Forced convection heat transfer characteristics of Al$_2$O$_3$ nanofluids in a minichannel - an experimental study

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Abstract. In this study, an experimental investigation on the convective heat transfer characteristics of Al$_2$O$_3$ nanofluids flowing through an horizontal minichannel under the laminar and turbulent flow and constant heat flux conditions is performed. Several sample nanofluids were prepared using two base fluids (water and the mixture 80/20 DW/EG vol.%.) and several low concentrations of Al$_2$O$_3$ nanoparticles ranging from 0.01 to 0.1 vol%. An existing experimental setup was modified for this study. The measurements were taken for the base fluid and nanofluids at each flow and heating conditions. The results are analyzed in terms of Nu and friction factor ($f$) in comparison with those of the base fluid. The results demonstrate that the used low concentrations of Al$_2$O$_3$ nanoparticles are not enough to yield any noticeable enhancement in heat transfer of the nanofluid samples. The deviations between the results of the nanofluids and the base fluid are small and within the uncertainty range of the experimental setup.

1. Introduction

New thermal fluids called nanofluids are considered as a promising media for the development heat exchange systems with high performance. Nanofluids which are defined as the suspensions of nanosized particles in a base fluid such as water and ethylene glycol exhibit enhanced thermal properties[1]. There are a lot of applications which contain heat transfer process of some sort and in an urgent need of thermal fluids to increase their performances, energy efficiency, reduce the size of the device, such as energy systems, chemical materials production, electronics and solar energy. So far, metallic and non-metallic nanoparticle were dispersed into conventional fluids to produce several types of nanofluids [2], [3]. However, nanofluids with Al$_2$O$_3$ nanoparticles showed a considerable improved thermal behavior in heat transfer applications [4]–[6]. Though, there is a lack of experimental studies on nanofluids flowing in minichannels. Among those handfuls of studies, an experimental study by Murshed et al. [7] investigated the fluid flow of TiO$_2$/water nanofluids in a minitube and found a considerable enhancement in convective heat transfer with increasing the nanoparticles concentration. Also, Briclot et al. [8] reported that heat transfer coefficient (HTC) achieved a slight enhancement in laminar flow with the increase of the concentration of the Al$_2$O$_3$ particles in the base fluid of water. However, no considerable enhancement in HTC was reported for turbulent flow. On the other hand, a significant increase in pressure drop is caused by adding nanoparticles to the base fluid for both laminar and turbulent flows.
Generally, most of the investigations both experimental and numerical presented an enhancement in convective heat transfer performance using nanofluids in comparison with the correlated base fluids [9]. In this study, an experimental investigation is carried out on the heat transfer of well-prepared Al$_2$O$_3$ nanofluid samples flowing through minichannel under constant heat flux conditions. The change of heat transfer performance of these nanofluids is investigated under different conditions such as particles concentrations and flow rate and regime. This study provides an important step for future investigations on different types of nanofluids for other conditions in heat transfer applications.

2. Nanofluids Preparation
In order to prepare nanofluids, Al$_2$O$_3$ dry nanoparticles of <50 nm (99.9% purity) was purchased from IoLiTec, Germany. Distilled water (DW) and EG/DW mixture are used as base fluids. Then sample nanofluids were prepared by dispersing four different concentrations (0.01, 0.02, 0.05, 0.1 vol.%) of this nanoparticle into these base fluids. The selected base fluids 20%EG+80%DW and DW are widely used for cooling applications [10], [11]. As required by the experimental setup 1.5L of the sample nanofluids were prepared and sonicated to improve their stability.

3. The Experimental Setup
A photograph and a schematic for the experimental set-up used are presented in Figure 1. The experimental setup is composed of a reservoir (4). The fluid is supplied to the reservoir through valve (2). To achieve the fluid flow, a vane pump coupled to an electric motor (5) was used which can reach a maximum flow rate of 100kg/h. To measure flow rate a Coriolis based technology mass flow meter (Mini CORI-FLOW M15) is utilized. A bypass valve (3) is used to control the fluid flow. The test section comprises a stainless steel (AISI 304) tube, having 3.5 mm inner diameter and a total of 2.4m in length. An initial length of 0.4m is reserved to guarantee hydrodynamically fully developed flow at the inlet of the heating section, remaining 2 m for the heat supply. Inlet and outlet fluid temperatures and pressure drop are measured in the heated section. This section has 4 equally spaced thermocouples fixed on the tube surface. Also, the setup contains a cooling system, which maintains the inlet temperature constant, having a deviation of less than 1K per-flow rate. Finally, the sensors signals were collected using a data acquisition system.

