



COB-2021-0629

SILVER-PVP DISPERSANT NANOFLUIDS FOR THE AUTOMOTIVE COOLING SYSTEM APPLICATION

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Abstract. An alternative proposed to intensify the thermal performance of the radiator is the use of nanofluids. This fluid class with enhanced thermal properties has shown great potential to replace the conventional fluids used, such as water (H_2O) and ethylene glycol (EG). In this work, the thermohydraulic performance of silver nanofluids using a mixture of water and ethylene glycol (50:50) as base fluid in an automotive radiator is presented. The two-step production method was used to disperse the nanoparticles at low weight concentrations, 0.01 wt%, 0.02 wt% and 0.03 wt%, in the base fluid. For further dispersion and stability of the nanoparticles in the base fluid, polyvinylpyrrolidone (PVP) surfactant was used. To evaluate stability, the UV-VIS spectrophotometry method was used relating the variation in absorbance and concentration according to Beer-Lambert's law. Thermophysical properties such as thermal conductivity, specific mass, and dynamic viscosity were also evaluated experimentally. The experimental setup consists of a wind tunnel, which simulates the airflow through the radiator, and a hot fluid circuit, which simulates the thermal load transferred from the engine to the coolant fluid. Influence on the heat transfer rate of parameters such as nanofluid concentration and inlet temperature were evaluated experimentally. The air velocity was kept constant at 2 m/s and the coolant mass flow rate was varied from 70 g/s to 90 g/s. Finally, with an increase of on average 3.5 % in the heat transfer rate, it can be concluded that the nanofluids obtained in the test conditions analyzed a thermohydraulic performance favorable for their application.

Keywords: Nanofluid, thermal conductivity, dynamic viscosity, surfactant, automotive cooling system.

1. INTRODUCTION

Nanofluid is a term established by (Choi and Eastman, 1995) to describe the dispersion of solid nanoparticles (<100 nm) of high thermal conductivity in a base fluid. Since their discovery, nanofluids have been widely studied to improve heat transfer in thermal systems. This advantage has drawn the attention of the automotive industry, seeking to design equipment with improved efficiency for the automotive cooling system.

In automobiles, the cooling system is indispensable because it keeps the engine in a temperature range suitable for its operation. Consequently, the higher the vehicle, the higher this system is. Therefore, replacing conventional heat exchange fluids with nanofluids in automobiles can improve the heat exchange capacity of the automotive cooling system and generate fuel savings of up to 10% by decreasing the radiator size. This reduction causes less aerodynamic drag and requiring less power to the radiator fan (Chougule and Sahu, 2014).

Several researchers conducted experiments using nanofluids in radiators and obtained promising results. Works such as those by (Elsaid, 2019) and (Kumar et al., 2018) showed improvements in heat transfer at near real operating conditions when nanofluids were compared to the base fluid. However, one factor that has limited the application of nanofluids in thermal systems is their stability (Chakraborty and Panigrahi, 2020). For this reason, several studies have been done to obtain stable nanofluids by using dispersing agents (Guo et al., 2017), (Hormozi et al., 2016). Due to the Brownian motion of the nanoparticles dispersed in the fluid, an interaction exists between them and the circulating fluid molecules. Although the addition of surfactant is an effective way to increase the dispersibility of nanoparticles, the non-affinity of the surfactant with the base fluid or high concentrations of surfactant can compromise the thermal performance of nanofluids (Chen et al., 2008). In their studies (Branson et al., 2013) concluded that nanoparticles should be well dispersed and stable in the base fluid, but to achieve this goal, some nanoparticle surface treatment techniques or the use of surfactants, is necessary to obtain high-quality colloidal dispersions. Recently (Ilyas et al., 2017) also found that surfactants can assist by strengthening the interactions between nanoparticles and liquid, thus improving their stability.

The present work aims to experimentally evaluate the thermal performance of Silver/PVP nanofluids in water-ethylene glycol (50:50) at weight concentrations 0.01%, 0.02% and 0.03%, operating in an automotive radiator. The mass flow rate (\dot{m}) was varied in the range of 0.080 – 0.095 kg/s and the inlet temperature from 70 to 80 °C. In addition, thermophysical properties such as thermal conductivity and dynamic viscosity were measured experimentally.

