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Experimental Assessment of the Thermal Performance of Two Water-based Nanofluids in Laminar Pipe Flow

Alexandre BRICLOT[1], Catalin POPA[1], Jean-François HENRY[1], Stéphane FOHANNO[1]
[1]ITheMM EA7548, Université de Reims Champagne-Ardenne
Campus Moulin de la Housse, 51100 Reims, FRANCE
alexandre.briclot@univ-reims.fr

Abstract **–** In this paper, the thermal performance of two water-based nanofluids is experimentally assessed in laminar developing flow and their interest as heat transfer fluids is critically discussed. To do so, the local convective heat transfer coefficient of three mass concentrations of Al_2O_3-water and TiO_2-water nanofluids is determined at different flow rates corresponding to Reynolds numbers between 650 and 1800. The results indicate that the addition of these particles in water strongly deteriorates heat transfer compared to water when the flow is developing while the thermal performances of all the studied fluids are similar when the flow tends to be fully developed. This can be explained by a faster development of the thermal boundary layer, corresponding to a diminution of the heat transfer coefficient, when nanofluids are used.

Keywords**:** Nanofluids, thermal performance, heat exchanger, heat transfer coefficient, infrared thermography

1. Introduction

Since 1995 and the pioneer work of Choi and Eastman [1], nanofluids (stable suspensions of solid particles in a base fluid) have received a lot of attention as they were promised to become new heat transfer fluids. First studies showed that the addition of a small fraction of nanoparticles can lead to an abnormal increase in the thermal conductivity. For example, Choi *et al.* [2] found that this enhancement can reach 150% when a volume concentration of 1% of multi-walled carbon nanotubes (MWCNT) is added to oil while the theoretical relationships predict no more than 10%. Later, numerous papers showed that the heat transfer coefficient (HTC) of nanofluids was higher than that of its base at the same Reynolds number in laminar flow. For example, Wen and Ding [3] proved that the addition of a moderate volume fraction of 1.6% of alumina nanoparticles (27-57nm) may increase the HTC by about 47% at a Reynolds number of 1600. They also showed that this enhancement decreases as the axial distance increases, suggesting that this phenomenon is related to the development of the thermal boundary layer. They proposed that the thermal entrance length of the nanofluids is greater than that of the base fluid at constant Reynolds numbers.

Lai *et al.* [4] came to the same conclusion by studying a similar nanofluid in a minichannel. They explained this result by the effect of the nanoparticles on the thermophysical properties of the nanofluids and especially by the increase in the Prandtl number.

More recently, Vafaei *et al.* [5] used two water-based and two ethanol-based nanofluids with alumina and titanium dioxide nanoparticles in laminar flow in microchannels. They showed that the heat transfer coefficient can be increased by up to 30% in the entrance region at Reynolds numbers between 150 and 200.

This observation was also reported on other nanofluids like MWCNT in a mixture of ethylene glycol and water by Ajeeb *et al.* [6]. In their study, a small volume fraction of 0.5% of MWCNT was sufficient to enhance the heat transfer coefficient by 10 to 14%. In the meantime, the authors also noted an increase in the pressure drop by 10 to 16%.

In all these studies, the heat transfer coefficient was investigated at a constant Reynolds number. However, it is far more interesting from an engineering point of view to study the thermal performance, that is to say, the heat transfer coefficient at a constant pumping power.

Therefore, we conducted experiments to determine the heat transfer coefficient of several concentrations of Al_2O_3-water and TiO_2-water nanofluids as a function of the axial distance under laminar conditions. From pressure drop measurements, we calculated the pumping power required to drive each nanofluid and compared the HTC of these nanofluids to that of water.

2. Nanofluid Characterisation

Two of the most common nanofluids were selected for this study: Al_2O_3-water (10±5nm) and TiO_2-water (5-30nm). The nanofluids were prepared and stabilized by Nanostructured & Anamorphous Materials, Inc. From the stock solutions, three mass concentrations of 1.5, 2.5 and 5.0% were prepared by dilution with deionized water.

Using a Zetasizer Nano ZS apparatus (Malvern Panalytical), zeta potential measurements were performed to assess the stability of these suspensions. The zeta potential of the Al_2O_3-water nanofluid was measured at 54mV while that of TiO_2-water was 47mV, indicating that both nanofluids present good stability characteristics [7].

