Experimental investigation of the thermal development of two nanofluids in laminar flow

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Abstract. In this study, we conducted an experimental investigation of the thermal development of two nanofluids (γ-Al₂O₃ and TiO₂ in deionized water) in a laminar pipe flow. To do so, the local Nusselt number is determined for Reynolds numbers from 650 to 1800. Experiments were carried out with water and two concentrations of water-based nanofluids with aluminum oxide and titanium oxide nanoparticles. The results show that the local Nusselt number remains unchanged with increasing mass concentration and that the process of thermal development is similar to that of water. Similarly, the friction factor is not affected by the addition of the nanoparticles, suggesting that these nanofluids behave like a homogeneous mixture.

1. Introduction
Nanofluids are colloidal suspensions of nanoparticles in a base fluid that present enhanced thermal properties. This idea was introduced by Choi and Eastman [1] in 1995 to produce a new class of heat transfer fluid. Metallic and ceramic nanoparticles are often used due to their high thermal conductivity compared to that of base fluids like water or oil. Although many publications deal with the thermophysical properties of nanofluids, large discrepancies are observed, especially concerning viscosity and thermal conductivity. As some studies report high enhancements of the thermal conductivity and an anomalous enhancement of the heat transfer coefficient (i.e. the increase of the heat transfer coefficient is not solely due to the increase of the thermal conductivity) [2], nanofluids have become good candidates for replacing conventional fluids in heat exchangers. However, a few dynamic studies show that the increase in viscosity is so high that the thermal performance of nanofluids is lower than that of the base fluid in turbulent flow [3, 4]. Our previous study also showed that the increase of the pressure drop due to the presence of the nanoparticles exceeds the enhancement of the heat transfer coefficient in both laminar and turbulent regimes [5].

As for the thermal entrance region of nanofluids, it has been previously studied [6, 7] but the determination of the thermophysical properties of the nanofluids often rely on theoretical models and are poorly or not measured [8]. In this study, we conducted an experimental investigation of the thermal development of two nanofluids (γ-Al₂O₃ and TiO₂ in deionized water) in a laminar pipe flow after having experimentally measured the viscosity and thermal conductivity.
2. Nanofluid characterisation

Two water-based nanofluids are studied in the present work: Al$_2$O$_3$-water and TiO$_2$-water of 10 and 15 nm mean diameter respectively. The mass concentrations of the stock solutions supplied by the manufacturer Nanostructured & Anamorphous Materials, Inc. are 20% and 15% respectively. De-ionized water is used to dilute the stock solutions and to obtain mass concentrations of 2.5% and 5% in both cases (volume concentrations of about 0.7% and 1.4%). The density and the specific heat capacity of these nanofluids are determined by the following mixture laws assuming that the thermal equilibrium between the base fluid and the nanoparticles is reached:

\[
\rho_{NF} = \phi_v \rho_{NP} + (1 - \phi_v) \rho_{BF}, \tag{1}
\]

\[
\rho_{NF} C_{p,NF} = \phi_v \rho_{NP} C_{p, NP} + (1 - \phi_v) \rho_{BF} C_{p, BF}, \tag{2}
\]

where subscripts NF, NP and BF denote respectively the nanofluid, the nanoparticles and the base fluid.

According to the manufacturer’s specifications, the density of the nanoparticles of Al$_2$O$_3$ and TiO$_2$ is 3700 kg·m$^{-3}$ and 3900 kg·m$^{-3}$. The specific heat capacity is taken to be equal to 773 J·kg$^{-1}$·K$^{-1}$ and 710 J·kg$^{-1}$·K$^{-1}$ respectively [9]. The volume concentration is determined from the mass concentration and the densities of the base fluid and the nanoparticles:

\[
\phi_v = \frac{\phi_m}{\phi_m + \left(\frac{\rho_{NP}}{\rho_{BF}}\right)(1 - \phi_m)}. \tag{3}
\]

The kinematic viscosity of the nanofluids has been measured with an Ubbelohde viscometer while the thermal conductivity has been determined using a 3ω method [10].

3. Methods

![Figure 1: Schematic diagram of the experimental set-up](image)

The flow loop used to determine the convective heat transfer coefficient is composed of a gear pump, a temperature-controlled bath, a test section, an ultrasonic bath and a flow meter. The test section consists of two identical stainless-steel tubes with a length of 1.61 m, inner diameter
$d_i = 4.4$ mm and outer diameter $d_o = 5.0$ mm. One of them is electrically heated by a DC power supply over a length of 95 cm while the other one is left to rest. Both tubes are covered with a matte black paint that has an emissivity of 0.93, thereby allowing the recording of the external wall temperatures of the tubes with a thermal camera (CEDIP-FLIR Titanium, $640 \times 512$ pixels, Spectral range from 1.5 to 5.1$\mu$m, NETD 20 mK at 20°C). The intensity, volume flow rate and pressure drop are respectively measured by a clamp meter (0-400 A with $\pm 0.5 \%$ accuracy), a gear flowmeter (0.5-100 L$\cdot$h$^{-1}$ with $\pm 0.5\%$ accuracy) and a pressure transmitter (0-0.5 bar with 0.1%(FS accuracy) and recorded by a GRAPHTEC data logger. Voltage is directly measured and recorded by the data logger.