2. EXPERIMENTAL PROCEDURE

2.1 Nanofluid preparation

For the synthesis of the nanofluids, the two-step method was used. Silver nanoparticles of 20 nm diameter purchased from Nanostructured & Amorphous Materials were diluted in a mixture of water-ethylene glycol (50:50 by volume) to ensure the desired concentrations. The values for thermal conductivity, density and specific heat were provided by the manufacturer ($k = 460$ W/m-K, $\rho = 10,400$ kg/m³, $C_p = 0.240$ kJ/kg-K). The surfactant polyvinylpyrrolidone (PVP) present in the nanoparticle has a 3:1 fraction. The high-pressure homogenization process was used to break nanoparticle agglomerations and disperse them in the base fluid. In Table 1, the final concentrations obtained for each prepared sample are shown.

Table 1. Description of nanofluids samples produced

Sample	Weight concentration [wt%]
Silver_01	0.01
Silver_02	0.02
Silver_03	0.03

Additionally, the samples were under ultrasonic vibration for 60 minutes with the fluid temperature kept below 40 °C to prevent evaporation. Fig. 2(a) shows the produced nanofluid samples that were stable after 15 days of preparation. Furthermore, a scanning electron microscopy (SEM) image, Fig 2(b), reveals the clusters with nearly spherical morphology of the silver nanoparticles.

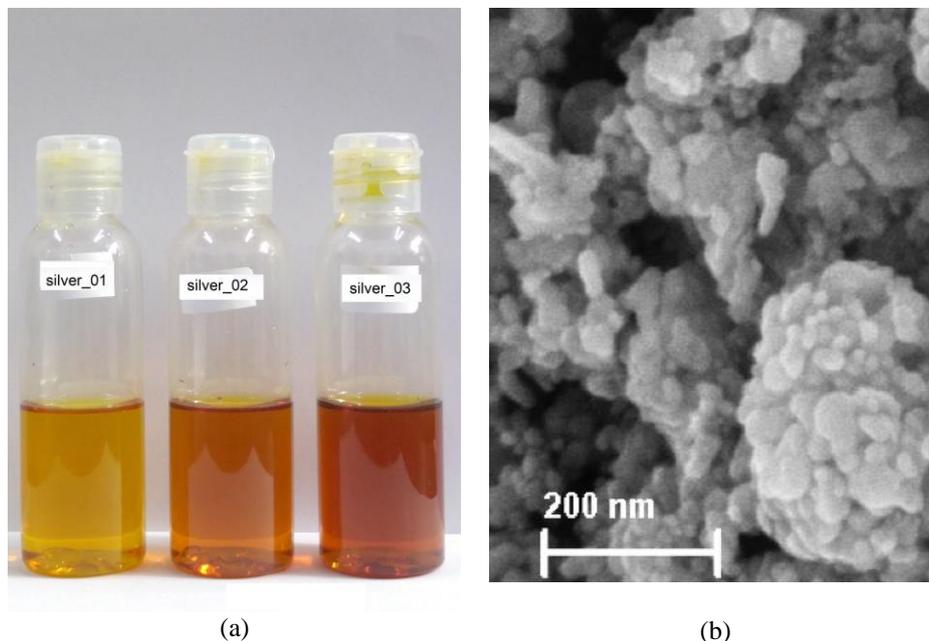


Figure. 1. (a) Silver nanofluid sample after 15 days of the preparation. (b) SEM image for silver nanoparticles

2.2 Stability

The UV-vis spectrum for the nanofluid samples prepared with different concentrations is shown in Fig. 2(a). The highest absorption peak for the nanofluids was found at the wavelengths of 248-259 nm, due to the presence of silver in the dispersion. Using the UV-vis spectrometer, photometric analysis was used to check through Beer-Lambert's law

(Swinehart, 1962) the relative concentration at different times for all nanofluids prepared for 15 days. The relative concentration of the nanofluids samples versus the number of days after preparation is shown in Fig. 4(b). From this, it can be seen that the concentrations of the samples decreased slightly, indicating the good stability of the nanoparticles in the base fluid. This was visually verified by the little sedimentation of nanoparticles.