All the thermophysical properties of these concentrations of nanofluids were experimentally determined. Density ρ was measured using a Gay-Lussac pycnometer, specific heat capacity C_p was determined by a differential scanning calorimeter, dynamic viscosity μ was calculated from kinematic viscosity measured with an Ubbelohde viscometer and finally, thermal conductivity k measurements were performed using the 3ω-method [8]. Table 1 summarizes the evolution of these thermophysical properties as a function of mass concentration. The results are presented as relative thermophysical properties, i.e. ratio of the properties of the nanofluid and those of water at the same temperature. It can be seen that density, dynamic viscosity and thermal conductivity increase with the addition of both types of nanoparticles. On the contrary, specific heat capacity decreases due to the lower C_p of the nanoparticles compared to that of water [9]. The increase in the density and the decrease in the specific heat capacity reach the same value for both nanofluids due to the similar properties of the two types of particles. On the other hand, dynamic viscosity increases much stronger with alumina (+49% at 5w%) than with titanium dioxide (+17% at 5w%). Likewise, the enhancement of the thermal conductivity is better using the former than the latter. In either case, the increase in viscosity outweighs the improvement in thermal conductivity.

Table 1: Relative thermal properties of nanofluids

	Al_2O_3-water			TiO_2-water		
ϕ_m (%)	1.5	2.5	5.0	1.5	2.5	5.0
ρ_r	1.012	1.019	1.037	1.011	1.018	1.037
$C_{p,r}$	0.990	0.983	0.958	0.990	0.981	0.958
μ_r	1.089	1.177	1.492	1.048	1.083	1.167
k_r	1.006	1.018	1.035	1	1.002	1.004

3. Material and Methods

Figure 1 represents the experimental setup composed of a reservoir tank immersed in an ultrasonic bath, a gear pump, a flowmeter, a thermostatic bath, and a test zone. The test zone itself consists of two identical stainless-steel tubes of inner diameter $d_i = 4.4\text{mm}$, outer diameter $d_o = 5.0\text{mm}$ and length $L_p = 1.61\text{m}$. Both tubes are covered with a black paint that has an emissivity $\varepsilon = 0.93$. One of the tubes is electrically heated over $L_c = 94.5\text{cm}$ and cooled by internal forced convection. The current intensity I and voltage U, as well as the volume flow rate Q_v, are measured and recorded by a data logger. The pressure drop between the inlet and the outlet of the unheated tube is directly measured by a differential pressure transmitter. A movable thermal camera allows recording the external wall temperature of both tubes at different locations x from the start of the heating as represented in Figure 2.

