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Thermal Performance of Ethylene-Based Aqueous Solutions Containing Silver (Ag), Copper Oxide (Cuo), Aluminum Oxide (Al_2o_3) or Titanium Dioxide (Tio_2) Nanoparticles in A Finned Flat Tube Compact Heat Exchanger (Automotive Radiator)

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ABSTRACT
The theoretical model (ε-NTU) was developed for the thermal performance of water, ethylene glycol water mixture and aqueous ethylene-based nanofluid solution. The nanoparticles used in this work are silver (Ag), aluminum oxide (Al_2O_3), copper oxide (CuO) and titanium dioxide (TiO_2). The relevance of using nanofluids specifically for a finned flat tube heat exchanger (automotive radiator) within the temperature range specified in the analysis is demonstrated by analyzing the heat exchange between the fluids. The maximum heat transfer rate using nanofluids can be up to 2.7 times higher than the use of 50% ethylene glycol and water, or pure water, for relatively low airflow. There is a maximum point of heat exchange in low airflow, where the properties of nanoparticles have a greater influence as a function of the high thermal diffusivity when compared to the water diffusivity. The heat transfer rate for high airflows approaches a single value, whatever the type of nanoparticle used, at a volume fraction of 0.05, reflecting the greater influence of the convection process.

Keywords: *Compact Heat Exchanger; Automotive Radiator; Theoretical Model (ε-NTU); Water-Ethylene Glycol; Nanofluid*

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I. INTRODUCTION

This is a research related to the addition of nanoparticles in an aqueous mixture of water and ethylene glycol. Results for ethylene glycol properties, tube, and air outlet temperatures, and heat transfer rates were obtained by considering the addition of silver (Ag), copper oxide (CuO), aluminum oxide (Al_2O_3) and dioxide of titanium (TiO_2).

Research involving compact heat exchangers of all types, mainly car radiators, has been developed over the years and automotive companies invest high resources in all sorts of techniques that can optimize energy performance[1].

Élcio Nogueira [2] presents a theoretical thermohydraulic performance analysis of a compact heat exchanger, type finned flat tube, used in automotive radiator performed in based water nanofluids. The theory of effectiveness (ε-NTU), and experimental data for water flow are used for comparison. Results were obtained for air and water outlet temperatures, heat transfer hate, the pressure drop in finned channels and tubes, as a function of the volume fraction of the oxides. The laminarization effect of the flow was observed in the analysis, and it is more significant with increasing the volume fraction of oxide.

Water is the most commonly used heat transfer fluid, however, in cooling systems, it may be necessary to mix water with ethylene glycol to decrease freezing point and prevent ice formation. In fact, in-car radiators or industrial heat exchangers, the boiling point of water can be changed by mixing ethylene glycol-based fluids[3].

M.J. Uddin et al. [4] demonstrated that nanofluids are designed by suspending medium-sized nanoparticles below 100 nm in traditional heat transfer fluids such as water, oil and ethylene glycol. Nanofluids are considered to offer important advantages over conventional heat transfer fluids.

C. Selvam et al. [5] report the thermophysical properties of ethylene glycol and water mixture-based silver nanofluids. Ethylene glycol (EG) has been used as an antifreeze in automobile radiators for many years because of its compatibility with metals. The mixture of ethylene glycol and water in various ratios like 30:70, 50:60 and 50/50 respectively are mostly used in automobiles. However, the low thermal conductivity of the fluids is a concern. To overcome this, a new class of heat transfer fluid named “nanofluid’ that has enhanced thermal conductivity superior to the respective base-fluid has been proposed. They conclude that the thermal conductivity of nanofluids increases with respect to concentration and temperature which is highly desirable for heat transfer applications.

Kohl Kai Liang Peter [6] investigates whether using nanofluids as a working fluid, as opposed to water, will reduce pipe dimensions in an industrial facility. One conclusion he came to is that while nanofluids have great potential to replace water, there are still many obstacles to get through. On the one hand, the cost of producing a nanofluid is very high. The viscosity of nanofluids tends to increase with increasing volume fraction. Finally, specific heat capacity decreases with increasing volume fraction, making nanofluids less suitable for refrigeration applications.