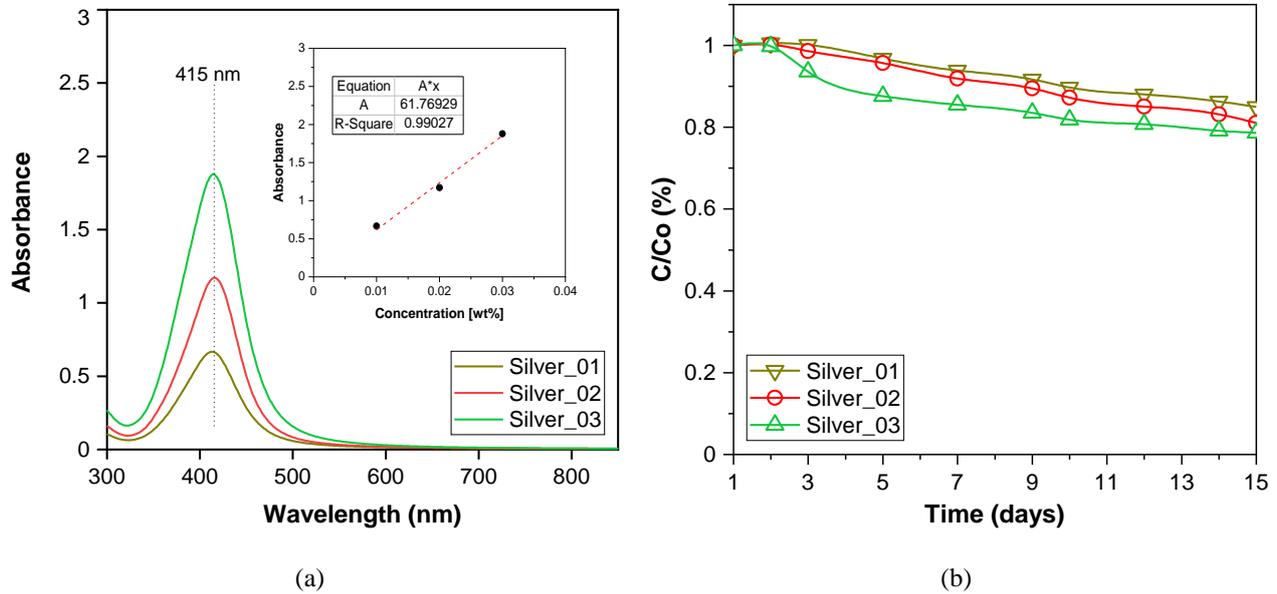


Figure 2. (a) UV-Vis absorbance spectrum for the nanofluid samples. (b) Relative concentration versus the number of days after preparation.

2.3 Thermophysical properties

The thermal conductivity of the samples was measured with the aid of the Linesis THB-1 sensor, which operates on the transient hot bridge principle. This sensor uses a planar heat source method that can be considered an evolution of the transient hot-wire. The measurement can be performed faster, indirectly and independently of the operator. No calibration or reference sample is required, and it has higher accuracy and a shorter lifetime. According to the manufacturer, the hot bridge method has a measurement uncertainty of $\pm 2\%$, and the deviation for each measurement was 2.4%. The nanofluid samples are placed in a stainless-steel chamber (volume 10 ml) connected to a thermal bath to maintain a constant temperature. The measurements were carried out over a temperature range from 25°C to 50°C.

The nanofluids viscosity was measured by the Anton Paar SVM 3000 viscometer, which is equipped with a rotor that rotates freely without friction. The determination of the viscosity is obtained by the measurement of parameters such as torque and speed. The small dynamic viscosity measuring cell contains a rotating tube with constant speed, which is filled with the sample. Another tube has an integrated magnet (rotor) that floats on the sample and rotates freely without friction. Due to the low density of the rotor, it is kept centered by centrifugal force. The small sample volume (~2.5 ml) allows for extremely rapid temperature changes (by Peltier effect) and short settling times. Dynamic viscosity and specific mass measurements were performed over a temperature range from 20°C to 80°C. More information about the equipment used in this work can be found in (Cárdenas et al., 2019).

In this study, thermal conductivity (k), and viscosity (μ), were measured experimentally. At the same time, the specific heat (C_p), and density, (ρ), were calculated from correlations found in the literature, proposed by (Xuan and Roetzel, 2000) and (Pak and Cho, 1998) as follows:

$$(C_p \rho)_{nf} = \phi (C_p \rho)_{np} + (1 - \phi) (C_p \rho)_{bf} \quad (1)$$

$$\rho_{nf} = \phi \rho_{np} + (1 - \phi) \rho_{bf} \quad (2)$$

where the subscripts bf , nf and np denote base fluid, nanofluid and nanoparticles.

