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EXPERIMENTAL STUDY OF THERMO-HYDRAULIC PERFORMANCE OF SWCNT NANOFLUIDS IN SINGLE-PHASE FLOW

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Abstract. *The present work deals on experimental study of thermal-hydraulic performance of single walled carbon nanotubes nanofluids dispersed in distilled water. The tests were performed in single-phase flow, fully developed turbulent regime, inside smooth and horizontal tubes with uniform heat flux applied on the surface. An experimental bench was modified to guarantee the nominal conditions imposed for the tests. The mass flow rate varied between 30 and 80 kg/s, related to Reynolds numbers between 4000 and 22000. The heat flux varied from 14 up to 22 kW/m2 and the inlet temperature was maintained constant in 25, 30 and 35°C. The physical properties of nanofluids such as thermal conductivity and viscosity were measured experimentally and its values used to evaluate the heat transfer coefficient. Pressure drop, friction factor and pumping power were also analyze. Effects such as nanoparticle shape, defined by the aspect ratio, and mass concentration of nanoparticles were evaluate as well. The heat transfer coefficient of SWCNT/water nanofluids increased, in average, 11.3%, in function of Reynolds number. In relation to the mass velocity, the heat transfer coefficient decreased 6.9%, in average, in comparison with the base fluid. Finally, the experimental results for pressure drop of nanofluids were, in average, 7.3%, greater than the base fluid.*

Keywords: *Nanofluids, Single-walled carbon nanotube, Convective Heat transfer, Pressure drop, Performance evaluation*

1. INTRODUCTION

One of the main challenges in the development of more efficient heat exchange systems with reduced dimensions, constructive and operating lower cost is the limited thermal performance of conventional coolants. For this reason, research groups have focused their work on the intensification of heat transfer in thermal processes through the development of fluids that enhance heat transfer without penalizing very much the consumption of energy by pumping.

The advent of nanotechnology became possible the synthesis of solid particles in nano scale, leading to an immediate potential application that consist in dispersing nanoparticles in conventional cooling fluids. In the last two decades, the dispersion of nanoparticles in the base fluid is denominated "nanofluids" being considered as a new generation of fluid with greater heat transfer potential than to the conventional heat transfer fluids. Due to the potential advantages using nanofluids, many researchers have studied the performance of heat transfer and flow characteristics of various nanofluids, produced with nanoparticles of different materials and different base fluids. For example, Ding *et al.* (2006) in their research have shown nanofluids of MWCNT/Water, containing 0.5% mass concentration of carbon nanotubes particles (CNT), reached a maximum enhancement of the local heat transfer coefficient of 350% in laminar flow for Re=800.

Garg *et al.* (2009) analyzed MWCNT/water nanofluid with 1% of mass concentration in laminar regime and found an enhancement of 32% in the heat transfer coefficient over to that of the base fluid for a Reynolds number of 600. Amrollahi *et al.* (2010) conducted experiments using functionalized nanofluids of MWCNT/water whose mass concentration of nanoparticles used was 0.25%. The authors observed an increase of 33% to 40% on the heat transfer coefficient compared to that of the base fluid for laminar flow regime. Now, the increases on the heat transfer coefficient for turbulent flow, at the same Reynolds number, were of 5% to 25%. Kumaresan *et al.* (2013) have shown an intensification of 150% and 92% on the local heat transfer coefficient, x/Di = 93.46, for MWCNT/EG-water (70:30) nanofluids, whose volumetric concentrations of nanoparticles were 0.45% and 0.15%. Sundar *et al.* (2014) evaluated experimentally the performance of heat transfer of hybrid MWCNT-Fe_3O_4/water nanofluids with 0.3% volume nanoparticles concentration in turbulent flow. Their results indicated an increases of 31.1% in the Nusselt number and an augmentation in the pumping power of 18% at Re=22,000.

On the other hand, Yu *et al.* (2009) performed experiments with nanofluids of silicon carbide (SiC) based on distillated water, with a volume concentration of 3.5%. At the same velocity flow, the heat transfer coefficient of the nanofluid was 7% lower than that of the base fluid. At the same pumping power, the heat transfer coefficient of the nanofluid reduced 20% in comparison with that of the base fluid.

Recently, Meyer *et al.* (2013) evaluated experimentally the heat transfer coefficient for MWCNT/water nanofluids. The autors presented an analysis of the heat transfer performance of nanofluids, which used the Reynolds number, flow velocity, and pumping power as criteria for comparison, and the results suggest that the last factor is the most relevant criterion. In this direction Cardenas *et al.* (2015), evaluated experimentally the performance of Thermo-hydraulic of nanofluids of multi-walled carbon nanotube (MWCNT) based in water distillated with a volume concentration of 0.24% and aspect ratio of r=2400. This sample showed promising performance, with an increase in the heat transfer coefficient greater than 15% and an increase in pumping power of less than 10%, related to the base fluid.

