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Experimental characterization of the flow and heat transfer inside a horizontal circular tube using C60/tetralin nanofluid

Caracterização experimental do escoamento e transferência de calor no interior de um tubo horizontal e circular utilizando o nanofluido C60/tetralin

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abstract

In this paper the flow and the heat transfer of C60/tetralin nanofluid is investigated in a horizontal, circular, smooth, mini-tube with 3.5 mm of inner diameter, under an imposed constant heat flux, for laminar, transition and turbulent flow regimes. Three mass concentrations of nanofluid (0.10%, 0.30% and 0.66 mass%) as well as pure tetralin were experimentally tested at different mass flow rates and at three different inlet temperatures (25ºC, 35ºC and 45ºC). Experimental measurements were taken, allowing to determine friction factors and convective heat transfer coefficients. The results revealed that the pressure drop raises with the increase in mass concentration of the nanoparticles and with temperature. It was also found that, in the laminar flow regime the Nusselt number is not affected by the addition of the nanoparticles. However, in the turbulent region, the Nusselt number increases with the increase in mass concentration of the nanoparticles, being this augmentation more pronounced as the temperature increases. The results also revealed that the addition of C60 nanoparticles allows to decrease the critical Reynolds number for the start of transition from laminar to turbulent.

Keywords: Nanofluid / Nanoparticles concentration / Friction factor / Convective heat transfer coefficient.

resumo

Neste artigo foi estudado o comportamento hidrodinâmico e a transferência de calor do nanofluido C60/tetralin dentro de um tubo horizontal e circular, com 3.5 mm de diâmetro interno, com um fluxo de calor imposto na superfície, em regime laminar, transição e turbulento. Foram experimentalmente testadas três concentrações diferentes do nanofluido (0.10%, 0.30% e 0.66% em massa) e tetralin puro, a diferentes caudais mássicos e a temperaturas de entrada diferentes (25ºC, 35ºC e 45ºC). Os resultados experimentais revelaram que a perda de carga aumenta com o aumento da concentração de nanopartículas e com a temperatura. Foi também observado que em regime laminar o número de Nusselt não é afetado pela adição de nanopartículas. No entanto, em regime turbulento, o número de Nusselt aumenta com o aumento da fração mássica de nanopartículas, sendo que este aumento se revelou mais pronunciado com o aumento da temperatura. Os resultados revelaram também que a adição de nanopartículas de C60 permite reduzir o número de Reynolds critico para o início da transição de laminar para turbulento.

Palavras-chave: Nanofluidos, Concentração de Nanopartículas, Fator de atrito, Coefᵉ de transferência de calor por convecção.

1. INTRODUCTION

It is well known that one of the main limitations in the development of energy-efficient heat transfer medium is the low thermal conductivity of the conventional fluids, such as water or oil, Li et al. (2009). To overcome this issue, several authors suggest the use of nanofluids, i.e. colloidal mixtures of nano-sized particles in a base fluid. This new type of fluid has heat transfer characteristics superior to both base fluid and suspend particles. It offers a compact, green approach when high thermal loads are in demand, having many potential applications from an engineering point of view, Sajid and Ali (2019). An increase in liquid thermal conductivity, heat capacity and heat transfer coefficients are currently reported in the literature when using nanofluids. However, an increase in nanoparticles concentration is also known to often increase the viscosity of the bulk solution, which results in increased pressure losses, Saidur et al. (2011).

In the present study the nanofluid used is a mixture of fullerene particles, C60, and tetralin. Fullerene is an allotrope of Carbon, one of the many forms that carbon-based materials can assume. It is a substance produced naturally, in small quantities, that was discovered in 1985, Kroto et al. (1985), being the Buckminsterfullerene (C60) the most common form to find. Its unique cage structure allows an interesting interaction with solvents, having the capability of dissolving in common organic solvents.

Tetralin, (1,2,3,4-Tetrahydronaphthalene) is a hydrocarbon. It is composed entirely by carbon and hydrogen, having the chemical formula of C10H12. It is a colourless liquid, with a strong mouldy smell. Tetralin has been widely used in liquefaction of coal and biomass and as coolant in nuclear power plants. C60 particles have a very good solubility in tetralin, which further improve as the fluid temperature increases, as explained in Kozlov et al. (2007). Fullerene particles are very easy to mix with tetralin, forming a stable mixture. Since the stability of the nanofluid is one of the most difficult obstacles to overcome when preparing a nanofluid, as aforementioned, and given its high potential to be used in heat transfer applications, at reduced costs, tetralin based nanofluids using fullerene nanoparticles are the nanofluids considered in the present work.