2.4 Experimental facility

The experimental bench shown in Fig. 3 is adapted to evaluate the thermal performance of nanofluids in automotive radiators. The coolant circuit (red) is equipped with a thermostatic bath, which heats the fluid, simulating the thermal load transferred from the engine to the coolant. A gear pump circulates the fluid between the thermostatic bath and the radiator. The mass flow rate of the fluid is measured using a Coriolis flowmeter. In addition, temperature measurements were taken at the inlet and outlet of the radiator.

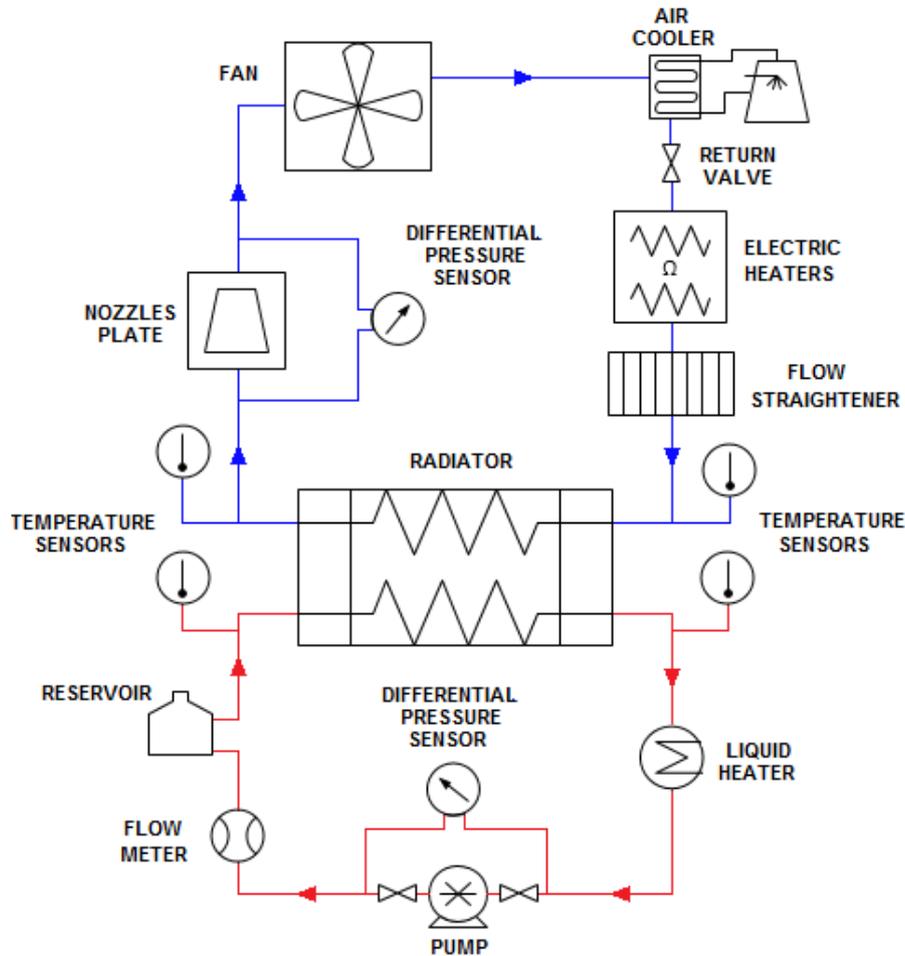


Figure 3. Schematic diagram of the experimental facility. Adapted to (Cárdenas et al., 2019)

The air circuit (blue) is composed of a wind tunnel where a centrifugal fan induces air circulation to supply a flow rate of up to 10000 m³/h. A frequency inverter allows fine adjustment of the airflow. To measure the mass flow rate, the bench has a plate of nozzles arranged following the standard (ASHRAE Standard 41.2, 1987). From the pressure differential at the nozzles and the known air properties, the mass flow rate is calculated using Eq. (3):

$$m_{air} = \sum_{i=1}^n Cd_i \cdot \frac{A_i \sqrt{2 \cdot \rho_{air} \cdot \Delta P_{air}}}{\sqrt{1 - \left(\frac{A_i}{A_t}\right)^2}} \quad (3)$$

where Cd_i is the discharge coefficient for each nozzle, A_i represents the area of the nozzle i measured at its discharge, A_t is the total area of the plenum where the nozzle plate is installed, ρ_{air} and ΔP_{air} represent the specific mass of the air and the pressure drop of the air as it passes through the nozzle.