The studies found in the literature about the thermal and hydraulic performance are controversial, being not possible a consensus of research groups around the world. In order to contribute with the research about nanofluids and reducing the controversies, this study aims to evaluate the thermal and hydraulic performance of nanofluids of Single-Walled Carbon Nanotubes based on distilled water (SWCNT/water) to determine their applicability in processes involving heat transfer and single-phase flow inside the circular horizontal tubes.

2. PROCEDURES AND EXPERIMENTAL SET-UP

2.1 Preparation of the nanofluids

In this work, the two-step method is used in the synthesizing of SWCNT nanofluids based on distilled water. In this method, an external energy is applied to obtain a homogenized dispersion through high-pressure. All samples were produced by a well-established routine, previously defined, in which, the samples called SNC01, SNC02, SNC03, were the result of the process of dilution and mixing of a functionalized solution (SWCNT/water) provided by Nanostructures & Amorphous Materials Inc., whose weight concentration was 6wt%.

The geometric characteristics of the nanoparticles used in the study: Length, l_{np} = 5-30 [µm] and Diameter, dnp = 1-2 [nm]; and the thermo-physical properties: density, ρ_{np} = 2.1 [g / cm3], and the specific heat, cp_{np} = 0.71 [kJ/ (kg ℃)], were also provided by the manufacturer. In Tab. 1 are specified the materials information, quantities used in preparing the samples as well as the mass and volumetric concentration of the nanofluids samples and the final volume of nanofluid produced for each sample

Table 1. Materials and quantities employed in the synthesis nanofluids.

SAMPLES	Nanopartícles SWCNT (Sol. 6wt%)	Base Fluid H_2O	*Φ* [%]	*Wt* [%]	Final Volume
SCN01	36,39 ml	3163,80 ml	0,032	0,0672	3200 ml
SCN02	59,31 ml	3025,74 ml	0,052	0,1092	3200 ml
SCN03	242,60 ml	2958,22 ml	0,205	0,4305	3200 ml

2.2 Density and specific heat of the nanofluid (SWCNT/water)

The density of the dispersions, ρ_{nf}, can be estimated using the known values of the volumetric concentration of the nanoparticles, (ϕ), the nanoparticle density, ρ_{np}, (provided by the manufacturer) and the density of the base fluid, through the Eq. (1).

$$\rho_{nf} = (1-\phi)\rho_{fb} + \phi\rho_{np} \quad (1)$$

Pak and Cho (1998) measured the density of nanofluids of dioxide of titanium and alumina based on water with volumetric concentration up to 31.6%. They found a maximum deviation of 0.6% in comparison with the results obtained by the mixture law, proving that this equation is applicable to estimate density of nanofluids.

The specific heat of the dispersions obtained was by the first law of thermodynamic, considering the thermal equilibrium between the particles and the surrounding fluid. Thus, the Eq. (2) is used to calculate the specific heat of the nanofluids, cp_{nf}, where: ϕ, is the volumetric concentration, $(\rho\cdot cp)_{fb}$ and $(\rho\cdot cp)_{np}$ are, respectively, the thermal capacities of the base fluid and the nanoparticle. The properties of the base fluid were acquired through the database of EES software. The manufacturer provided the density and the specific heat of the nanoparticles.

$$C_{p_{nf}} = \frac{(1-\phi)\rho_{fb}C_{p,fb} + \phi\rho_{np}C_{p,np}}{(1-\phi)\rho_{fb} + \phi\rho_{np}} \quad (2)$$

2.3 Thermal conductivity of the nanofluids (SWCNT/water)

The thermal conductivity of samples of nanofluids SWNTC/water was measured by the transient hot wire method (THW), also known as a linear probe. Hukseflux the TP-08 probe, installed in cooling laboratory EESC-USP, was used. This equipment is indicated for the evaluation of materials with thermal conductivity between 0.1 and 6 [W/mK]. The uncertainty of equipment measurement was ± 3% + 0,02W / m.K, as specified by the manufacturer.

Thermal conductivity measurements were carried out for samples of the nanofluids SWNTC/H2O in a temperature range between 20 °C and 50 °C with increments of 5 °C. The probe was previously calibrated for the water (k = 0.6W/m.K).

