Comparison of the Heat Transfer Efficiency of Nanofluids

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The continuously increasing power involved in many applications, coupled with the very small size of a number of component devices, is pushing the technical community to look for more efficient heat transfer systems, to remove the heat generated and keep the system under controlled operating conditions. In particular, significant interest has been devoted to the use of the so-called nanofluids, obtained by suspending nano-sized particles in conventional heat transfer liquids. According to some literature, these suspensions present enhanced heat transfer capabilities, without the inconveniencies of particles settlement and clogging of the channels encountered using larger particles. However, other results show that the actual improvement in the heat transfer efficiency may depend on the adopted working conditions and on the reference parameters (fluid velocity, Reynolds number, pressure drop, etc.) assumed to compare the performances of the nanoparticles suspensions with those of the clear thermal fluid.
In the present work heat transfer experiments were carried out on a number of nanofluids systems, varying the type and the concentration of the nanoparticles, and the fluid dynamic regime. The investigated suspensions gave rise to heat transfer coefficients different from those of their respective clear thermal fluid, the thermal efficiency being higher or lower, depending on the fluid dynamic parameter used as a base for comparing the systems. Generally speaking, in most cases nanofluids may give an advantage from the heat transfer point of view only when the conditions are unfavorable for the traditional thermal fluids.

1. Introduction

Nanofluids are obtained by suspending solid particles in the range 1-100 nm in a homogeneous fluid and they have been developed mainly for use in cooling small hi-tech equipment. The small size of the nanoparticles prevent the occurrence of the problems usually encountered with larger particles (ranging from millimeters to micrometers), such as settling of the solid phase, high pressure drops, erosion and clogging of the channels, etc. Referring only to some review papers, authors like Saidur et al. (2011), Das et al. (2006), and Wang and Mujundar (2007), focus their attention mainly on results denoting a marked increase in the heat transfer capabilities associated to the use of nanofluids, while other authors (Lee and Mudawar, 2007; Yu et al., 2008) note that many experiments reported a heat transfer coefficient in agreement with the classical theoretical models. As a consequence, all of them agree that, in order to assess the actual behavior of the nanofluids, the need for an accurate measurement of the heat transfer coefficients of the fluids containing nanoparticles is required, along with a proper comparison of the obtained values versus those of the corresponding clear fluids, under equivalent operating conditions.

2. Experimental

The nanofluids used in the experiments were prepared suspending the nanoparticles in a thermal fluid and adding small quantities of surfactants to prevent particle agglomeration. The main characteristics of the tested nanofluids are listed in Table 1, where density and viscosity ratios of the nanofluids are referred to water; in all cases, surface modifiers have been added to prevent agglomeration of the nanoparticles.

Table 1: Properties of the tested nanofluids

Nanofluid	Mass %	Heat transfer fluid	Viscosity ratio	Density ratio	Particle size [nm]
TiO$_2$ (type a)	9	water	1.88	1.099	20-30
TiO$_2$ (type b)	9	water	1.16	1.095	15
ZrO$_2$	9	water	1.972	1.084	100
SiC	9	water	1.9	1.047	25
SiC	6	water	1.52	1.027	25
SiC	3	water	1.32	1.01	25
Al$_2$O$_3$	9	water	1.475	1.076	100-200
Al$_2$O$_3$	3	water	1.124	1.036	100-200
Al$_2$O$_3$	9	50 % water – 50 % Antifrogen N	4.3	1.146	150
Al$_2$O$_3$	20	50 % water – 50 % ethylene glycol	6.3	1.259	100
Heat trasfer fluid	0	water	1.184	1.0047	-
Heat trasfer fluid	0	50 % water – 50 % Antifrogen N	3.2	1.066	-
Heat trasfer fluid	0	50 % water – 50 % ethylene glycol	3.1	1.057	-

The experiments were carried out using the HETNA facility (Hydraulic Experiments on the Thermo-mechanics of Nanofluids), consisting of two parallel sections (about 1.2 Liters in volume each) which allow the simultaneous measurement of the performances of the nanofluid and of the corresponding clear thermal fluid. Each section of the facility includes a volumetric gear pump, a Coriolis flow-meter, a pressure control system, a pre-heater to control the temperature at the inlet of the test section, a heat exchanger to cool the fluid before the pump, thermocouples to measure the external temperature of the pipe, and 2 PID controllers. Three vessels for storing some metal targets were also used to assess possible erosion effects of the suspensions (Celata et al., 2013).