The air temperature was measured using two grids located upstream and downstream of the radiator, obtaining an average temperature distribution in each section. The temperature in the test section is controlled with a set of electrical resistors fixed upstream of the test section. This resistor set has a rated power of 6 kW and is connected to a power

converter, which controls the power dissipated between zero and the rated power. In addition, the wet-bulb temperature was also measured to characterize possible changes in the physical properties of the air throughout the test section. Finally, a thermo-hygrometer was positioned at the entrance of the wind tunnel, this sensor being able to measure relative humidity, dew point, and dry bulb temperature. The uncertainties of the measured variables are provided by the manufacturers of the instruments used. Thus, Table 2 presents the uncertainties of this equipment. The confidence interval adopted for the uncertainties in the independent variables was 95%. The ESS software determined the uncertainty analysis of the secondary or calculated parameters directly, based on the method suggested by (Taylor and Kuyatt, 1994). Furthermore, to check the reproducibility of the experiments, some runs were repeated later, which proved to be excellent.

Table. 2 Accuracy of measured parameters

Parameter		Accuracy
Temperature	(T_{in}, T_{out})	$\pm 0.2 \text{ }^\circ\text{C}$
Coolant mass flow rate	\dot{m}_{liq}	$\pm 0.15\%$
Nozzles pressure drop	ΔP_{air}	$\pm 0.075\%$
Air mass flow rate	\dot{m}_{air}	$\pm 0.018 \text{ kg/s}$

3. RESULTS AND DISCUSSION

3.1 Thermophysical Properties

Thermal Conductivity

The thermal conductivity of the nanofluids and the base fluid were measured by the transient hot bridge method described in section 2.3. The temperature range of the tests was 25 °C to 50 °C, with 10 °C intervals. In order to ensure higher reliability of the results, the tests were repeated ten times for each temperature. The thermal conductivity values of the base fluid were verified with tabulated theoretical values (ASHRAE Standard, 2001), with a maximum deviation of 3% being observed, as per Fig. 4.

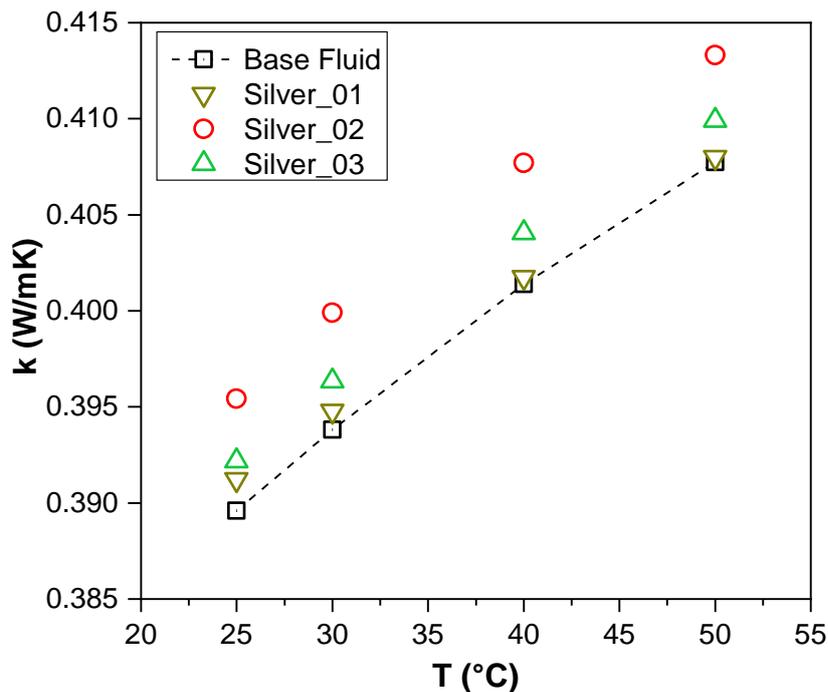


Figure 4. Thermal conductivity of nanofluid samples.