Fig. 1 illustrates the experimental results of the thermal conductivity of samples of nanofluids SWNTC/H2O for different temperatures at which the measurements were made. The conductivity measurement results in SNC01 sample prepared with the lowest volumetric concentration of dispersed nanotubes, 0.032%, presented the lowest thermal conductivity, with an average increase of 11% above to the thermal conductivity of the base fluid (distilled water), demonstrating the effect of concentration on increasing the thermal conductivity of nanofluids. The SCN02 and SCN03 samples with a volumetric concentration of 0.052% and 0.205%, respectively, the conductivity showed different increments, 24% for SCN02 and 29% for SCN03.

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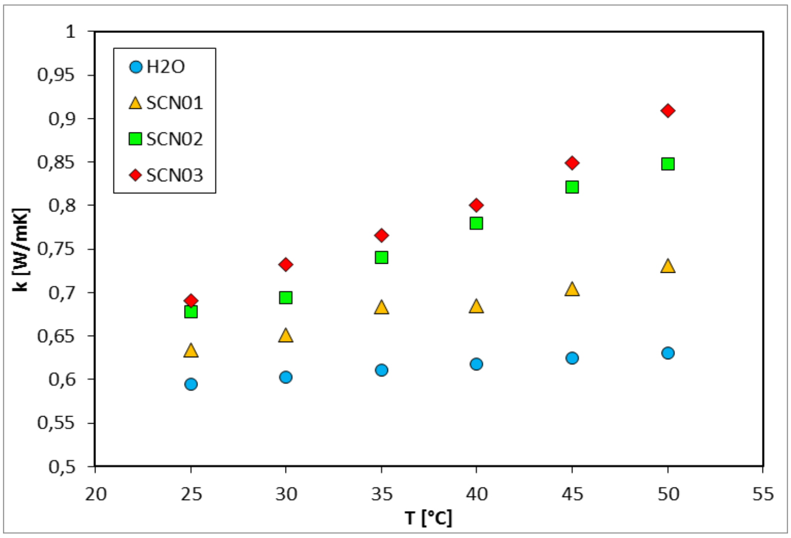

Figure 1. Experimental results of thermal conductivity of distilled water and 3 SWCNT nanofluids according to the temperature.

It is worth mentioning the aspect ratio (l_{np}/d_{np}) is approximately 11666 for all samples, so the fact that nanofluid has achieved a high thermal conductivity, even at low volumetric concentrations might be explained by the fact that nanoparticles that have lower diameter have a larger specific area. This favors the Brownian movement, which is considered an important factor in increasing the thermal conductivity of nanofluid, Xuan *et al.* (2003). Moreover, a larger specific area means that more liquid molecules near the surface of SWCNT. These liquid molecules may form a layer structure (called by Yu *et al.* (2000) interfacial layer) that can increase the thermal conductivity of nanofluid.

2.4 Viscosity of the nanofluids (SWCNT/water)

In this paper, measurements of viscosity of the samples of MWCNT/H_2O nanofluids were performed using a rheometer Brookfield LDDV-IIIU, type cone-plate with a measurement uncertainty of ± 1% of full scale of the equipment, which is 3 [cP], and 1% of measured value. Due to the fact that apparently the viscosity of the samples was very close to the viscosity of water, the rheometer was calibrated with distilled water (μH2O = 0.89 [cP]) and the conic element used in the measurements was the spindle CPE-41, requiring a 1 ml sample. In Fig. 2 are shown the experimental results for the viscosity of different samples nanofluids of SWCNT/water depending on the temperatures at which the measurements were made.

Five measurement tests were performed for each value of the temperature of the range. As all three samples, SCN01, SCN02 and SCN03, were produced from the process of dilution and mixing of a functionalized solution (SWCNT / water) at concentration of 6 mass%, it was expected that the sample with lower volume concentration of nanoparticle (SCN01), presented the lowest effective viscosity, that was of 2.2%. The SCN02 samples, whose volume concentration is 0.052%, showed an increase of 11.8% and finally the sample SCN03, with a volumetric concentration of 0.21%, showed an increase in effective viscosity of 63.4% over the base fluid.