Xiaoze Du et al. [7] perform numerical simulations to study the fluid transfer and flow characteristics of a liquid-cooled water/glycol mixture heat sink as a working refrigerant. They conclude that the water/glycol has an ideal operating temperature to provide maximum cooling performance.

M. Chandra Sekhara Reddy [8] demonstrated experimentally that heat transfer coefficients in a commercial automobile, with the presence of ZnO nanoparticles in the range of 0.01% to 0.035% based on volume, in 40/60% EG/W, can improve the rate of heat transfer. At the concentration of 0.035%, the improvement in heat transfer was measured to be 10.02% over the base fluids.

II. OBJECTIVES

To analyze the thermal performance of ethylene glycol in relation to the use of pure water in a compact flat finned tube heat exchanger (automotive radiator).

To analyze the thermal performance of ethylene glycol (AG50%) associated with a silver (Ag), aluminum oxide (Al_2O_3), copper oxide (CuO) and titanium dioxide (TiO_2) nanoparticles in a compact finnedtube heat exchanger (automotive radiator).

III. METHODOLOGY

The experimental data relevant to the comparisons, heat transfer rate, were obtained for water by Ribeiro, L.N. [9] in the wind tunnel of Behr Brasil Ltda, the constructor of automotive radiators, are represented by Tables1 and 2. Thermophysical properties of ethylene-based aqueous solutions and nanoparticles are presented in Tables 3 and Table 4.

Table 1 - Dimensions of a finned flat tubes heat exchanger

Features	Value
Heat Exchanger Width	396 mm
Heat Exchanger Height	436 mm
Heat Exchanger Thickness	55 mm
Dimensions of tubes	13.3 x 2.6 x 448 mm
The wet perimeter of each tube	31.8 mm
Hydraulic diameter	4.36 mm
Number of pipe rows	3
Tubes per row	43
Total number of tubes	129
Cross-tube spacing	8.8 mm
Distance between tubes	18.3 mm
Thickness of fins	0.05 mm
Spacing between fins	2.8 mm
Number of fins	155

Dissertation of Ribeiro, L.N. (2007; Behr Brasil Ltda) [9]

Table 2 – Initial thermophysical properties of air

Property	Value
Cp	1.008 kJ/(kg . K)
k	28.816 W/(m . K)
ν	19.31 10-6 m^2/s
ρ	1.048 kg/m^3
Pr	0.702

Dissertation of Ribeiro, L.N. (2007; Behr Brasil Ltda) [9]

Table 3 – Thermophysical properties of Water-Ethylene Glycol based fluids

SI	Property	Water H_2O	Ethylene Glycol EG20%	Ethylene Glycol EG30%	Ethylene Glycol EG50%
1	k W/(m . K)	0.605	0.5068	0.5539	0.4222
2	ρ kg/m^3	1000	1018.88	1033.57	1058.33
3	C_p J/ (kg . K)	4184	4010	3580	3879
4	μ kg/m.s	$4.78\ 10^{-4}$	$5.278\ 10^{-4}$	$7.896\ 10^{-4}$	$9.809\ 10^{-4}$
5	ϑ m^2/s	10^{-6}	$0.5180\ 10^{-6}$	$0.7639\ 10^{-6}$	$0.9268\ 10^{-6}$
6	∝ m^2/s	$1.44\ 10^{-7}$	$1.2404\ 10^{-7}$	$1.4969\ 10^{-7}$	$1.0284\ 10^{-7}$

Table 4 - Thermophysical properties of nanoparticles

SI	Property	Silver Ag	Titanium Oxide TiO_2	Copper Oxide CuO	Aluminum Al_2O_3
1	k W/(m . K)	429	8.95	400	31.92
2	ρ Kg/m^3	10500	4250	8933	3950
3	C_p J/ (Kg . K)	235	686	385	873.34
4	μ Kg/m s	-	-	-	-
5	ϑ m^2/s	-	-	-	-
6	∝ m^2/s	$1.74\ 10^{-4}$	$3.07\ 10^{-6}$	$1.16\ 10^{-4}$	$0.93\ 10^{-6}$

In order to compute the experimental data, interpolations were performed within the available Reynolds number range and equations were used by Élcio Nogueira, André Aroucha e Fernando Lamim [10] and Élcio Nogueira [2].
The interpolations of the experimental data are used to obtain the equations for the dimensionless Colbourn Factor J [2].