The highest enhancement in thermal conductivity was about 1.7 % for the concentration of 0.02 wt% at a temperature of 40 °C. For sample Silver_01 containing a nanoparticle concentration of 0.01 wt.%, its behavior was similar to the nanofluid for temperatures above 25 °C. Similarly, for sample Silver_03, an increasing trend of on average 0.7% was observed. Moreover, it was identified that even with a higher concentration of nanoparticles than sample Silver_02, the increments in thermal conductivity were smaller. This probably caused by the higher amount of surfactant in the sample. According to (Xia et al., 2014), there is an optimal surfactant concentration at which the thermal conductivity and stability of the nanofluid are higher than the other concentrations. On the other hand, some researchers such as (Iyahraja and Rajadurai, 2015) and (Zhai et al., 2019) used PVP as a surfactant and reported a significant reduction in the thermal conductivity of the prepared nanofluids as a function of increasing the concentration of surfactant added above the optimum.

Dynamic Viscosity

The dynamic viscosity of the nanofluids and the base fluid were measured experimentally using the Stabinger SVM 3000 rotational viscometer. The results obtained for the base fluid were compared with the theoretical values, exhibiting a maximum deviation of 4.3 %.

The results obtained for the relative viscosity are shown in Fig. 5. As expected, increasing the temperature of the nanofluid resulted in a decrease in the fluid viscosity. This reduction is due to the weakening of the adhesive forces between fluid molecules, and to shear the fluid layers at higher temperatures, a smaller force is required. The viscosity was increased as a function of nanoparticle concentration, with the higher increase observed being 4.6 % for the Silver_03 sample at 50 °C.

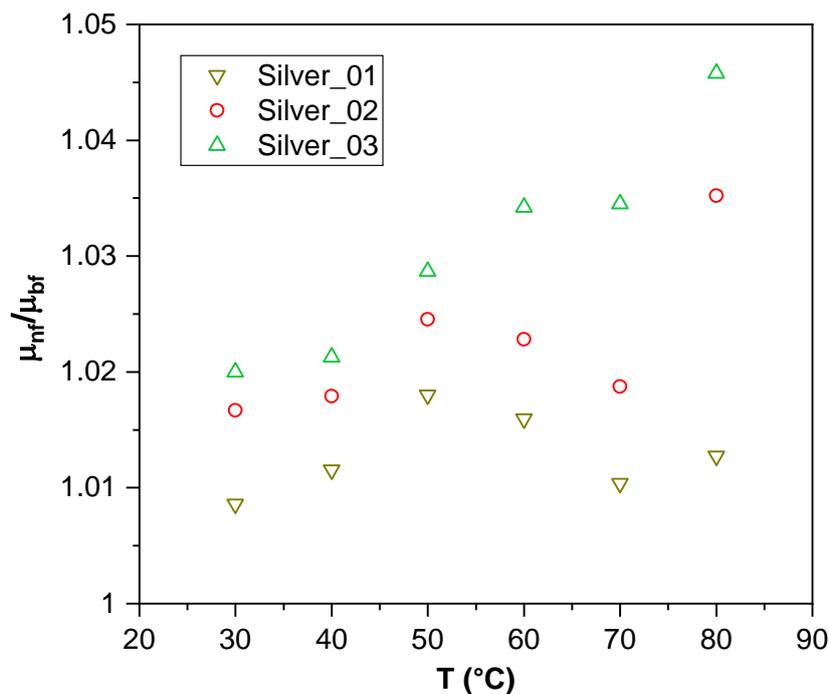


Figure 5. Relative viscosity of nanofluid as a function of temperature.

Research shows that at low concentrations of nanoparticles, small increases are observed in the viscosity of the nanofluid (Rohini Priya et al., 2012). However, when surfactants are used, they can lead to a significant increase in viscosity. This because the added micelles act as another dispersed phase causing the intensification effect on viscosity, even for small surfactant concentrations (Mingzheng et al., 2012).