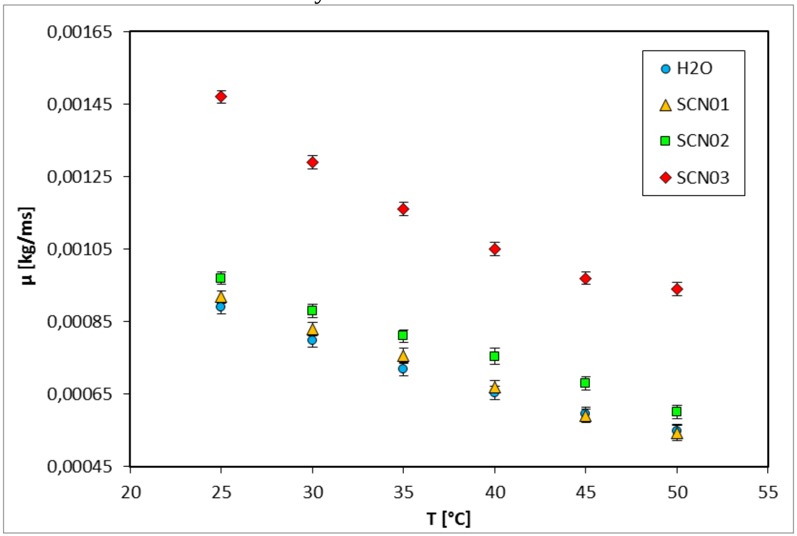

Figure 2. Experimental values of viscosity of distiled water and 3 SWCNT nanofluids with respect to temperature.

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2.5 Experimental facility

An experimental bench was designed and built to achieve the fluid dynamic and thermal conditions necessary, due the assumptions made. Therefore, Fig. 3 presents a picture of the experimental setup developed in the laboratory LEST-nano, in the Federal University of Uberlândia-UFU.

Figure 3. Experimental facility for study of thermo-hydraulic performance of SWCNT nanofluids.

The test section, through which circulates the nanofluid by the action of a magnetic gear pump, is constituted by a circular brass tube with smooth inside, length 2460 mm, outside diameter 12.7 mm and wall thickness of 3.175mm . The wall temperature was acquire by 24 T-type thermocouple, fixed on the tube at different positions. The temperature and pressure conditions in the inlet and outlet are measured by RTD sensors, PT100 model and piezo resistive, respectively. A Coriolis sensor made the measurement of mass flow. The sensor has been installed in the main flow line, after the display section and prior to the preheater inlet. For the constant heat flux boundary condition in the test section, heat was supplied through an electrical resistance type flexible tape 1500 W, whose power is supplied by a DC electrical source. The thermal insulation of the test section was performed with a rock wool layer of 25 mm thickness. To prevent heat escape by axial driving, the tube was supported tecnil nylon bushings, and then the whole assembly was covered with an insulating batt of synthetic rubber elastomeric foam with a thickness of 20 mm.

3. DATA REDUCTION AND RESULTS

3.1 Heat transfer results

The three samples of nanofluids shown in Tab. 1 were tested for the Reynolds number ranges from 3500 to 22000. The nominal conditions were maintained, that is, with inlet temperature of 25, 30 and 35 ° C, heat flux supplied to the test section 14, 18 and 22 kW/m^2 and the mass flow, which varied from 30 to 80 g/s with increments of 10 g/s. All results were compared with distilled water as a function of the mass velocity and the Reynolds number.

The results for the heat transfer coefficient, h_{exp} [kW/m^2°C], of the sample SCN01 and distilled water as a function the variation of mass velocity, G [kg/sm^2] is illustrated in Fig. 4a. Also the experimental results for the heat transfer coefficient by convection as a function of Reynolds number Re is shows in Fig. 7b.

It was noticed in Fig. 4a that the sample (SCN01) of nanofluid (SWCNT/H_2O), with 0.032% volume concentration showed that the heat transfer coefficient is lower with an average of 3.6% compared to the one obtained from the base fluid for the same nominal test conditions. As observed also in Fig. 4b, there was a slight reduction of 0.15% for the heat transfer coefficient as a function of Reynolds number, Re, compared to distilled water. This behavior is related to the fact that the effects of the surfactant were not considered in the case of base fluid because the fluid was considered as being only distilled water. Importantly, the thermal conductivity and viscosity of the sample SCN01 obtained experimentally had an average of 11% and 2.2% higher than that of the base fluid respectively.