In the past few years, many studies have been carried out to investigate nanofluids. Many of them focus on nanofluid development, preparation techniques and characterization, others in heat transfer enhancement, convection, applications and challenges, Li et al. (2009), Saidur et al. (2011), Sarkar (2011) and Ambreen and Kim (2018).

The addition of nanoparticles changes the thermophysical properties of the base fluid, allowing to artificially tune them for a specific application. The most important properties to tune are thermal conductivity, viscosity, density, and specific heat.

Since thermal conductivity of the particles is higher than that of the base fluid, an enhancement of the thermal conductivity of the nanofluid is expected to occur. This enhancement depends on some factors related with particle motion, such as the dispersion of the particles, thermophoresis, diffusiophoresis. Other factors influencing the thermophysical properties of the nanofluid, mostly thermal conductivity and viscosity, are the volume concentration, the shape of the particles, the size of the particles, temperature, and pH, Azmi et al. (2016) and Sezer et al. (2019).

Several studies have been published for experimental heat transfer characteristics of various types of nanofluids. Pak and Cho (1998) investigated the forced convection in smooth, horizontal tubes with a constant heat flux applied. The authors studied the turbulent friction and heat transfer of Al_2O_3/water and TiO_2/water nanofluid. Their results showed that heat transfer increased with increasing volume concentration: for 1.34% volume of Al_2O_3 particles the enhancement was 45% and 75% at a concentration of 2.78%.

Li and Xuan (2002 and 2003) studied the laminar and turbulent convective heat transfer and friction factor of Cu/water nanofluid. The suspended particles enhance the heat transfer process, increasing the heat transfer coefficient about 60% for 2.0% volume concentration of Cu nanoparticles.

The literature review introduced in the previous paragraphs provide the context for the investigation of the effects of adding nanoparticles on the convective heat transfer in a horizontal, circular, smooth tube with constant heat flux condition. Most of the published data show a thermal conductivity and a heat transfer coefficient enhancement with increased particle concentration, being the heat transfer coefficient enhancement more pronounced for flows with high Reynolds number. However, different results of this coefficient were reported depending on the analysis method. On the other hand, a penalty in pumping power for using the nanofluids is also reported, due to the increase of the friction factor.

2. MATERIALS AND METHODS

2.1. Experimental setup description

The experimental setup used in this study is represented in Figure 1. The description of the experimental setup used for hydrodynamics and heat transfer experiments and its validation was reported in detail in Andrade et al. (2019).

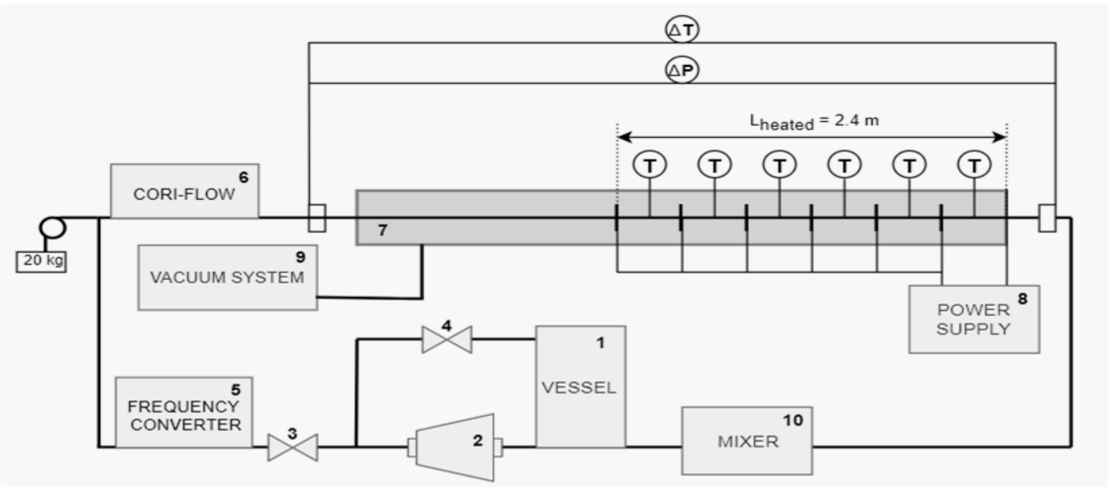

Fig. 1 | Experimental setup.

