the pipe it was up to three times higher than that at the top. The liquid superficial velocity was a major factor affecting the local heat transfer coefficient around the tube. The results show a clear enhancement of the heat transfer coefficient with the pipe inclination, local and average Nusselt number correlations were developed. Coutier and Grief [7] studied both experimentally and numerically laminar flow heat transfer within a horizontal tube surrounded by a liquid medium. It was found that the wall temperature has a marked effect on the secondary flow patterns within the tube as well as on the heat transfer.

Laminar air flow mixed convection in a horizontal circular cylinder was studied by Mohammed and Salman [8] to investigate the average and local heat transfer for hydro-dynamically fully developed, thermally fully developed, and thermally developing air flow. An increase was found in the Nusselt number values as the heat flux increased for all entrance sections. It was concluded that the free convection effects tended to decrease the heat transfer results at low Re numbers while increasing the heat transfer results for high Re numbers. The average Nusselt numbers were correlated with the (Rayleigh numbers/Reynolds numbers).

Water, oils, glycols and fluorocarbons are considered as traditional heat transfer fluids although, the heat transfer performance is inherently poor due to their low thermal conductivities. Development and research activities have been undertaken to enhance the heat transport properties of fluids. Thermal conductivity of non-metallic materials, such as CuO, Al_2O_3, Sic, and metallic materials is much higher than the thermal conductivity of the traditional heat transfer fluid [2].

One of the techniques used to enhance the heat transfer is by utilizing nanofluids. Nanofluids are a popular word in the heat transfer community nowadays. They have significant ability to enhance the thermal properties, including viscosity, specific heat, convective heat transfer coefficient, thermal conductivity, and heat flux. Several comprehensive review articles and books have addressed the thermal transport properties of nanofluids [3,4].

A numerical investigation of a fully developed laminar mixed convection, using a nanofluid consisting of Al_2O_3/water through a horizontal tube and an inclined tube was presented by Akbari et al. [9]. It was demonstrated that the heat transfer coefficient increased by 15 at 4% vol nanoparticles of Al_2O_3. The skin friction coefficient increased with the tube inclination, but the heat transfer coefficient showed the maximum value when the angle of the tube was 45°.

As a consequence, the idea of suspending these nanoparticles in a base liquid to enhance the thermal conductivity has been suggested by Masuda et al. [10], Choi [11]. Such suspension of nanoparticles in a base fluid is known as a nanofluid. Due to their small size, nanoparticles are liquefied easily inside the base fluid, and as a consequence, clogging of channels and erosion in channel walls are no longer a problem, as found by Chein and Chuang, Lee and Mudawar [12,13]. When presenting the stability of the suspension, it was shown that particles' sedimentation can be prevented by using proper dispersants.

Studies of nanofluids' thermal conductivity show that high enhancement of thermal conductivity can be achieved by using nanofluids. It is possible to obtain thermal conductivity enhancement, larger than 20%, at a particle volume fraction smaller than 5%, [14–16], and Xuan and Roetzel [17]. They [14–17] suspended ultrafine particles to change transport properties and heat transfer performance of the nanofluid, which exhibited substantial potential in enhancing heat transfer.

From the literature, it has been found that many investigations have been done on the horizontal and vertical using both conventional and nanofluids flows. While some were done to investigate the inclination angle on the heat and the flow characteristics, very few studies utilized nanofluids in assisting flow to investigate the effect of different orientations on the heat transfer and fluid flow characteristics, but there is no study done with the opposing flow, thus providing the motivation for this study.

2. Problem description and governing equations

The geometry of the present study has the length and the diameter of 2000 mm and 4 mm respectively. Boundary conditions for all boundaries are specified for the computational domain. The general pipe computational model has been selected for this study. Heat flux was supplied at the top and bottom surfaces of the pipe in the range of 1000–10,000 W/m^2. The inlet velocity of working fluid had a temperature of 295 K the boundary of the outlet is the pressure and the inlet velocity has been calculated based on the required Reynolds number as shown in Fig. 1a. Also.

Thermophysical properties equations of nanofluids are affected by the buoyancy force and the nanofluid is considered to be Newtonian and compressible.

2.1. Goeverning equations

In completing a CFD analysis of the pipe's entire domain, it was