Theoretical analysis

Determination of ethylene-based aqueous solution properties

The properties of the ethylene-based aqueous solution are obtained by the expressions below:

$$\rho_{solution} = \rho_{EG\%}V + (1 - V)\rho_w \quad (01)$$

$$\mu_{solution} = \mu_{EG\%}V + (1 - V)\mu_W \quad (02)$$

$$Cp_{solution} = Cp_{EG\%}V + (1 - V)Cp_w \quad (03)$$

$$k_{solution} = k_{EG\%}V + (1 - V)K_w \quad (04)$$

$$\alpha_{solution} = \frac{k_{solution}}{\rho_{solution}Cp_{solution}} \quad (05)$$

$$\vartheta_{solution} = \frac{\rho_{solution}}{\mu_{solution}} \quad (06)$$

$$Pr_{solution} = \frac{\alpha_{solution}}{\vartheta_{solution}} \quad (07)$$

where V and Eg% are the volume fraction percent of nanoparticles and weight fraction percent of Ethylene Glycol, respectively.

Determination of heat transfer rate

The theoretical determination of the heat transfer rate depends on the overall heat transfer coefficient, which in turn depends on the heat transfer coefficients, ha, and hw, on the airside and the waterside, respectively.

To begin the calculations, it becomes necessary to determine the physical properties in the function of the average temperatures of the fluids. However, the exit temperatures, in theory, are unknown a priori, and the average temperatures should be initially estimated.

With the initially stipulated output temperatures, defined physical properties, and the geometric quantities of the exchanger supplied, we have,
For the air:

$$G_a = \frac{m_a}{A_{mín}} = \frac{m_a}{\sigma_a A_{fr}} \quad (08)$$

$$Re_a = \frac{G_a D_{ha}}{\mu_a} \quad (09)$$

$$J = \frac{h_a}{G_a c_{pa}} {Pr_a}^{2/3} \quad (10)$$

The Prandtl number for air, Pra, is obtained by interpolating the data, valid for air as the ideal gas, published by Çengel and Boles [11; page 934]:

$$Pr_a = 1.005351636d0 + 0.01292094145Tsa + 2.524174317^{-5}Tsa^2 - 5.074647769^{-8}Tsa^3 + 1.564763295^{-8}Tsa^4 \quad (11)$$

then,

$$h_a = J\frac{G_a c_{pa}}{{Pr_a}^{2/3}} \quad (12)$$

For water ethylene-based nanofluid properties we have:

$$\rho_{nano} = \emptyset\rho_{particle} + (1-\emptyset)\rho_{solution} \quad (13)$$

$$\mu_{nano} = \mu_{solution}(1 + 2.5\emptyset) \quad (14)$$

$$Cp_{nano} = (\emptyset\rho_{particle}Cp_{particle} + (1-\emptyset)\rho_{solution}Cp_{solution})/\rho_{nano} \quad (15)$$

$$k_{nano} = [(k_{particle} + 2k_{solution} + 2(k_{particle} - k_{solution})(1-0.1)^3\emptyset)/(k_{particle} + 2k_{solution}(k_{particle} - k_{solution})(1+0.1)^2\emptyset)]\, k_{solution} \quad (16)$$

$$\alpha_{nano} = \frac{k_{nano}}{\rho_{nano}Cp_{nano}} \quad (17)$$

$$\vartheta_{nano} = \frac{\rho_{nano}}{\mu_{nano}} \quad (18)$$

$$Pr_{nano} = \frac{\alpha_{nano}}{\vartheta_{nano}} \quad (19)$$

at where $\emptyset$ is the volume fraction of nanoparticles, and $\emptyset = 0.05$ for every condition in this work.
Equation 14 is the Einstein equation, used for very dilute suspension, and $\emptyset$ is the volume fraction of nanoparticles.
Other quantities associated with the flow are obtained by:

$$Re_{nano} = \left[4\left(\frac{m_{nano}}{N_{tubes}}\right)\right]/(\pi D_{hnano}\mu_{nano}) \quad (20)$$

at where

$$D_{hnano} = 4.36\ 10^{-3} \quad (21)$$

and

$$m_{nano} = 2.0\frac{kg}{s} foreveryconditionsinthiswork \quad (22)$$

Considering the flow regime of the Newtonian flow of a water-base nanofluid in the tube as completely developed, we have, for turbulent flow, approximately:

$$Nu_{nano} = 0,023\ {Re_{nano}}^{0,8}{Pr_{nano}}^{0,4} \quad (23)$$

If the flow regime in the water-base nanofluid is laminar, it is used to interpolate the data of the Master Thesis of Nogueira, E.[12, page 130], for the thermal input region under development:

$$Nu_{nano} = 1.409019812d0{Z_{nano}}^{(-0.3511653489)} \qquad 10^{-5} \le Z_{nano} < 10^{-3} \quad (24.1)$$

$$Nu_{nano} = 1.519296981d0{Z_{nano}}^{(-0.3395483303d0)} \quad 10^{-3} \le Z_{nano} < 10^{-2} \quad (24.2)$$

$$Nu_{nano} = 10.8655 - 570.4671787Z_{nano} + 28981.67578{Z_{nano}}^2 - 950933.9838{Z_{nano}}^3 + 20237498.47Z_{nano}^4 - 276705269.6{Z_{nano}}^5 + 2340349265{Z_{nano}}^6 - 1.112482493^{10}{Z_{nano}}^7 + 2.269345238^{10}{Z_{nano}}^8$$

$$10^{-2} \le Z_{nano} \le 10^{-1} \quad (24.3)$$

$$Nu_{nano} = 5.261d0 - 19.93019048nano + 139.4921627{Z_{nano}}^2 - 605.9954034{Z_{nano}}^3 + 1716.100694Z_{nano}^4 - 3217.96875{Z_{nano}}^5 + 3954.86111{Z_{nano}}^6 - 3056.051587{Z_{nano}}^7 + 1344.246031nano^8 - 256.2830687{Z_{nano}}^9 \quad 10^{-1} \le Z_w \le 10^0 \quad (24.4)$$

Then, we have:

$$h_{nano} = Nu_{nano}\frac{k_{nano}}{D_{hnano}} \quad (25)$$

The overall heat transfer coefficient is obtained in relation to the air exchange area and, in order to perform the calculations, it is necessary to determine the efficiency of the fin since there is a variation of temperature between the entrance of the plate of the exchanger (base of the fin) and its outlet:

$$\eta = \frac{tgh(mL)}{mL} \tag{26}$$

at where

$$mL = \sqrt{2h_a/k_a t} \tag{27}$$

The efficiency of the fin, weighted by area, is determined by:

$$\eta' = \beta\eta + 1 - \beta \tag{28}$$

where

$$\beta = \frac{Finarea}{totalarea} \tag{29}$$

Then, we have:

$$\frac{1}{U_a} = \frac{1}{\eta' h_a} + \frac{1.0}{A_{med}K_{aleta}} + \frac{1}{(A_w/A_a)h_{nano}} \tag{30}$$

where

$$A_{med} = \frac{A_a + A_{nano}}{2.0} \tag{31}$$

and

$$\frac{A_w}{A_a} = \frac{watersideheattransferarea}{airsideheattransferarea} \tag{32}$$