One section of the circuit is shown in Figure 1. The test section is an AISI 316 pipe 200 mm long, with internal diameter 4 mm. The pipe wall is heated by Joule effect with a DC power supply, and is insulated. The wall temperature is measured at 20, 73, 127 and 180 mm from the inlet of the pipe.

The experiments were carried out by filling one section with the nanofluid and the other with the clear heat transfer fluid, and maintaining the same velocity or the same mass flow-rate or Reynolds number in the two sections.
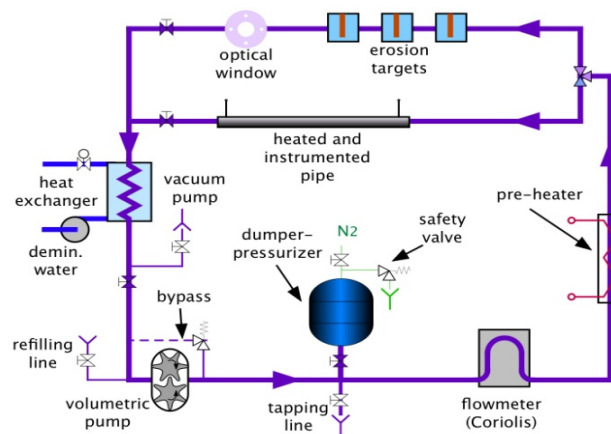

Figure 1. Schematic diagram of HETNA facility

2.1 Heat transfer coefficient
The heat transfer coefficient can be defined as:

$$h = \frac{q}{\left(T_{wi} - T_f\right)} = \frac{W}{\pi \cdot D_i \cdot L \left(T_{wi} - T_f\right)}$$

(1)

where q (W/m^2) is the thermal flux, T_{wi} and T_f (°C) are the temperatures of the inner wall of the pipe and of the bulk fluid, respectively, D_i and L (m) are the internal diameter and the length of the pipe; W is the net heat

exchanged per unit time (W), calculated based on the electric power dissipated in the test section, and accounting for the heat losses through the insulation (W_{dis}).

An enthalpy balance allows the calculation of T_f at the axial abscissa x of the test section:

$$T_f = T_{in} + \frac{q \cdot \pi \cdot D_i \cdot x}{\Gamma \cdot c_p} \tag{2}$$

where T_{in} (°C) is the fluid temperature at the inlet section, Γ (kg/s) is the mass flow rate of the fluid, and c_p its specific heat (J/kg°C). The Fourier's equation, written in cylindrical coordinates, under steady-state conditions, including the heat losses and neglecting the axial conduction allows the calculation of T_{wi}:

$$-\frac{q}{k} = \frac{1}{r} \cdot \frac{dT}{dr} + \frac{d^2T}{dr^2} \tag{3}$$

where k (W/m°C) is the thermal conductivity and r (m) the radius of the pipe. Taking into account the boundary conditions: $T = T_{in}$ at R_i, inner radius of the pipe; $dT/dr = W_{dis}/(k \cdot \pi \cdot 2 \cdot R_e \cdot L)$ at R_e, external radius of the pipe. Solving this equation, the inner wall temperature is obtained as:

$$T_{wi} = T_{we} + \frac{1}{2 \cdot \pi \cdot L \cdot k} \cdot \left[\frac{W}{2} + \left(W_{dis} + \frac{W \cdot R_e^2}{R_e^2 - R_i^2} \right) \cdot \ln\left(\frac{R_e}{R_i}\right) \right] \tag{4}$$

The average value of the heat transfer coefficient, h_{av}, is estimated as the arithmetic mean of the values calculated from eq.(2) based on the measurements of the four thermocouples placed on the external wall of the pipe. Suspension density was measured directly by the Coriolis flow meter during the test with an accuracy better than 0.7 %, and thermal conductivity and viscosity were known with an accuracy of 2 and 4 %, respectively, from the supplier.

The specific heat is calculated from the heat capacities of the two phases with an accuracy of about 2 %.The resulting maximum uncertainty on the calculated heat transfer coefficient is 8 %.

3. Results

The heat transfer coefficients obtained from the experimental runs can be plotted against different variables. Figure 2 shows the comparison between the heat transfer coefficients of water, and of nanofluids containing TiO_2, ZrO_2, and Al_2O_3 as a function of the Reynolds number, Re:

$$Re = \frac{u \cdot D_i \cdot \rho_f}{\mu_f} \tag{5}$$

where u, ρ_f and μ_f are the velocity (m/s), the density (kg/m^3) and the viscosity (Pa·s) of the fluid.