The working fluid is introduced in the vessel (1) and is pumped by a magnetically coupled vane pump (2) through the closed loop. The pump is connected to a frequency converter (5) that allows to regulate the flow rate of the working fluid. The flow rate can also be regulated by a bypass valve (4). Once the valve is open it forces the fluid to recirculate to the vessel, reducing the flow in the installation. After the pump, the fluid enters a Coriolis mass flow meter (mini CORI-FLOW M15 Bronkhorst) (6) where the mass flow rate, the inlet temperature, and the density of the fluid are measured. The Coriolis mass flow meter working in the range from 0.2 to 300 kg/h with the accuracy of 0.2% and with a density accuracy of 5 kg/m^3. Then, the fluid flows through the test section (7), a smooth round tube with 3.5 mm in inner diameter and 0.25 mm in wall thickness. An initial 0.4 m length without heating is used for flow hydrodynamic developing. The heated section has 2.4 m and is divided into six equal parts with six type K thermocouples (T) installed on the tube wall. A high current power supply (VOLTEQ HY5050EX) (8) was used to generate and control a constant heat flux to the wall of the test section. To minimize the heat losses to the ambient, the test section is placed in a vacuum chamber (9), where a dynamic vacuum of the order of 100 Pa is created by a vacuum system. The mass flow rate was measured with a Coriolis mass flow meter (mini CORI-FLOW M15) working in the range from 0.2 to 300 kg/h with the accuracy of 0.2% and with a density accuracy of 5 kg/m^3. Platinum resistance thermometer installed in the flow meter was used to measure the inlet temperature and a cooling system was used to maintain a desired inlet temperature in a range of 1 K. Also, a differential thermocouple and a differential pressure transducer (Omega PX2300) were used to measure the variation of temperature and pressure along the test section. All measurements were performed with a data acquisition system (RIGOL M300) in a steady state mode. For the experimental procedure description and data processing we refer readers to Andrade et al (2019).

The experimental process consisted in testing four fluids at three different inlet temperatures. The fluids tested were pure tetralin and C60/tetralin nanofluid with 0.10%, 0.30% and 0.66 mass% of nanoparticles. The temperatures at which they were tested were 25ºC, 35ºC and 45ºC.

2.2 Preparation and characterization of the nanofluids

In this study, particles of fullerene, C60 (CAS 99685-96-8) with a purity of 98%, were dissolved in pure tetralin (1,2,3,4-Tetrahydronaphthalene, CAS 119- 64-2) to prepare the nanofluid. The mass measurements were made in an analytical balance (model ABS80-4N by Kern) with a resolution of 0.1 mg and an accuracy of 0.3 mg.

The total mass of tetralin used for the tests in the experimental setup was 1447.448 g. Figure 2 shows the pure tetralin (left) and tetralin containing 0.10356, 0.29953 and 0.65529 mass fraction of fullerene C60 in tetralin. Ultrasonication was used to break the nanoparticles cluster and form a well dispersed suspension. The power applied was fixed for the three concentrations, to the value of 35 W.

The density of the nanofluid is in general considered to be a mixed property of the density of the base fluid, and the density of the nanoparticles. The density of the working fluid was measured with the help of the Coriolis mass flow meter, with an accuracy of ± 5 kg/m^3. The dependence of the density versus temperature is linear for the solutions and pure tetralin. The values of the

Fig. 2 | Pure tetralin (left) and tetralin containing 0.10356, 0.29953 and 0.65529 mass fraction of fullerene C60 in tetralin (from the left to right).

density slightly increase with the mass fraction of C60. However, for the mass fraction of fullerene C60 in tetralin considered in this work the maximum influence of C60 on the density does not exceed 0.7%.

The dynamic viscosity of the samples was measured by implementation of the capillary rheometer theory. The results obtained show that C60/tetralin nanofluid is a Newtonian liquid, regardless of the concentration or temperature. The viscosity increases with the mass fraction of the C60 up to 0.25 mPa s (15%) and 0.4 mPa s (35%) at 25°C and 45°C, respectively.

The thermal conductivity of tetralin and C60/tetralin nanofluids was measured by the transient hot wire method. There are several techniques which can be used with this purpose, however, the transient hot wire technique is the most used due its accuracy, as it eliminates the errors caused by natural convection in the nanofluid, being very fast compared to other techniques. The results on the thermal conductivity that have been obtained spread within the range of 1% and show low influence of C60 additives on the thermal conductivity of tetralin.