By the theory of effectiveness (ε-NUT) we have:

$$N = NTU = \frac{A_a U_a}{C_{min}} \tag{33}$$

The thermal capacities of air and nanoparticles water-based are calculated by:

$$\mathrm{Ca} = \mathrm{m_a} * \mathrm{Cp_a} \tag{34}$$

and

$$\mathrm{Cnano} = \mathrm{m_{nano}} * \mathrm{Cp_{nano}} \tag{35}$$

Cmin is the lowest value between the thermal capacities of water and air. Finally,

$$\mathrm{Q} = \varepsilon \mathrm{C_{min}}\left(\mathrm{T_{h,af}} - \mathrm{T_{c,af}}\right) \tag{36}$$

$$\Delta\mathrm{T_{Ln}} = \frac{\mathrm{Q}}{\mathrm{U_a A_{total}}} \tag{37}$$

and

$$\mathrm{QK_{teo}} = \frac{\mathrm{Q}}{\Delta\mathrm{T_{Ln}}} \tag{38}$$

at where

$$\varepsilon = 1 - \exp\left[\left(\frac{c_{min}}{c_{max}}\right)^{-1} (\mathrm{NTU})^{0,22}\left\{\exp\left[-\frac{c_{min}}{c_{max}}(\mathrm{NTU})^{0,78}\right] - 1\right\}\right] \tag{39}$$

according to Kakaç, S[13, page 35].

$\mathrm{QK_{teo}}$ is the theoretical value for the ratio between the heat transfer rate in the air and the mean logarithmic temperature difference – MLTD.

With the heat transfer rate determined, as the first approximation, one can calculate the air and water exit temperatures, through the energy balance equations:

$$\mathrm{Q} = \varepsilon \mathrm{C_{min}}\left(\mathrm{T_{h,af}} - \mathrm{T_{c,af}}\right) \tag{40}$$

and

$$\mathrm{Q} = \mathrm{m_a c_{pa}}\left(\mathrm{T_{a,af}} - \mathrm{T_{a,ef}}\right) \tag{41}$$

The average outlet, air, and water temperatures can then be determined and compared to the initial set temperatures:

The mean air and water temperatures can then be determined and compared to the initially defined temperatures:

$$\mathrm{T_{m,a}} = \frac{\mathrm{T_{a,af}} + \mathrm{T_{a,ef}}}{2} \tag{42}$$

and

$$\mathrm{T_{m,nano}} = \frac{\mathrm{T_{nano,af}} + \mathrm{T_{nano,ef}}}{2} \tag{43}$$

With the average temperatures finally calculated, the values obtained for the heat transfer rate were compared and, if they are outside of an admissible value, when compared with experimental values or empirical expressions, the calculations for thermophysical properties can be re-started, until a satisfactory convergence is obtained for the problem.

IV. RESULTS AND DISCUSSION

Thermophysical characterization of Ethylene Glycol

We initially determined the thermophysical properties of Ethylene Glycol, which will serve as the base fluid associated with water, for different weight and volume fractions. Below we have the properties as a function of temperature, within the range of interest of this work.

Figure 1 presents the relation between volume fraction percent (V) and weight fraction percent (EG%), obtained of Ethylene Glycol Products Guide - Union Carbide Corporation [14] and Engineering and Operation Guide for DOWTHER SR-1 and DOWTHERM 4000 [15], G. I. Egorov et al. [16] and Laird Thermal System Application Note [17], Omer El_Amim Ahmed Sdam [18].

Figures 2, 3, 4 and 5 presented properties of Aqueous Solution of Ethylene Glycol by weight fraction percent, obtained of Ethylene Glycol Products Guide - Union Carbide Corporation [14] and Engineering and Operation Guide for DOWTHER SR-1 and DOWTHERM 4000 [15], G. I. Egorov et al. [16] and Laird Thermal System Application Note [17], Omer El_Amim Ahmed Sdam [18].