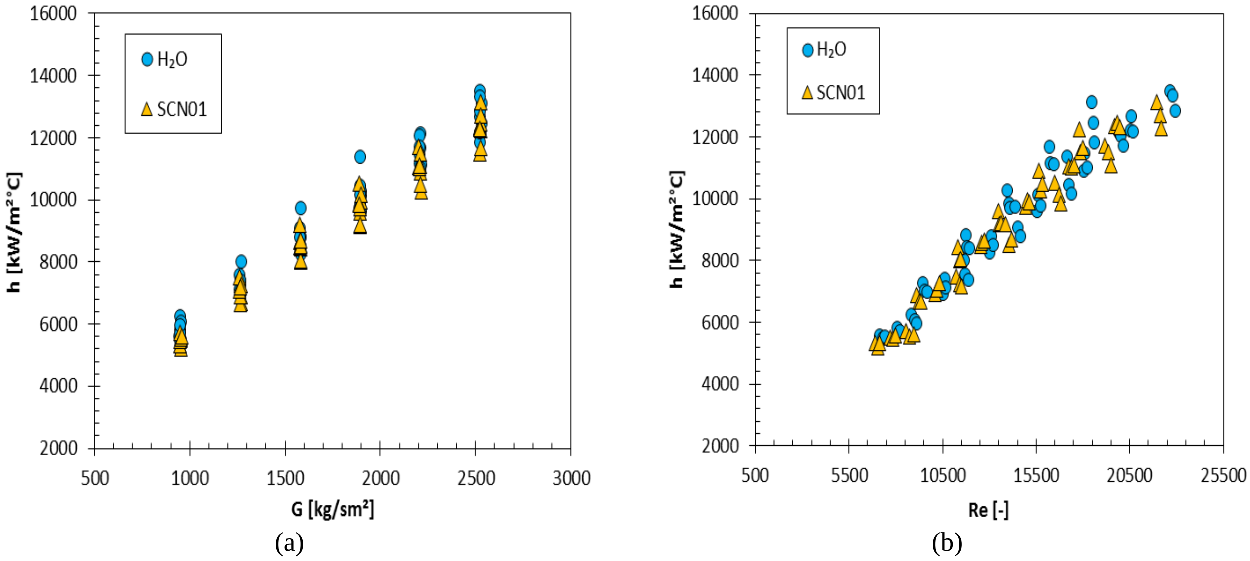
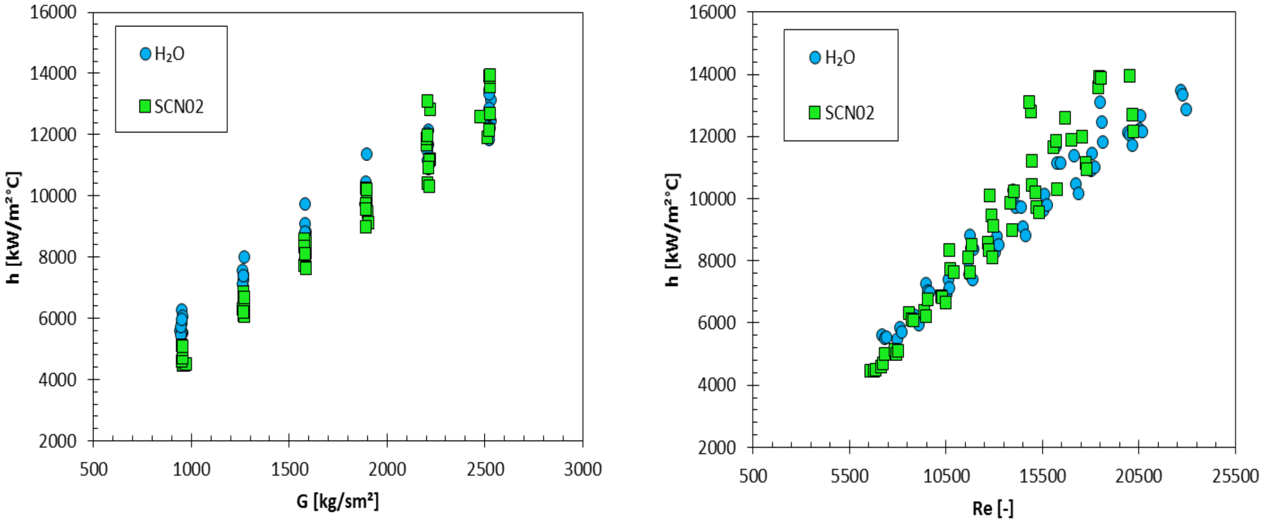


Figure 4. Comparison of the heat transfer coefficient obtained for distilled water and nanofluid SCN01, (ϕ=0,032% and r=11666) against mass velocity (a) and Reynolds number (b).

Fig. 5 shows the experimental results of the heat transfer coefficient of distilled water and the sample SCN02 of nanofluid. Therefore, the graph of the coefficient of heat transfer h_{exp}, as function of mass velocity and the parameter h_{exp} - Reynolds number graph were plotted as shown in fig 5a e Fig 5b respectively.