The specific heat capacity used in this work was obtained by Zhelezny et al. (2019). The additives of C60 to tetralin decrease the specific heat capacity. Nonetheless, the maximum decreasing of the c_P can be estimated in 2.1% at the lowest temperature, while at the highest temperature the impact is less than 0.5%. Thus, we may conclude that C60 do not significantly affect the c_P of the tertalin.

For the mass fraction of fullerene C60 in tetralin considered in the present study, the major role of the nanoparticles addition was to alter the viscosity, which dominated over the variation of other properties such as the thermal conductivity.

3. RESULTS AND DISCUSSION

3.1. Flow conditions

To assess the flow conditions inside the tube, hydrodynamic and thermal entry lengths were calculated. The hydrodynamic entry length just depends on the tube diameter and on the Reynolds number, not being affected by the type of fluid used. It was concluded that for laminar and turbulent regions, the flow will be hydrodynamically fully developed, regardless of the concentration of the nanofluid being used.

For the thermal entry length, properties of the flow affect this value in the laminar flow regime, as the thermal entry length in this region depends on the Prandtl number. However, for all the tests carried in this study, the results are similar, so, in the laminar region the flow will be developing thermally. For the turbulent region, the flow will be fully developed thermally.

The convection type in the flow was identified based on the Richardson number method. The four fluids were evaluated at the three inlet temperatures, and, for all cases, the Richardson number is smaller than 0.1, meaning that only forced convection is present in the flow.

3.2. Pressure drop and Nusselt number

Figure 3 depicts the pressure drop as a function of Reynolds number for tetralin and for various mass fractions of tetralin/C60 solutions at T_i = 45ºC. Figure 3 reveals that pressure drop is larger for an increased concentration of the nanoparticles. It should be noted that the viscosity of tetralin/C60 solutions increases with the mass fraction of the C60. So that, when compared to pure tetralin, the viscosity of the nanofluids increases with the nanoparticles mass fraction, and this difference is more significant at larger inlet temperatures.

It was also observed that in the laminar flow regime, the friction factor does not depend on the particles concentration, being the values of the friction factor versus Reynolds number the same as for pure tetralin. The largest difference obtained between the nanofluids and tetralin was about 4% for an inlet temperature of 45ºC. The difference in the friction factor between the nanofluids and the tetralin is slightly larger in the turbulent flow, particularly as the inlet temperature and the nanoparticles concentration increases. Hence, the largest values of the friction factor were obtained for the 0.66 mass% nanofluid, at 45ºC, which was observed to be about 8.8% larger, for a Reynolds number of 3600, when compared to that of tetralin.

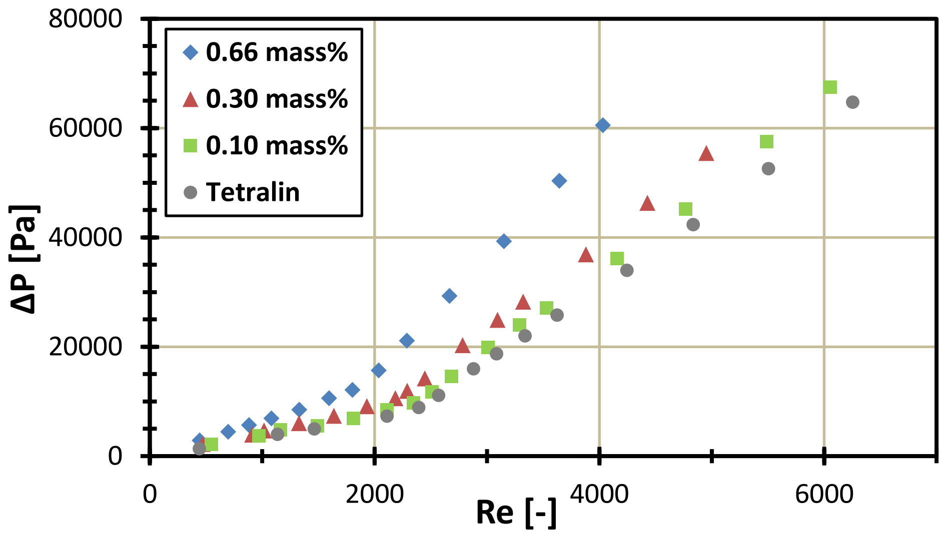

Fig. 3 | Pressure drop as a function of Reynolds number for tetralin and for various mass fractions of tetralin/C60 solutions at T_i = 45ºC.