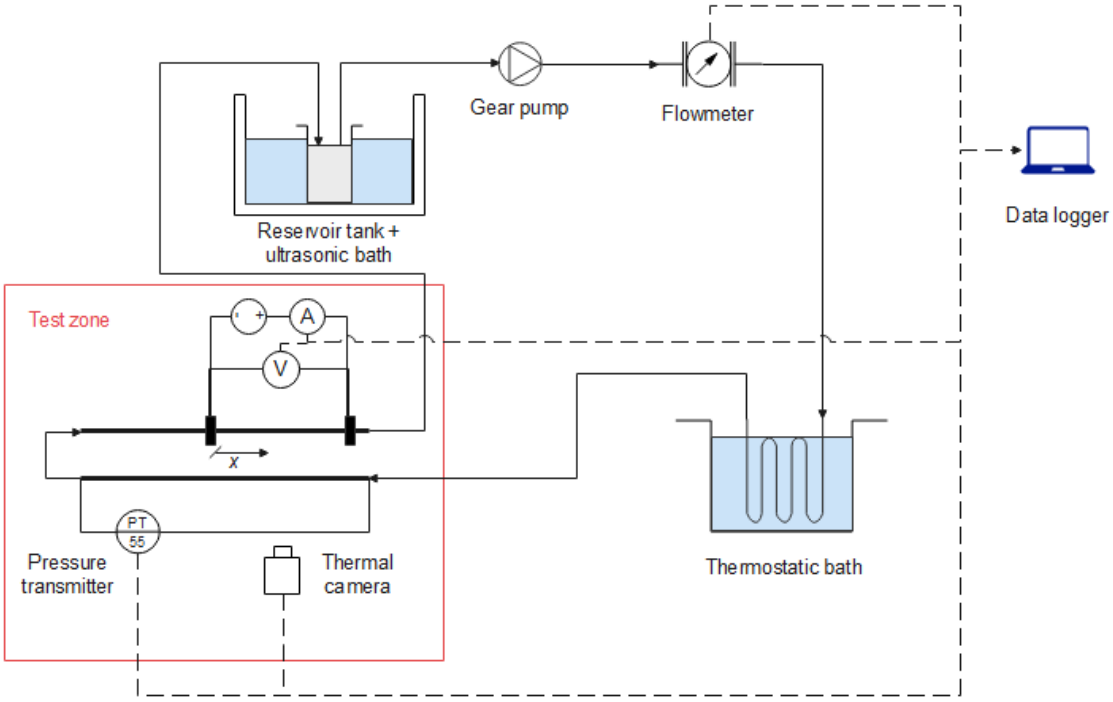


Figure 1: Experimental setup

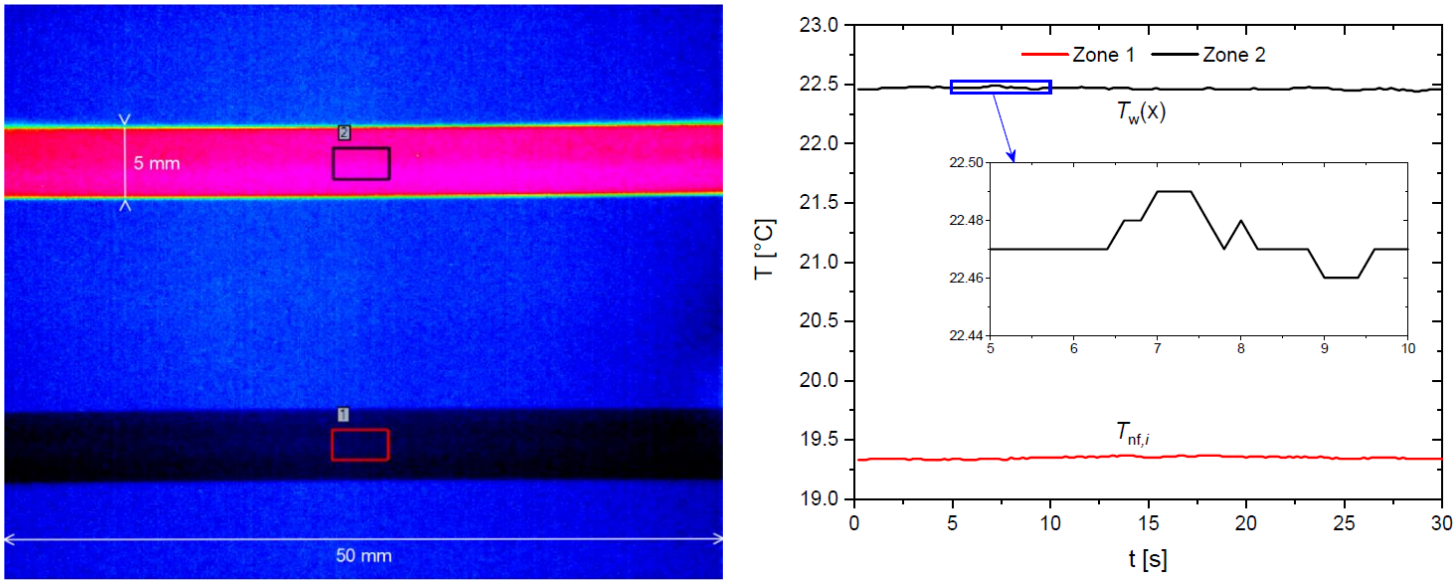


Figure 2: Thermal camera image of the tubes (left) and temperature profiles as a function of time (right).