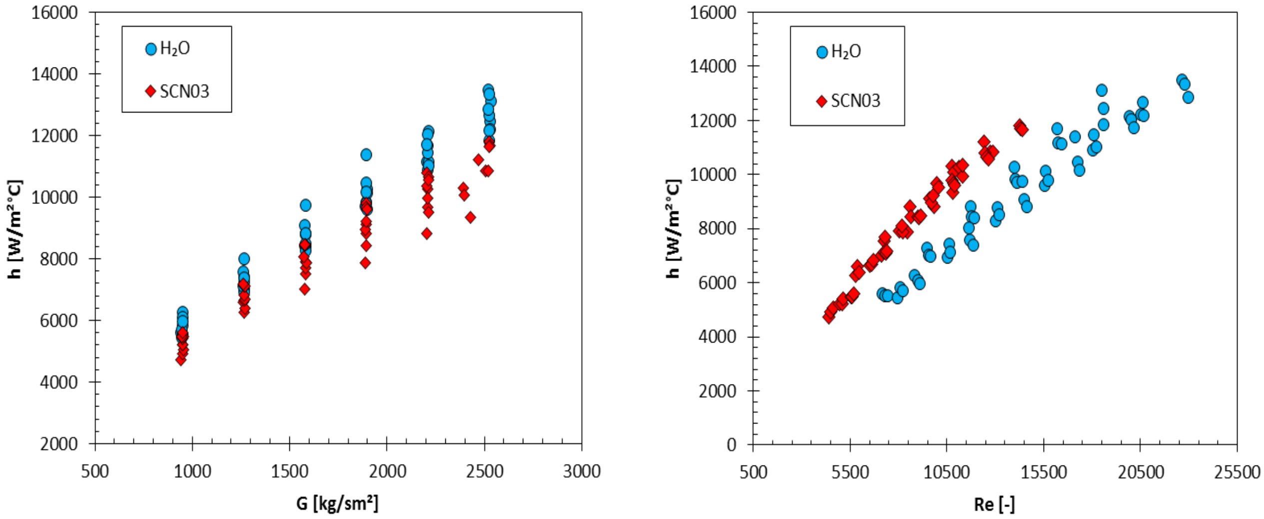
It is important to note that the in Fig 5a the sample SCN02 of nanofluid with 0.052% volume concentration indicated an average of 6% heat transfer coefficient less than the one obtained in the case of base fluid. Moreover, the heat transfer coefficient of nanofluid is than the base fluid for mass flow of 70 and 80 g/s for the same nominal conditions of test. As shown in Fig. 5b, there was a slight increase of 1.5% for the heat transfer coefficient as a function of Reynolds number, Re, compared with distilled water.

Alike as for the first two samples, the experimental results for heat transfer coefficient nanofluid of the sample (SCN03) with 0.205% volume concentration, were compared with that of the base fluid (distillate water) on the same nominal conditions. Therefore, Fig. 6a illustrates the comparison of the heat transfer coefficient of the sample (SCN03) and distilled water as a function of the mass velocity (G) indicated an average of 10,5% heat transfer coefficient less than the one obtained in the case of base fluid. Fig. 6b there was an increase of 34.6% for the heat transfer coefficient as a function of Reynolds number, Re, compared with distilled water. However, it is important to note that for the same mass velocity, the Reynolds number (Re) of the nanofluid it is less than of the distillate water. This can be explained because the Reynolds number is inversely proportional to viscosity increase, which for the sample (SNC03) was 63.4% higher than the base fluid.



(a) (b)

Figure 5. Comparison of the heat transfer coefficient obtained for distilled water and nanofluid SCN02, (ϕ=0,052% and r=11666) against mass velocity (a) and Reynolds number (b).



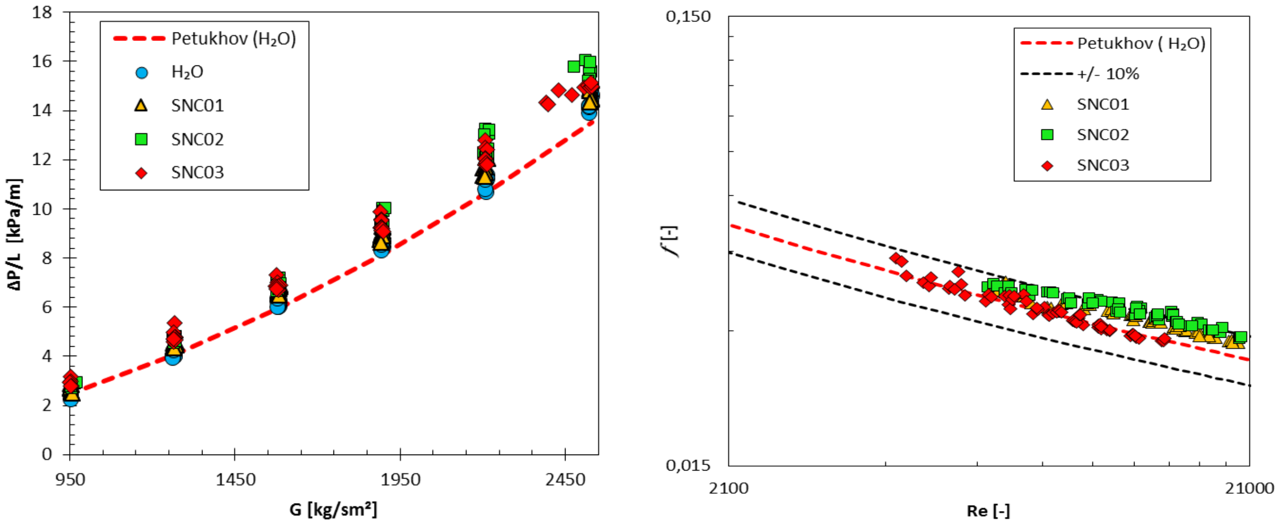
(a) (b)