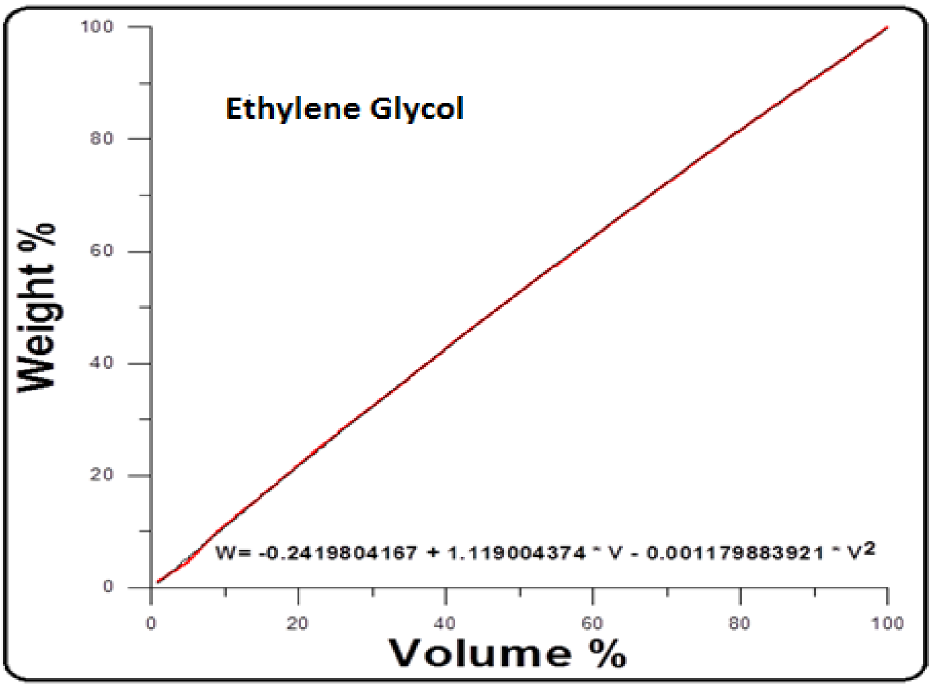

Figure 1 – Volume fraction percent versus weight fraction percent for Ethylene Glycol

