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Pressure drop and thermal characteristics of CuO–base oil nanofluid laminar flow in flattened tubes under constant heat flux☆

Pooyan Razi, M.A. Akhavan-Behabadi *, M. Saeedinia

School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

An experimental investigation has been carried out to study the heat transfer and pressure drop characteristics of nanofluid flow inside horizontal flattened tubes under constant heat flux. The nanofluid is prepared by dispersion of CuO nanoparticle in base oil and stabilized by means of an ultrasonic device. Nanofluids with different particle weight concentrations of 0.2%, 0.5%, 1% and 2% are used. Copper tubes of 11.5 mm I.D. are flattened into oblong shapes and used as test sections. The nanofluid flowing inside the tube is heated by an electrical heating coil wrapped around it. Required data are acquired for laminar and hydrodynamically fully developed flow inside round and flattened tubes.

The effect of different parameters such as flow Reynolds number, flattened tube internal height and nanofluid particle concentration on heat transfer coefficient and pressure drop of the flow is studied. Observations show that the heat transfer performance is improved as the tube profile is flattened. Flattening the tube profile resulted in pressure drop increasing. In addition, the heat transfer coefficient as well as pressure drop is increased by using nanofluid instead of base fluid. Furthermore, the performance evaluation of the two enhanced heat transfer techniques studied in this investigation shows that applying flattened tubes instead of the round tube is a more effective way to enhance the convective heat transfer coefficient compared to the second method which is using nanofluids instead of the base liquid.

1. Introduction

Thermal load removal is a great concern in many industries including power plants, production and chemical processes, transportation and electronics. In order to meet the ever increasing need for cooling the high heat flux surfaces, different enhanced heat transfer techniques have been suggested. Most of these methods are based on structure variation, vibration of heated surface, injection or suction of fluid and applying electrical or magnetic fields which are well documented in literature [1,2]. However, applying these enhanced heat transfer techniques are no longer feasible for cooling requirement of future generation of microelectronic systems, since they would result in undesirable cooling system size and low efficiency of heat exchangers. To obviate this problem, nanofluids with enhanced thermo-fluidic properties have been proposed since the past decade. Nanofluid is a uniform dispersion of nanometer-sized particles inside a liquid which was first pioneered by Choi [3].

Excellent characteristics of nanofluids such as enhanced thermal conductivity, long time stability and little penalty in pressure drop increasing and tube wall abrasion have motivated many researchers to study on thermal and flow behavior of nanofluids. These studies are mainly focused on effective thermal conductivity, phase change behavior, tribological properties, flow and convective heat transfer of nanofluids.

A wide range of experimental and theoretical studies has been performed on effective thermal conductivity of nanofluids within past decade. In these studies, the effect of different parameters such as particle concentration, particle size, mixture temperature and Brownian motion on thermal conductivity of nanofluids was investigated. The results showed an increase in thermal conductivity of nanofluid with the increase of nanoparticles concentration and mixture temperature [4–7]. Also it was shown that larger enhancement in thermal conductivity is attributed to the finer particle size [6–8].

Due to the enhanced thermal properties of nanofluids, majority of recent studies are focused on convective heat transfer behavior of nanofluids in laminar and turbulent flows. Almost all of these works report the enhancement of nanofluid convective heat transfer. Several numerical and experimental studies have considered nanofluid convective heat transfer in turbulent flow [9–12]. Some other studies have investigated the convective heat transfer of nanofluids in laminar flow. Wen and Ding [13] have studied Al_2O_3/water nanofluid heat transfer in laminar flow under constant wall heat flux and reported an increase in nanofluid heat transfer coefficient with the increase in Reynolds number and nanoparticles concentration particularly at the entrance region. Convective heat transfer of CNT nanofluids in laminar regime with a constant heat flux wall boundary

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* Corresponding author.
E-mail address: akhavan@ut.ac.ir (M.A. Akhavan-Behabadi).

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Nomenclature

Cp	[J/kg K]	Specific heat
D	[m]	Round tube diameter
Dh	[m]	Flattened tube hydraulic diameter
H	[mm]	Flattened tube internal height
h	[W/m^2 K]	Convective heat transfer coefficient
$\bar{h}$	[W/m^2 K]	Mean heat transfer coefficient
L	[m]	Length of the tube
$\dot{m}$	[kg/s]	Mass flow rate
Nu	[–]	Nusselt number
P	[m]	Tube cross section perimeter
Δ*P*	[Pa]	Pressure drop along the test section
Pr	[–]	Prandtl number
q″	[W/m^2]	Heat flux
Re	[–]	Reynolds number
T	[°C]	Temperature
V	[m/s]	Fluid velocity
W	[mm]	Width of flat area
x	[m]	Distance from entrance of tube

Greek symbol

η	[–]	Performance index
μ	[Pa.s]	Dynamic viscosity
φ	[–]	Weight concentration
ϕ	[–]	Volume concentration

Subscripts

BF	Base fluid (base oil)
i	Inlet
m	Mean fluid bulk temperature
nf	Nanofluid
s	Surface
RT	Round tube

condition was investigated by Ding et al. [14]. They observed a maximum enhancement of 350% in convective heat transfer coefficient of 0.5 wt.% CNT/water nanofluid at $Re = 800$.