Figure 6. Comparison of the heat transfer coefficient obtained for distilled water and nanofluid SCN03, (ϕ=0,205% and r=11666) against mass velocity (a) and Reynolds number (b).

3.2 Pressure Drop and Friction Factor

The experimental results from all tests for the pressure drop of fluid flow between the inlet and the outlet of the test section are shown in Fig. 7a as a function of the mass rate, G [kg/sm^2], being one of the parameters that most affects the pressure drop. All prepared samples of nanofluid (SCN01, SCN02 and SCN03) showed pressure drop values above base fluid (distilled water). The sample SCN01 with a volume concentration of 0.032% had an average of 7.5% pressure drop higher than the source fluid. The increase in pressure drop for the sample SCN02, with a volume concentration of 0.052% was 12.1%, noting that the increase in viscosity was 11.8%. The increase in pressure drop for sample SNC03 with the highest volume concentration (0.205%) had an average of 12.3%, noting that the increase in viscosity for this sample was 11.8% compared with the base fluid.

The friction factor results for the three samples were compared with the model of Petukhov. Therefore, all values obtained experimentally for the friction factor as a function of the Reynolds number for the nanofluids SWCNT / water in single-phase flow and turbulent regime were demonstrated in Fig. 7b. Importantly, thermal and hydraulic tests were carried out simultaneously and experimental results displayed a good similarity with the values obtained from Petukhov equation, with an average deviation less than ± 11%.



(a) (b)

Figura 7. Test section pressure gradient versus mass velocity for all samples (a) Experimental results of the Darcy's friction factor, f_{exp} versus Reynolds number (b).

3.3 Thermal-hydraulic performance

The evaluation of the thermal hydraulic performance of the three tested samples of nanofluids was performed by specifying the relative heat transfer coefficient as a function of the relative pump power following the method proposed by Cardenas *et al* (2015). The experimental values of pumping power were calculated with pressure drop values measured in the test section for each mass flow condition imposed on the tests of the evaluated nanofluids. The pumping power consumed in the test section was calculated from Eq. (3), for both all tested samples (SCN01, SCN02 and SCN03) and the base fluid, using the same nominal conditions, in other words, same flow mass, inlet temperature and heat flow imposed on the test section.

$$\dot{W}_B = \frac{\dot{m}\Delta P}{\rho} \tag{3}$$

The results obtained from the three samples (SCN01, SCN02 and SCN03) are shown in Fig. 8. Also, it was use as a validation performed parameter a comparison on heat transfer coefficient as a function of pumping power from experimental results by Meyer et al. (2013) and Cardenas et al. (2015), for MWCNT/water nanofluids only to turbulent flow region, in nominal terms outlined in Tab. 2. Therefore, it can be concluded that generally, all test samples of SWCNT / water (SCN01, SCN02 and SCN03) did not show satisfactory results of thermal-hydraulic performance by the criteria adopted.

Table 2. Nominal conditions used in the comparison.

Nanofluids	Works	Flow Regime	$r=l_{np}/d_{np}$	T_{in} S.T. [°C]	q"[kW/m]
SWCNT/water ϕ=0,032%	Present work	Turbulent	≈11666	30	18
SWCNT/water ϕ=0,052%	Present work	Turbulent	≈11666	30	18
SWCNT/water ϕ=0,205%	Present work	Turbulent	≈11666	30	18
MWCNT/water ϕ=0,12%	Cárdenas *et al.* (2015)	Turbulent	≈600	20	14
MWCNT/water ϕ=0,24%	Cárdenas *et al.* (2015)	Turbulent	≈100	20	14
MWCNT/water ϕ=0,24%	Cárdenas *et al.* (2015)	Turbulent	≈2400	20	14
MWCNT/water ϕ=0,33%	Meyer *et al.* (2013)	Turbulent	≈1333	20	13
MWCNT/water ϕ=0,75%	Meyer *et al.* (2013)	Turbulent	≈1333	20	13

In Meyer et al. (2013) work, they concluded that nanofluids MWCNT/water are not ideal for applications as coolant in turbulent flow since, adopting the criteria for evaluation of the thermo-hydraulic performance, expressed by Prasher et al. (2006), the increase in viscosity may not exceed four times the increase in conductivity assuming the Nusselt number of nanofluid equal to the Nusselt number of the base fluid and this ratio was calculated by Meyer et al. (2013) in approximately 8.5 times.