(LotfizadehDehkordi et al., 2013) studied the effect of adding the surfactant sodium dodecylbenzene sulfonate (SDBS) on the viscosity of Al₂O₃/water-ethylene glycol nanofluids and observed minimal variations in viscosity for small quantities of SDBS. The results showed that increasing the surfactant concentration caused a 16% increase in the nanofluid viscosity. (Phuoc et al., 2011) observed in their experiments, an increase in the viscosity of MWCNT/water nanofluids with increasing concentration of the surfactant chitosan in the nanofluid. For low concentrations of chitosan, the nanofluid behaved similarly to the base fluid. In contrast, an increase in viscosity and non-Newtonian behavior of the nanofluid was observed for high concentrations. Recently (Ma et al., 2021), in their work with Al₂O₃-TiO₂ water-based nanofluids, reported that the viscosity of nanofluid increased 2 times for a concentration of 0.05 wt% PVP. However,

when the temperature was increased, these increments dropped 1.2 times. Thus, the authors highlight an optimal surfactant concentration for significant enhancement in thermal conductivity with small increases in viscosity. This value was described as 0.1 wt% PVP.

3.2 Heat transfer

The three types of nanofluids shown in Table 1 were tested for a range of coolant mass flow rate between 0.08 kg/s and 0.095 kg/s, and the following parameters were maintained as nominal imposed conditions: the coolant inlet temperature with values held constant at 70 °C and 80 °C, air inlet temperature at 25 °C. The results for the heat transfer rate of the analyzed samples are shown in Fig. 6. A trend of increasing heat transfer rate for all tested Silver-PVP samples was observed. However, with increasing temperature, the relative values for the heat transfer rate are negatively affected. In the 70 °C tests, a maximum increase of 3.6 % and 3 % was observed for Silver_03 and Silver_02, respectively. For sample Silver_0.1, an increase of 1.4% can be considered similar to the base fluid. For a temperature of 80 °C, sample Silver_03 proved to be the nanofluid with the highest relative heat transfer rate increase, with an increase of 3.1 %. Samples Silver_01 and Silver_02 had an increase of on average 0.8 % and 1.7 %, respectively.

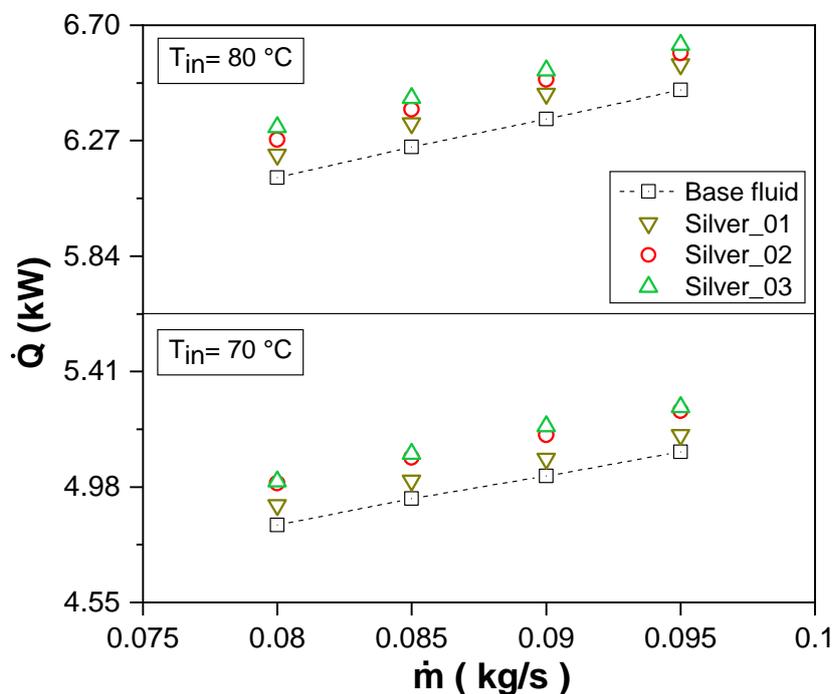


Figure 6. Heat transfer rate for nanofluid samples.

Heat transfer is also strongly affected by the use of surfactants in nanofluids. Results found in the literature exhibit that the nanofluids can become thermally inefficient depending on the type and concentration of surfactant used. (Xuan et al., 2013) studied the influence of SDBS surfactant on the thermal performance of copper nanofluid, indicating a negative effect of surfactant concentration used on the convective heat transfer coefficient. On the other hand, (Askar et al., 2020) evaluated an optimal surfactant concentration for improving the stability of Al₂O₃ nanofluids, obtaining increases for the Nusselt number of up to 13.4 % compared to the base fluid.