Figure 4 depicts the Nusselt number as a function of Reynolds number for tetralin and for various mass fractions of tetralin/C60 solutions at T_i = 45ºC. The results reveal that in the laminar region the Nusselt number is not affected by the addition of the nanoparticles, having just a slight increase as the Reynolds number increases. However, in the turbulent region, the Nusselt number increases with the increase in mass concentration of the nanoparticles. The results show a raise of the Nusselt number of about 56% for 0.66 mass% nanofluid, at a Reynolds number of about 4100. It was also observed that this augmentation is more pronounced as the temperature increases.

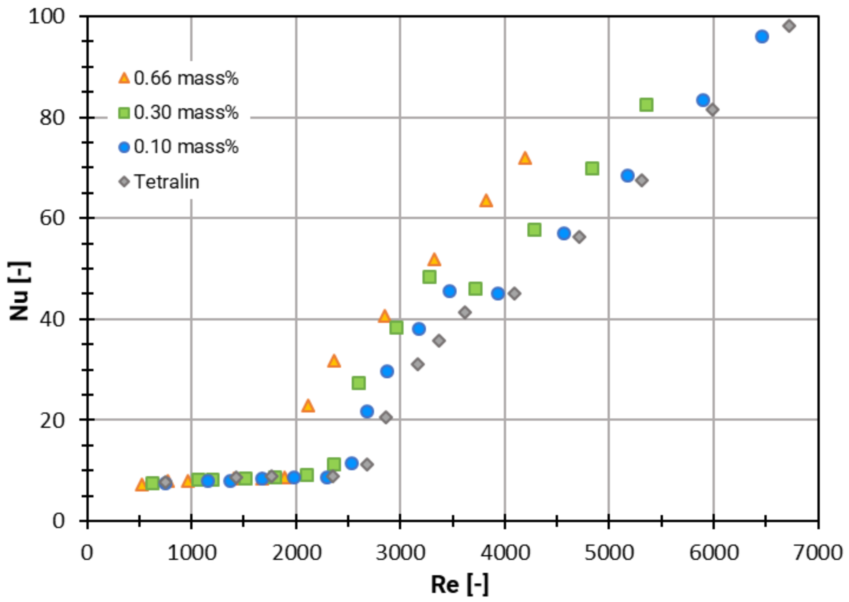

Fig. 4 | Nusselt number as a function of Reynolds number for tetralin and for various mass fractions of tetralin/C60 solutions at T_i = 45ºC

As can be seen from the Figure 3 and 4, the additives of C60 to tetralin lead to the earlier laminar-turbulent transition. Moreover, Figure 3 and 4 clearly reveals a decrease of the critical Reynolds number that indicates the start of transition from laminar to turbulent as the nanoparticles mass concentration increases. This trend was observed for all the temperatures tested. Minakov et al. (2016) also observed that with increasing concentration of nanoparticles, the transition occurred at smaller Reynolds numbers.

4. CONCLUSIONS

This work presents a study on the effects of adding fullerene nanoparticles on the heat transfer and hydrodynamic behavior on C60/tetralin nanofluid flowing inside a horizontal, circular and smooth tube with a constant heat flux applied. Particular emphasis is given to the effect of increasing the mass concentration of the particles and the inlet temperature of the working fluid.

The results revealed that pressure drop raise with mass concentration of the nanoparticles increase and with temperature increase, representing a pumping power penalty when using the nanofluids.

It was observed that in the laminar region the Nusselt number is not affected by the addition of the nanoparticles. However, in the turbulent region, the Nusselt number increases with the increase in mass concentration of the nanoparticles. For an inlet temperature of 45ºC, the results shown a raise of the Nusselt number of about 56% for 0.66 mass% nanofluid, at a Reynolds number of about 4100.

It was also observed that the addition of C60 nanoparticles allows to decrease the critical Reynolds number for the start of transition from laminar to turbulent.

It was concluded that for the mass fraction of fullerene C60 in tetralin considered in the present study, the major role of the nanoparticles addition was to alter the viscosity, which dominated over the variation of other properties such as the thermal conductivity. Overall, these effects became dominant leading to a significant increase of the Nusselt number despite of the penalty in the pumping power. So, the use of this nanofluid is recommended as a working fluid with enhanced thermal properties, although the concentration of the nanoparticles should be carefully considered due to the increase pumping power penalty.

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