4. Results and discussion
4.1. Heat Transfer
The heat transfer performance of the nanofluid samples is determined from the $Nu$ values which can be depicted from Eq. (1),

$$Nu = \frac{\dot{h}D}{k}$$

where $k$ is the thermal conductivity of the fluid, and $\dot{h}$ is the heat transfer coefficient can be found by Eq. (2),

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Figure 1. Experimental setup: (a) schematic diagram; (b) general view of the components.
where $T_w$ is the temperature at the wall, $T_f$ the mean fluid temperature and $q$ is the applied heat flux.

Moreover, Reynold number, $Re = \frac{\rho u D}{\mu}$ is determined based on the velocity ($u$) and properties (viscosity $\mu$ and density $\rho$) of sample fluids.

The experimental results of $Nu$ for the base fluid and nanofluids are presented in Fig. 2 for several $Re$ and compared with the results from theoretical correlations of Gnielinski [12] for laminar flow presented in Eq. (3) and for turbulent flow presented in Eq. (4).

\[
Nu = \left\{ 4.364^3 + 0.6^3 + \left[ 1.953^3 \left( \frac{Re Pr D}{L} - 0.6 \right) \right]^{\frac{1}{3}} \right\}^{\frac{1}{3}} \quad (3)
\]

\[
Nu = \frac{\left( \frac{2}{1 + 12.7 \left( \frac{D}{L} \right)^{\frac{2}{3}}(Pr^{\frac{1}{3}} - 1) \left( \frac{D}{L} \right)^{\frac{2}{3}} \right) \right)}{1 + 12.7 \left( \frac{D}{L} \right)^{\frac{2}{3}}(Pr^{\frac{1}{3}} - 1) \left( \frac{D}{L} \right)^{\frac{2}{3}}} \quad (4)
\]

It can be depicted from Fig. 2 that the experimental $Nu$ values agree with those of theoretical correlations with a maximum deviation of 4% for laminar flow and a maximum deviation of 7% for turbulent flow. Also, $Nu$ values are not showing enhancement with the increase of nanoparticles concentrations for all $Re$ in laminar and turbulent regimes. This can be explained by the very low concentrations of $Al_2O_3$ used in this study and the error ranges of the experimental setup ($\pm 6\%$), where the deviations between the results set into the error range. In addition, particles might be lost within the systems and tubes resulting lower effective concentration of nanoparticles in the flowing nanofluids. Nevertheless similar results were reported from the similar studies in the literature [8], [12]. Using previous setup Artem et al. [13] investigated different type and concentrations of $Al_2O_3$ nanofluids and their results for lower particles concentrations didn’t indicate any noticeable heat transfer enhancement. On the contrary, some studies reported a significant enhancement in HTC [9], [14].

\[
h = \frac{q}{T_w - T_f} \quad (2)
\]

4.2. Friction factor

Friction factor $f$ for the nanofluids and base fluids are calculated at each $Re$ using the Darcy-Weisbach equation (Eq. 5) based on the obtained experimental results of pressure drop.

\[
f = \frac{2 \Delta P D}{\rho u^2 L} \quad (5)
\]

where $\Delta P$ is the pressure drop along test section (Pa), $\rho$ is the density of the fluid (kg/m$^3$), $u$ is the velocity (m/s) and $L$ is the tube length (m).

The results of the friction factor are presented in Fig. 3 and compared with the common theoretical equations i.e., Poiseuille equation ($f=64/Re$) for laminar flow, and the Blasius correlation ($f=0.316Re^{0.25}$) for turbulent flow.
Fig. 3 confirms that there is no significant increase in friction factor by adding nanoparticles to the base fluids for both flow regime. Also, the used theoretical correlations (Poiseuille and Blasius correlations) agreed with the experimental results for friction factor.

5. Conclusions
The experimental investigations on convection heat transfer of Al₂O₃ nanofluids in minichannel were conducted and the heat transfer characteristics were determined. The results of Nu and f were compared with the theoretical correlations for laminar and turbulent flows showing acceptable agreement. Also, the changes in the results of Nu and f caused by adding nanoparticles to the base fluids are not significant and set into the error range of the experimental setup. The latter leads to suggest investigating higher particles concentrations where the results can show higher enhancement. Also, the used experimental setup for investigating nanofluids behavior should be in a high level of accuracy in order to note the little changes in the results.

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