3.3 Pressure Drop

When evaluating the performance of nanofluids, it is important to understand that adding nanoparticles to a fluid modifies its thermophysical properties, affecting the pumping power required to keep it circulating. The pressure drop, which directly affects the pumping power, was experimentally evaluated using a pressure transducer positioned parallel to the pump. The results showing the relative pressure drop are shown in Fig.7. The results exhibited an increase in pressure drop for nanofluids when the nanoparticle concentration was increased.

Similarly, and for the same mass flow rate, Silver_02 and Silver_03 nanofluid samples exhibited a decrease in pressure drop when the temperature was increased from 70 °C to 80 °C, the effect of which can be attributed to the decrease in the dynamic viscosity of the fluids. For the Silver_01 sample, the relative pressure drop showed a behavior slightly above that of the base fluid for the entire temperature range analyzed.

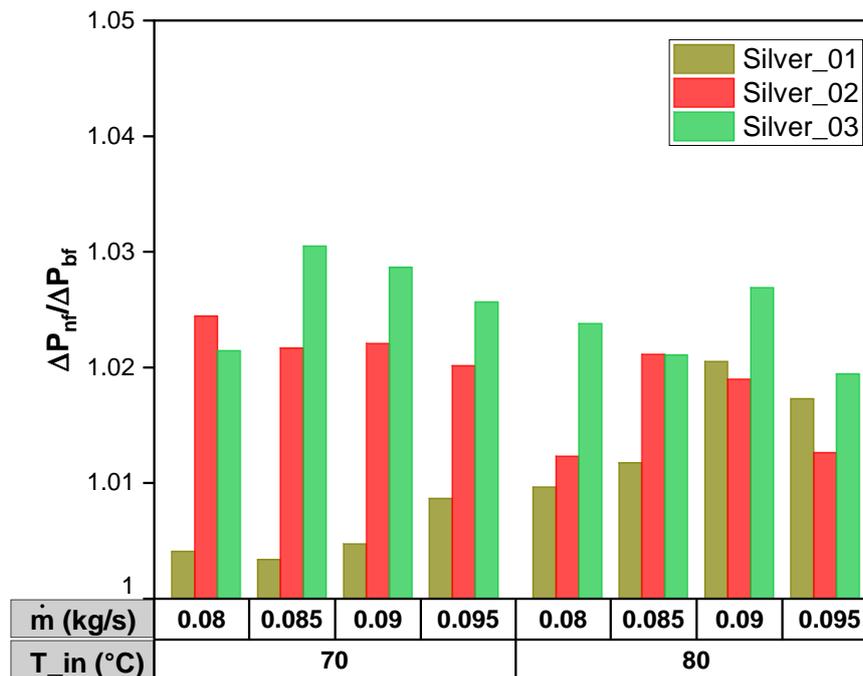


Figure 6. Pressure drop for nanofluid samples.

4. CONCLUSIONS

Among the three concentrations analyzed, it was found that increasing the concentration did not cause a significant improvement in thermal conductivity. The maximum increment of this property was 1.7% for the Silver_02 sample, followed by the others that had similar behavior to the base fluid.

The viscosity of the nanofluids was higher than the base fluid for all temperatures analyzed, exhibiting a maximum increase of about 4.7% at 80 °C. Increasing the concentration resulted in increases in viscosity over the entire temperature range of the tests, with this effect being more pronounced at elevated temperatures.

The nanofluids exhibited a higher heat transfer rate than the base fluid; furthermore, improving results was observed with increasing concentration, reaching a maximum increase trend of 3.7%, obtained at 70 °C for Silver_03.

It was possible to see that increasing the concentration did not necessarily cause increases in pressure drop. For most tests, the Silver_02 nanofluids exhibited higher pressure drop compared to the other fluids. The maximum increase was close to 2.8 %.

In general, the nanofluids exhibited similar behavior to the base fluid. Therefore, the results can be classified as not promising due to the low improvement the analyzed nanofluids would bring to the cooling system. Further tests will be carried out with different concentrations and surfactant types.

5. ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided for this research by CAPES, CNPq and FAPEMIG. The authors also wish to extend their gratitude to FCA, FIAT CHRYSLER AUTOMOVEIS BRASIL LTDA.

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