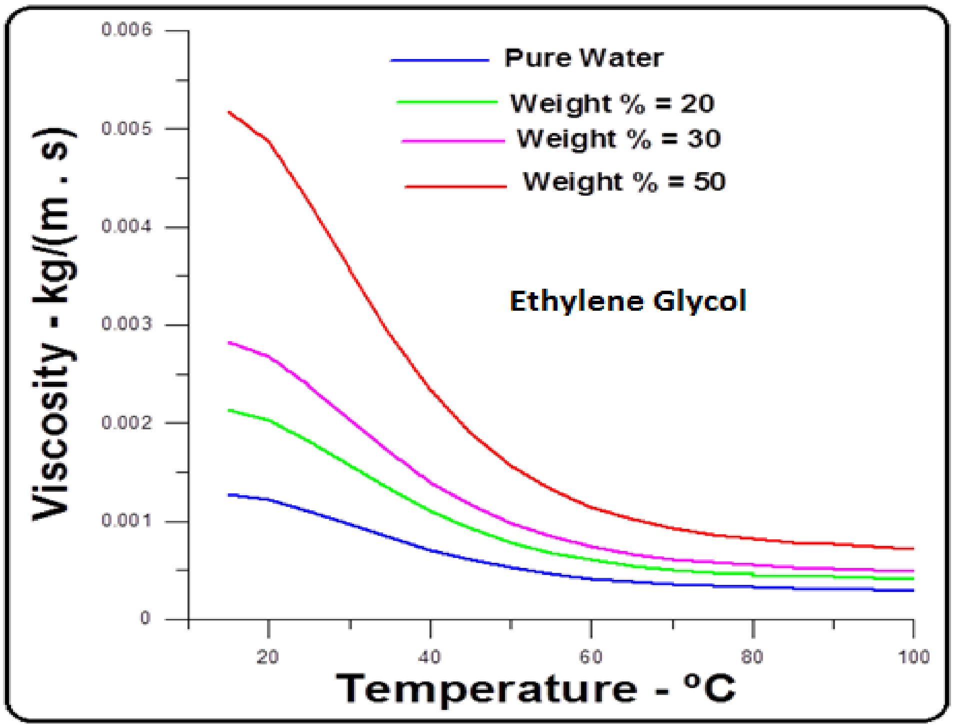

Figure 2 – Viscosity of aqueous ethylene glycol by weight%

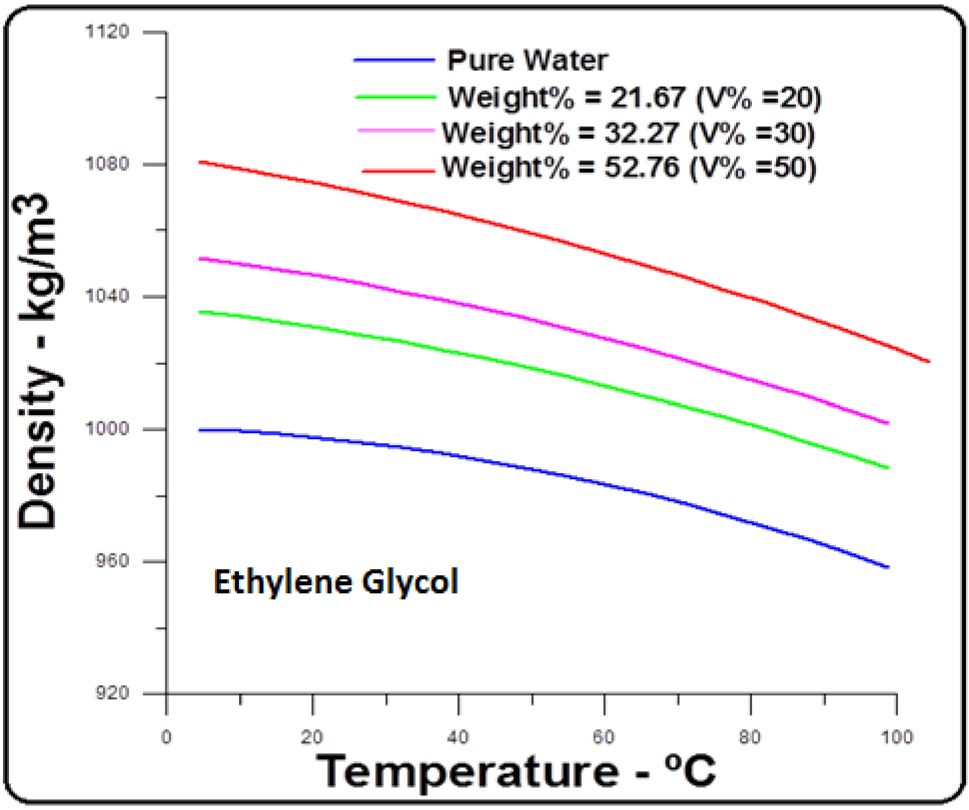

Figure 03 - Density of aqueous ethylene glycol by weight%