From an energy balance, developed elsewhere [10], the convective heat transfer coefficient can be determined, taking into account the heat losses into the surroundings empirically computed Φ_e, and the radial conduction in the heated tube:

$$h_i(x) = \frac{UI - \Phi_e}{\pi d_i L_c \left(T_w(x) - UI \frac{\ln(d_o/d_i)}{2\pi k_t L_c} - T_{nf,i} - \frac{UI}{\dot{m} C_p} \frac{x}{L_c} \right)}, \quad (1)$$

where k_t and $\dot{m}$ respectively denote the thermal conductivity of stainless steel and the mass flow rate calculated from the measurements of the volume flow rate and the density. $T_w(x)$ and $T_{nf,i}$ represent the external wall temperatures of the heated and unheated tubes respectively (Figure 2)

To assess the thermal performance of these nanofluids as heat transfer fluids, this convective heat transfer coefficient has to be compared to that of water at a constant pumping power:

$$PP = Q_v \, \Delta P. \quad (2)$$

4. Results and Discussion

Figure 3 shows the evolution of the local heat transfer coefficient as a function of the pumping power required to drive the fluid per unit length. At the entrance of the heated section, (Figure 3(a and 3(b), the local heat transfer coefficient is higher for water than for any concentration of nanofluids. Moreover, the thermal performance of nanofluids decreases with the increasing mass concentration. When x increases (Figure 3(c) Al_2O_3-water, x = 39cm(c and 3(d), the convective heat transfer coefficient of nanofluids approaches that of water for all pumping powers. Finally, at the outlet of the heated section (Figure 3(e(c) Al_2O_3-water, x = 39cm and 3(f), all the studied fluids have the same thermal performance as water. This observation may be related to a faster development of the thermal boundary layer of nanofluids for a given pumping power. This contrasts with the comparison at constant Reynolds numbers, for which Wen and Ding [3] showed that the thermal entrance length of nanofluids was greater than that of water. Indeed, the thermal entrance length x_{dev} in laminar regime can classically be expressed as [9]:

$$x_{dev} = 0.05 \, \mathrm{Re_D} \, \mathrm{Pr} \, \mathrm{d_i} \quad (3)$$

where $\mathrm{Re_D} = \frac{4\rho Q_v}{\pi \mu d_i}$ is the Reynolds number and $\mathrm{Pr} = \frac{C_p \mu}{k}$ is the Prandtl number.

In our previous study, we showed that the process of development of the thermal boundary layer of these nanofluids was the same as water [11]. In other words, the non-dimensional law of Kays and Crawford [12] that relates the local Nusselt number to the axial distance in laminar thermally developing flow is still valid for these two nanofluids. Therefore, equation (3) is also applicable to nanofluids.

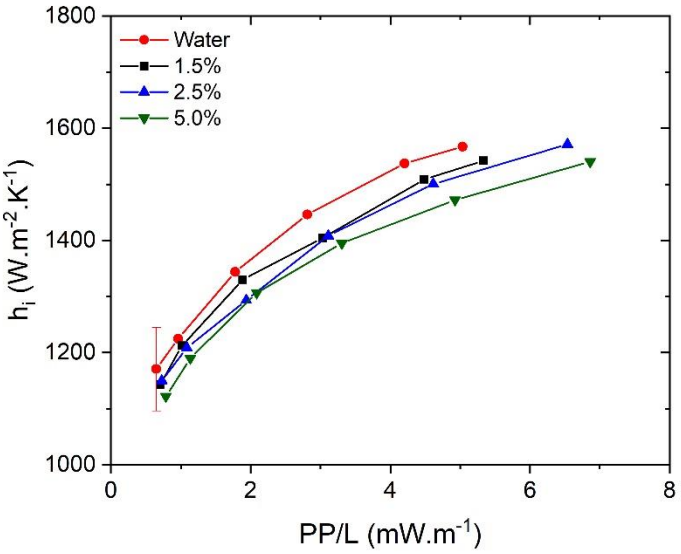
Combining equations (2), (3) and the Poiseuille law for the determination of the pressure drop in laminar flow:

$$\Delta P = \frac{128 \, \mu \, L_p Q_v}{\pi d_i^4}, \quad (4)$$

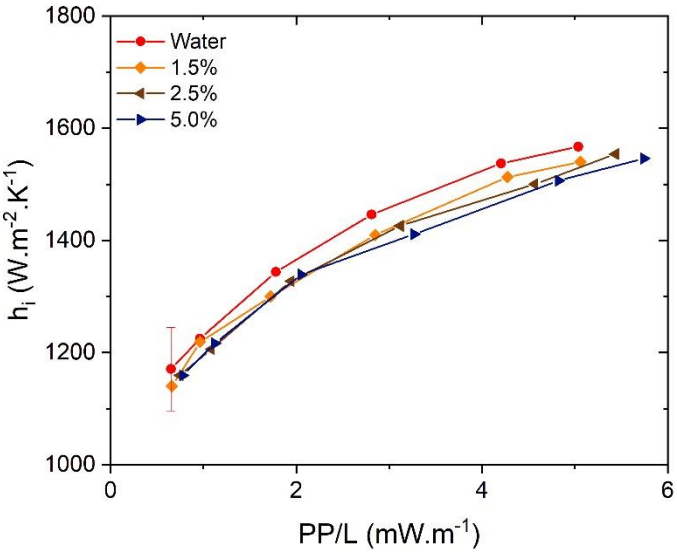
the ratio of the entrance length of a nanofluid to that of its base fluid at a constant pumping power can be written as:

$$\frac{x_{dev,NF}}{x_{dev,BF}} = \frac{(\rho C_p)_{NF}}{(\rho C_p)_{BF}} \frac{(k\sqrt{\mu})_{BF}}{(k\sqrt{\mu})_{NF}} = \frac{\rho_r C_{p,r}}{k_r \sqrt{\mu_r}}. \quad (5)$$

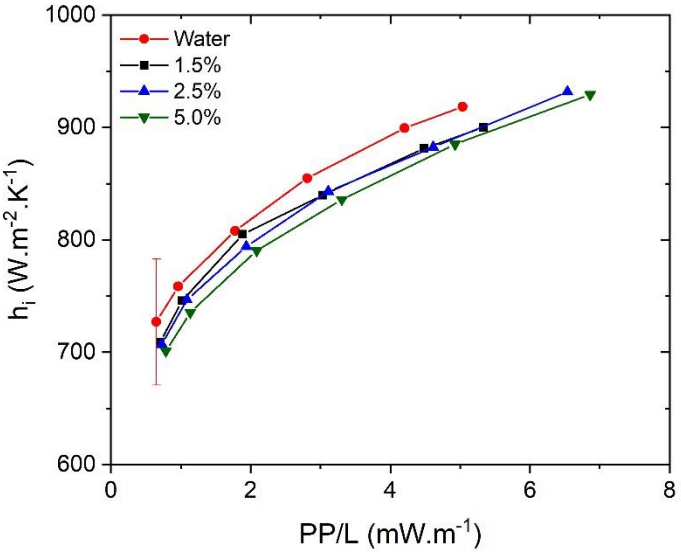
Interestingly, this ratio only depends on the relative properties of the nanofluids and therefore, it can be computed from the measurements detailed in Table 1. The results presented in Table 2 show that in all cases, the thermal entrance length of the nanofluids studied here is, indeed, shorter than that of water.