Due to the very great number of data points (some hundreds) obtained from each run, and for the sake of visibility, only a small portion of the experimental points have been reported in the graphs.

It can be noticed that the heat transfer coefficients of the tested aqueous suspensions of nanoparticles are invariably higher than that of clear water over all the examined range of Re, which covers both laminar and transition flow regions. By increasing the concentration of particles in the nanofluids the heat transfer coefficient increases as well. The chemical nature of the solid also affects the results with Al_2O_3 being more effective than ZrO_2 and TiO_2. The maximum increase of the heat transfer coefficient is obtained with 9 % mass suspensions of Al_2O_3, with a value of about 60 % higher than that of clear water at Re values around 3000.

The same data were then plotted versus the fluid velocity (u), as shown by the results in Figure 3. It can be noticed that quite different trends are obtained, since higher values of the heat transfer coefficients are associated to clear water, and to Al_2O_3 suspensions (independently of the solid concentration).

The heat transfer coefficients of ZrO_2 and TiO_2 based nanofluids are similar to the others at low velocity (up to 0.5 m/s); however, with increasing fluid velocity the difference increases too, and at highest tested velocity (about 1.4 m/s), their values are about 40 % (ZrO_2) and 45 % (TiO_2) lower than those of water and Al_2O_3 suspensions.

The observed differences in the heat transfer coefficients of clear water and aqueous nanofluids are more evident by plotting the ratio of the heat transfer coefficients of the nanofluids and water as a function of Reynolds number (Figure 4a) or of the fluid velocity (Figure 4b). In this case the data refer to nanofluids obtained using nanoparticles of TiO_2 (mass concentration 9 %) and SiC (mass concentration ranging from 3 to 9 %).

In order to avoid the effect of values averaged based on the measurements of the 4 temperature probes on the comparisons, only the value of the heat transfer coefficient derived from the measurements of the temperature probe n. 4 (axial position x = 180 mm, that is the one closer to the exit of test section), was considered.
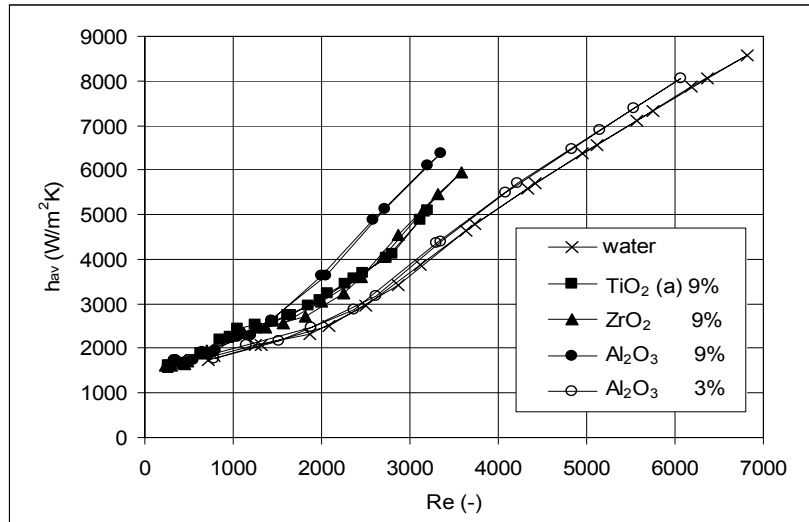
Figure 2: comparison of the average heat transfer coefficients of water and of suspensions of nanoparticles in water vs. Reynolds number.
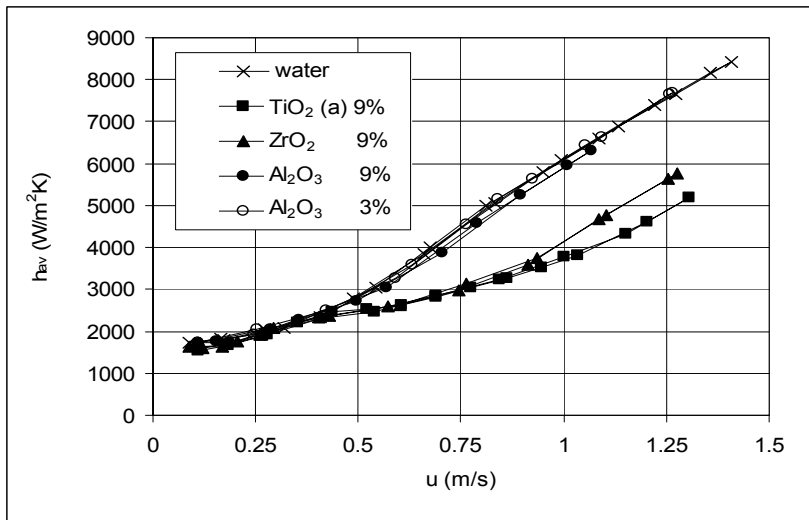
Figure 3: comparison of the average heat transfer coefficients of water and of suspensions of nanoparticles in water vs. the fluid velocity.