Due to the very small thickness of the tube ($e = 0.3$ mm), the internal and external wall temperatures are considered to be equal. Thus, the wall temperature of the unheated tube corresponds to the temperature of the fluid entering the heated tube. As the tubes cannot be thermally isolated, the heat losses to the surroundings are estimated considering that the overall heat transfer coefficient $h_e$ is 10 W$\cdot$m$^{-2}$$\cdot$K$^{-1}$ [11].

Knowing the external wall temperature of the heated tube $T_e$ at the $x$ location, the ambient temperature $T_a$ and assuming that the heat flux $q''$ is constant over the entire heating length $L$, the energy balance writes as:

$$q'' = \frac{UI}{\pi d_i L} = h_i(x) (T_e(x) - T_{NF}(x)) + h_e \frac{d_o}{d_i} (T_e(x) - T_a),$$

where $T_{NF}(x)$ denotes the temperature of the nanofluid at the $x$ location. Considering that the local temperature of the fluid follows a linear profile, one can write:

$$T_{NF}(x) = T_{NF,in} + \frac{ULx}{LmC_p},$$

where $m$ is the mass flow rate. Combining equations (4) and (5), the local convective heat transfer coefficient writes as:

$$h_i(x) = \frac{UI - h_e \pi d_o L (T_e(x) - T_a)}{\pi d_i L (T_e(x) - T_{NF,in} - \frac{ULx}{LmC_p})}.$$

By moving the thermal camera in the axial direction, it is possible to determine the heat transfer coefficient at different locations and then to study the thermal development of the nanofluids.

In the next section, the relevant quantities will be represented by the following dimensionless numbers:

Reynolds number : $Re_D = \frac{\rho V d_i}{\mu}$, Nusselt number : $Nu_x = \frac{h_i(x) d_i}{k}$, Graetz number : $Gz = Re_D Pr d_i x = \frac{V d_i^2}{\alpha x}$, Friction factor : $\lambda = \frac{2 \Delta P d_i}{\rho V^2 L_p}$,

where $V$, $\Delta P$, $L_p$, $\mu$, $\alpha$ and $Pr$ respectively denote the flow velocity, the measured pressure drop, the length between the pressure taps, the dynamic viscosity, the thermal diffusivity and the Prandtl number.

4. Results and discussion

Figure 2 depicts the evolution of the friction factor as a function of the Reynolds number for each mass concentration of nanofluids and for water in the laminar region. One can note that the present results are very close to the theoretical Poiseuille law $\lambda = \frac{64}{Re_D}$ suggesting that these nanofluids behave like single-phase fluids. However, the dimensional pressure drop
Figure 2: Friction factor versus Reynolds number for all tested fluids.

\[ \Delta P = \lambda \frac{\rho V^2 L_p}{d} \]

does increase with mass concentration at a constant Reynolds number as the flow velocity is higher to balance the increase of viscosity (not shown here).

Figures 3 and 4 show the evolution of the local Nusselt number as a function of the inverse of the Graetz number for Al\(_2\)O\(_3\)-water and TiO\(_2\)-water nanofluids. For both nanofluids, the value of the local Nusselt number is not affected by the presence of the nanoparticles. It means that the convective heat transfer coefficient does increase but its enhancement is totally balanced by the increase of the thermal conductivity. Hence, there is no anomalous enhancement of the heat transfer coefficient and the conventional correlations developed for single-phase flow seem to be valid for these two nanofluids if their properties are correctly determined. Moreover, as all the curves follow the trend of the theoretical law of Kays and Crawford [12], the thermal developing process is the same for these nanofluids and for water.
Conclusion
In this experimental study, the thermal development of two nanofluids in laminar flow has been investigated through the evolution of the local Nusselt number as a function of the inverse of the Graetz number. The addition of these nanoparticles of Al$_2$O$_3$ and TiO$_2$ in water does not affect the thermal development neither the friction factor whatever the concentration, up to 5wt%. This means that these nanofluids behave like homogeneous mixtures and more generally that it is possible for nanofluids to follow the conventional correlations developed for single-phase fluid, if the particles are small enough and if their properties are correctly determined.

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