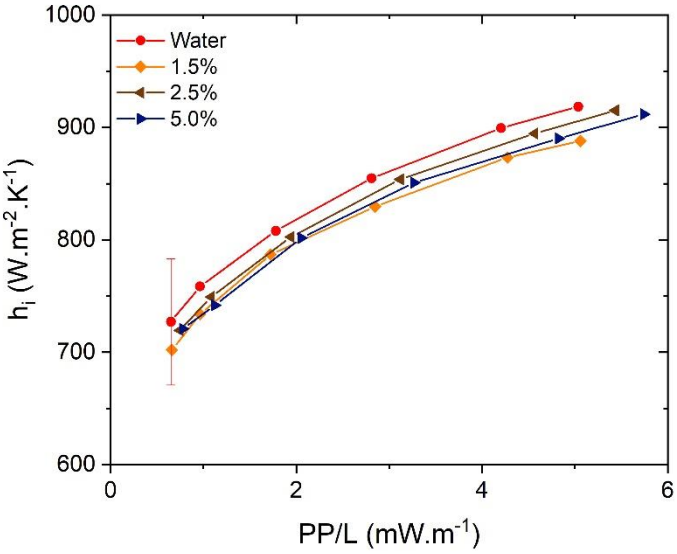
(a) Al_2O_3-water, $x = 9$cm



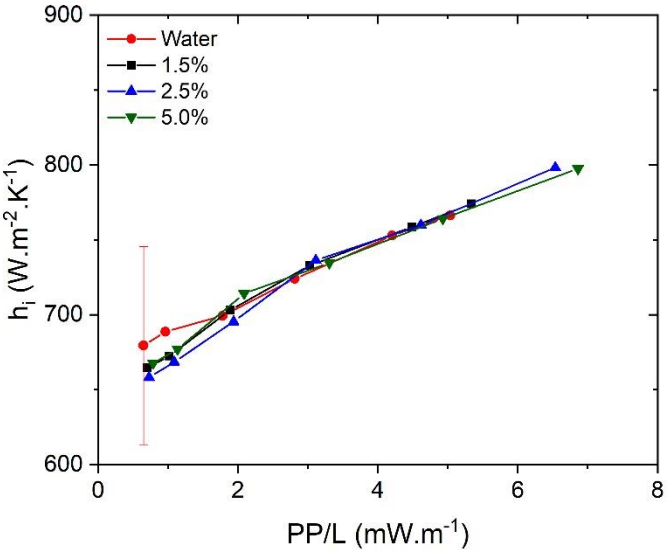
(b) TiO_2-water, $x = 9$cm



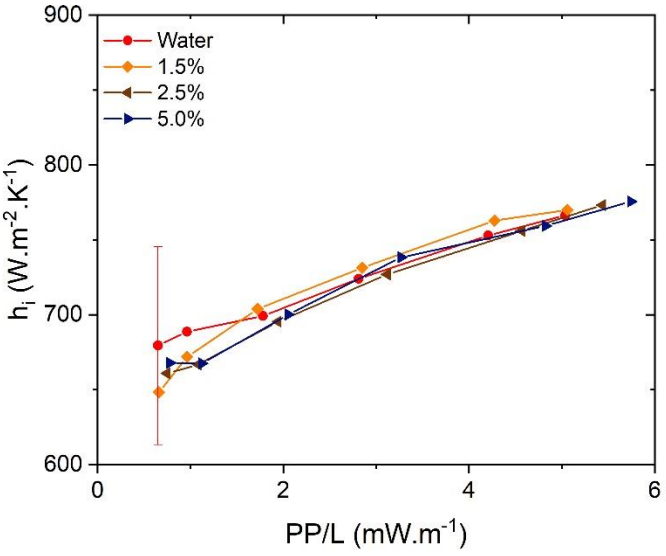
(c) Al_2O_3-water, $x = 39$cm



(d) TiO_2-water, $x = 39$cm



(e) Al_2O_3-water, $x = 69$cm



(f) TiO_2-water, $x = 69$cm

Figure 3: Heat transfer coefficient as a function of the pumping power per unit length for different axial positions

This phenomenon allows understanding the results presented in Figure 3. As the boundary layer grows faster for nanofluids, its thickness will be lower for water for a given location x in the entrance region, favouring heat transfer. This explains the fact that the heat transfer coefficient of water is much larger than that of any concentration of nanofluid at $x = 9$cm. On the other hand, when $x \to \infty$, i.e. when the flow tends to be thermally developed, the rate of growth of the boundary layer is much more reduced. This means that the boundary layers of water and these nanofluids almost have the same thickness at a constant x. As a result, the heat transfer coefficient is the same for all the studied fluids here. Therefore, these two nanofluids should not be used as heat transfer fluids in thermally developing laminar flow as they degrade heat transfer.

Table 2: Ratio of the entrance length of the nanofluids to that of water

ϕ_m (%)	$\frac{x_{dev,NF}}{x_{dev,BF}}$	
	Al_2O_3-water	TiO_2-water
1.5	0.954	0.978
2.5	0.907	0.958
5.0	0.786	0.916

4. Conclusion

The thermal performance of two water-based nanofluids has been assessed by studying the evolution of the local heat transfer coefficient as a function of pumping power.

First, all the thermophysical properties of three concentrations of each nanofluid have been measured. Density, thermal conductivity, and especially dynamic viscosity increase with the increasing mass concentration while specific heat capacity decreases.

Obviously, the alteration of these properties has an impact on heat transfer. In detail, the results show that the addition of nanoparticles of alumina and titanium dioxide degrades the thermal performance of water at the same pumping power and a constant axial distance. This can be explained by a faster thermal development when nanofluids are used. This results in a thicker thermal boundary layer for nanofluids than water. Therefore, in these conditions, the heat transfer coefficient decreases with the increasing concentration contrary to the comparison at constant Reynolds numbers.

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