It can be noticed that the heat transfer coefficients ratio is generally higher than 1, and presents a maximum for Reynolds numbers close to 2500 for SiC suspensions, and close to 1000 for TiO_2 ones. Conversely, when plotting the heat transfer coefficients ratio versus the velocity of the fluid, most values are lower than 1: the trends exhibit a small maximum (around 1.1) at low velocity (around 0.3 m/s) and a deep minimum (0.85-0.5) at higher velocity, in the range of u = 0.55-0.8 m/s; by further increasing the velocity the heat transfer ratio increases again to values rather close to 1.

By changing the characteristics of the base thermal fluid, in particular selecting more viscous ones (50% mixtures of water with Antifrozen N or Ethylene glycol), the heat transfer ratio appears less variable with the hydrodynamic parameters: Figure 5 shows the results obtained plotting the heat transfer ratio vs. the fluid velocity.
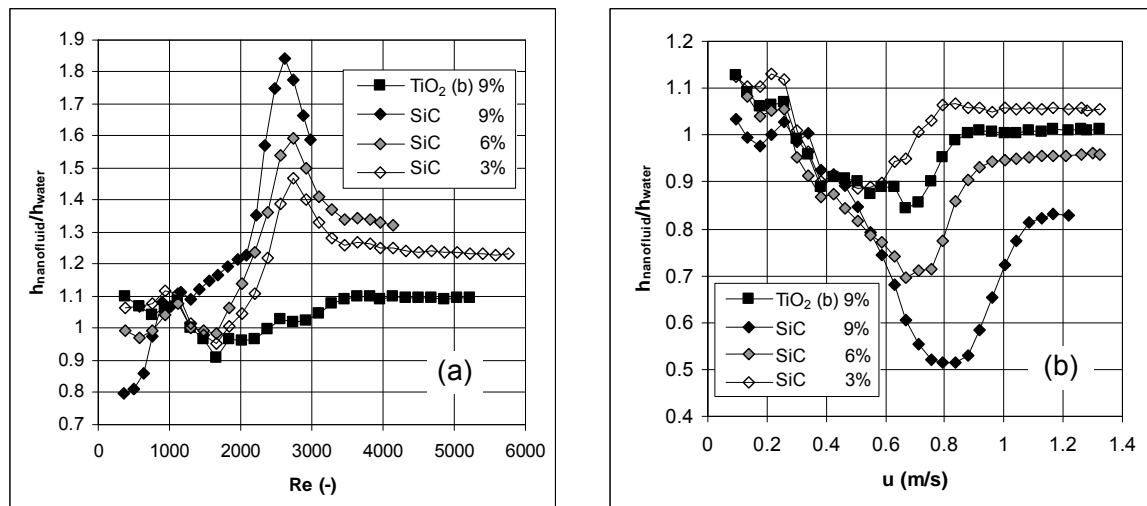
Figure 4: ratio of the heat transfer coefficient of suspensions of nanoparticles in water with respect to the clear water one: a) as a function of Reynolds number; b) as a function of fluid velocity.

In fact, in this case, the heat transfer ratio appears more constant: a rather flat maximum (around 1.1), is observed at velocities in the range 0.4-0.9 m/s, followed by a minimum (around 0.85-0.9) at a velocity of about 1.1 m/s. The heat transfer coefficients ratio is more variable for the nanofluid with a higher concentration of nanoparticles (20 % vs. 9 %, by mass).
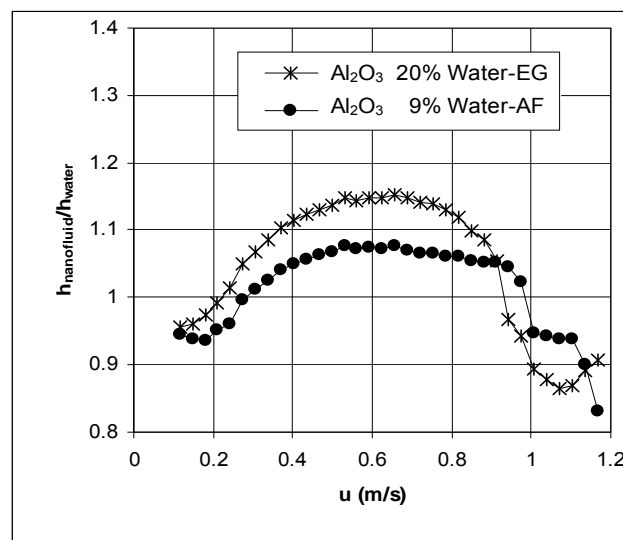