However, Cárdenas et al (2015), for the sample with 0.24% volume concentration and aspect ratio of 2400 showed increase of over 15% on heat transfer coefficient with increase lower than 10 % on pumping power. Thus the three samples (SCN01, SCN02 and SCN03), which were the main subjects of research in this study didn't show a desirable thermo-hydraulic performance, according to the proposed criteria.

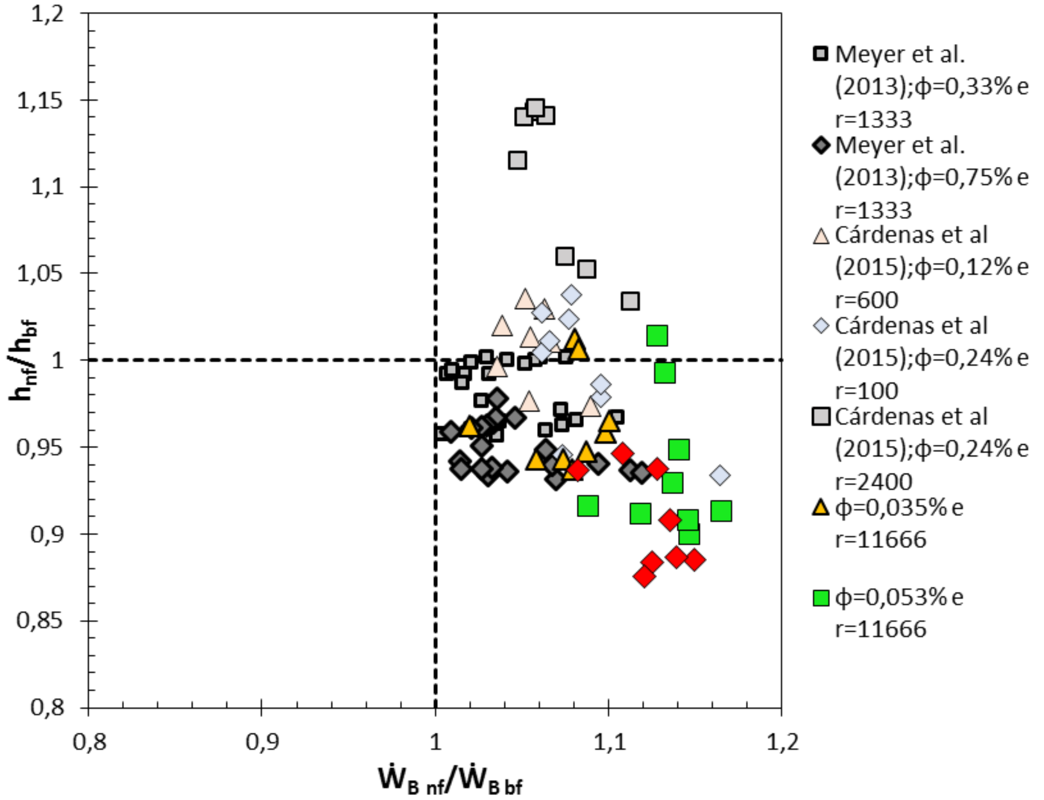


Figure 8. Comparison of the thermal hydraulic performance for all samples tested, including the experimental results from Meyer *et al.* (2013) and Cárdenas *et al.* (2015).

4. CONCLUSIONS

The experimental results obtained in the present work permitted the following conclusions:

- In general, the thermal conductivity of the nanofluids, primarily those with a higher volumetric concentration (0.205%), was greater than that of the base fluid. The sample (SCN03) presented the largest increase in the thermal conductivity, 29%, relative to the base fluid.
- The results showed that the viscosity obtained for the nanofluids was greater than that for distilled water, with the largest increase in viscosity of 63.4% obtained for the sample (SCN03).
- The NT03 showed the largest increase in the heat transfer coefficient (34.6%) when compared as a function of number Reynolds and a decrement of 10,5% as a function of the mass velocity.
- Regarding the pressure drop, the sample with the lowest concentration, SCN01, exhibited an increase of 7.5% relative to the base fluid, whereas samples SCN02 and SCN03 exhibited increases of 11.8% and 12.3%, respectively, relative to that of distilled water.
- Can be conclude that, generally, all test samples of SWCNT/water (SCN01, SCN02 and SCN03) did not show satisfactory results of thermal-hydraulic performance by the criteria adopted.

5. ACKNOWLEDGEMENTS

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