In addition, a few works have studied friction factor characteristics of nanofluids flow besides the convective heat transfer. Xuan and Li [15] investigated the flow and convective heat transfer characteristics for Cu/water nanofluids inside a straight tube with a constant heat flux at the wall, experimentally. Results showed that nanofluids give substantial enhancement of heat transfer rate compared to pure water. They also claimed that the friction factor for the nanofluids at low volume fraction did not produce extra penalty in pumping power. In laminar flow, Chandrasekar et al. [16] investigated the fully developed flow convective heat transfer and friction factor characteristics of Al_2O_3/water nanofluid flowing through a uniformly heated horizontal tube with and without wire coil inserts. They concluded that for the nanofluid with a volume concentration of 0.1%, the Nusselt number increased up to 12.24% compared to that of distilled water. However, the friction factors of the same nanofluid were almost equal to those of water under the same Reynolds numbers.

Another technique which is employed for heat transfer augmentation is using flattened tubes instead of round tubes. Flattened tubes are geometrical modification of round tubes which can be manufactured by flattening the round tubes into an oblong shape. There are only a few articles which have reported the privileges of these kinds of tubes in the favor of heat transfer augmentation which are focused mainly on the two phase flow regimes [17,18].

Review of literature shows that only a few articles have considered nanofluid flow inside a tube other than straight round tube. In the present work, the simultaneous effects of adding nanoparticles to the base fluid and flattening the round tube on flow heat transfer and pressure drop is studied. A new suspension of nanofluid namely CuO/Base oil is selected for this investigation. The main reason for choosing CuO/base oil nanofluid is that copper oxide nanoparticles are used as additives for industrial oils such as engine oil, heat transfer oil and lubricating oil in order to remove heat from high heat flux surfaces. These additives also have shown anti wear and anti friction characteristics due to their spherical shapes [19,20]. Also, to study on the behavior of CuO nanoparticles more effectively, a type of oil with no additives (SN-500) is used. This type of oil is the basic component of the industrial oils. It is apparent that the effect of nanoparticles on heat transfer performance of the specified oil can be generalized to the mentioned industrial oils for the sake of heat transfer enhancement.

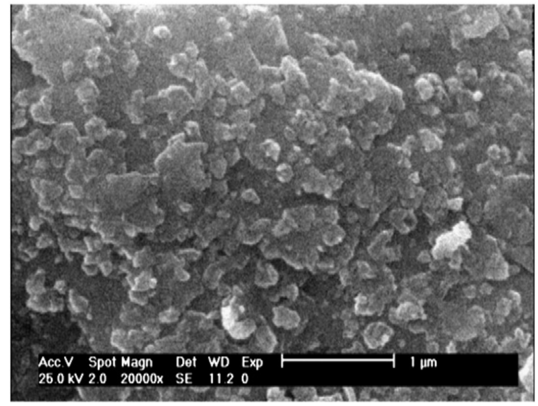

Fig. 1. SEM image of CuO nanoparticles.

2. Nanofluid preparation

The solid particles used in this study were CuO. They were produced with an average particle size of 50 nm and purity of 99% by means of chemical analysis method. The SEM (scanning electron microscope) micrograph of the CuO nanoparticles and the XRD (X-ray diffractions) Pattern are shown in Figs. 1 and 2, respectively. Reflections in the XRD pattern can be attributed to the CuO using JCPDS (Joint Committee on Powder Diffraction Standards). Also it can be seen from the SEM image of the sample that the majority of nanoparticles are in the form of large agglomerates before dispersion.

Nanofluids with particle weight concentrations of 0.2%, 0.5%, 1% and 2% were prepared by dispersing specified amount of CuO nanoparticles in oil using an ultrasonic processor (Hielscher Company, Germany) generating ultrasonic pulses of 400 W at 24 kHz frequency. This device is used to break large agglomerates of nanoparticles in the fluid and make stable suspension. No surfactant

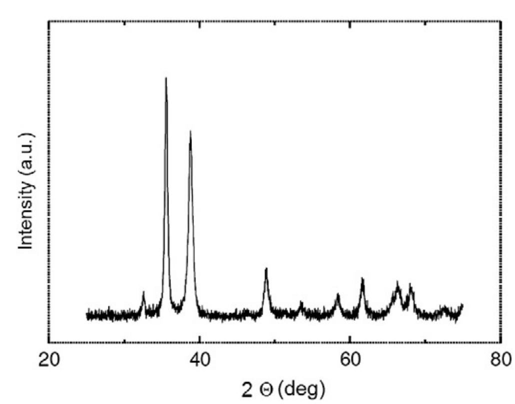

Fig. 2. XRD analysis of CuO nanoparticles.