Figure 5: ratio of the heat transfer coefficient of suspensions of nanoparticles in water-glycol mixtures (AF = Antifrogen N; EG = Ethylene glycol) with respect to the clear mixtures as a function of fluid velocity.

4. Discussion

The experimental results show evidence of the importance of the hydrodynamic parameter adopted as a basis for comparing the performances of the nanofluids with the corresponding clear thermal fluid. At the same Reynolds number, the heat transfer coefficients obtained using nanofluids are higher (and in some cases, remarkably higher) than those of the corresponding clear fluids, but, due to the much higher viscosity of the nanofluids, in order to achieve the same Reynolds number, the velocity of the solid suspensions should also be higher. This, obviously, implies higher friction losses, which means higher pumping energy (and possibly higher erosion). These non-negligible inconveniences may make the use of the nanofluids less attractive.

However, when the comparison is carried out based on the same fluid velocity, the behaviour of the nanofluids is quite different, depending on the value of the velocity and the characteristics of the thermal fluid and of the nanoparticle suspensions.

Generally speaking, the heat transfer coefficients of the nanofluids fluctuate around the value of that of the clear thermal fluid, varying in the range + 15 %/-55 %, for the tested suspensions.

The highest (negative) deviations have been obtained using concentrated SiC nanoparticles, while TiO_2 and Al_2O_3 present lower positive/negative deviations, with values ± 15 % of those of the clear heat transfer fluid. At a first glance, from Figure 4a, it seems that SiC provided the largest increase in the heat transfer coefficient of the nanofluids. This could be ascribed to the higher thermal conductivity of SiC (about 120 W/mK), with respect to that of TiO_2 (about 11 W/mK, i.e. one order of magnitude less), and this result would be in agreement with the often accepted opinion that the higher thermal conductivity of the added particles is the main responsible of the claimed enhanced heat transfer capability of the nanofluids. However, when the comparison is carried out at equal flow rate (Figure 4b), it turns out that SiC-based suspensions are characterized by the largest reduction in the heat transfer coefficient. This is most likely due to the large difference in the viscosities of the suspensions: only at the lowest concentration (and correspondingly at the lowest suspension viscosity), the behaviour of the SiC-based nanofluid becomes similar (actually slightly better) to that of TiO_2, indicating that the influence of viscosity more than balance that of the thermal conductivity.

As a matter of fact, for all the investigated nanofluids, by increasing the concentration of the particles, the amplitude of the oscillations increases, too, while, increasing the viscosity of the clear thermal fluids, the trends become smoother.

At present, no reliable prediction of the expected heat transfer capabilities of a nanofluid with respect to the corresponding clear fluid seems possible, and further work would be needed to assess their thermal behaviour. Nevertheless, it can be stated that their use will not lead to a generalized increase of the heat transfer coefficient, which may be achieved only under carefully selected operating conditions.

5. Conclusions

The thermal behaviour of nanofluids, with respect to the corresponding clear thermal fluids, is complex, and different conclusions can be drawn depending on the hydrodynamic parameters used for the comparisons. At the same Reynolds number, the use of nanofluids gives rise to heat transfer coefficients invariably higher than those of the clear thermal fluids, with an increase up to 60 %, in the tested conditions. On the contrary, operating at the same fluid velocity (which is a more practical assumption for the applications), the addition of nanoparticles to a thermal fluid may result in higher, as well as lower, heat transfer coefficient values depending on the characteristics of the nanoparticles, their concentration in the thermal fluid, the viscosity of the latter, and the assumed fluid velocity. In this case, the maximum increase of the heat transfer coefficient hardly reaches 20 % of the value of that of the clear fluid, while a decrease of 55 % may be possible.

Therefore, based on the present results, the use of nanofluids may be beneficial in some applications, but should be carefully considered, based on the requested operating conditions.

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