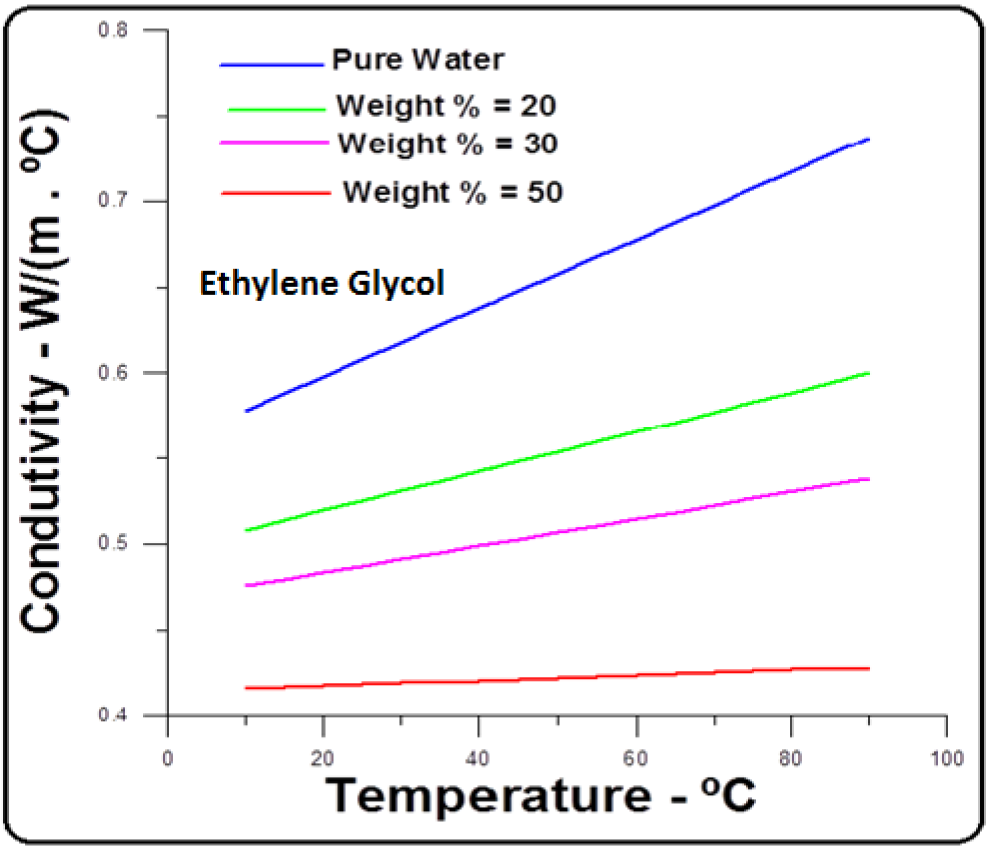

Figure 4 - Conductivity of aqueous ethylene glycol by weight%

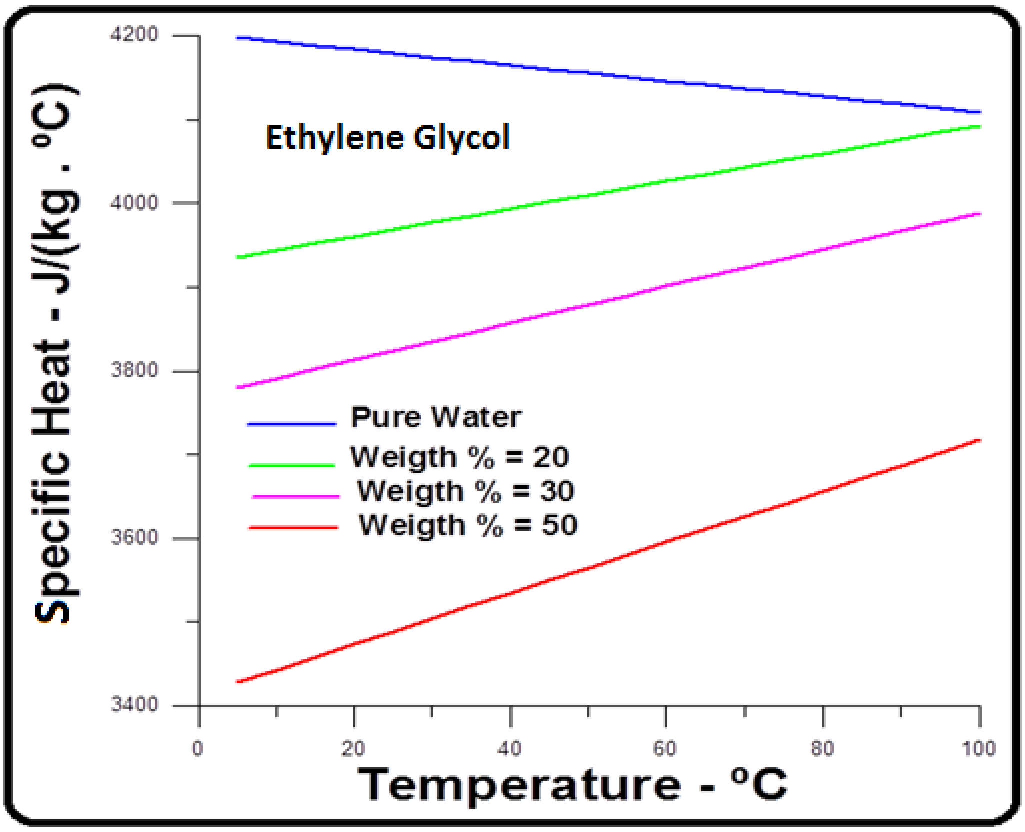

Figure 5 – Specific heat of aqueous ethylene glycol by weight%

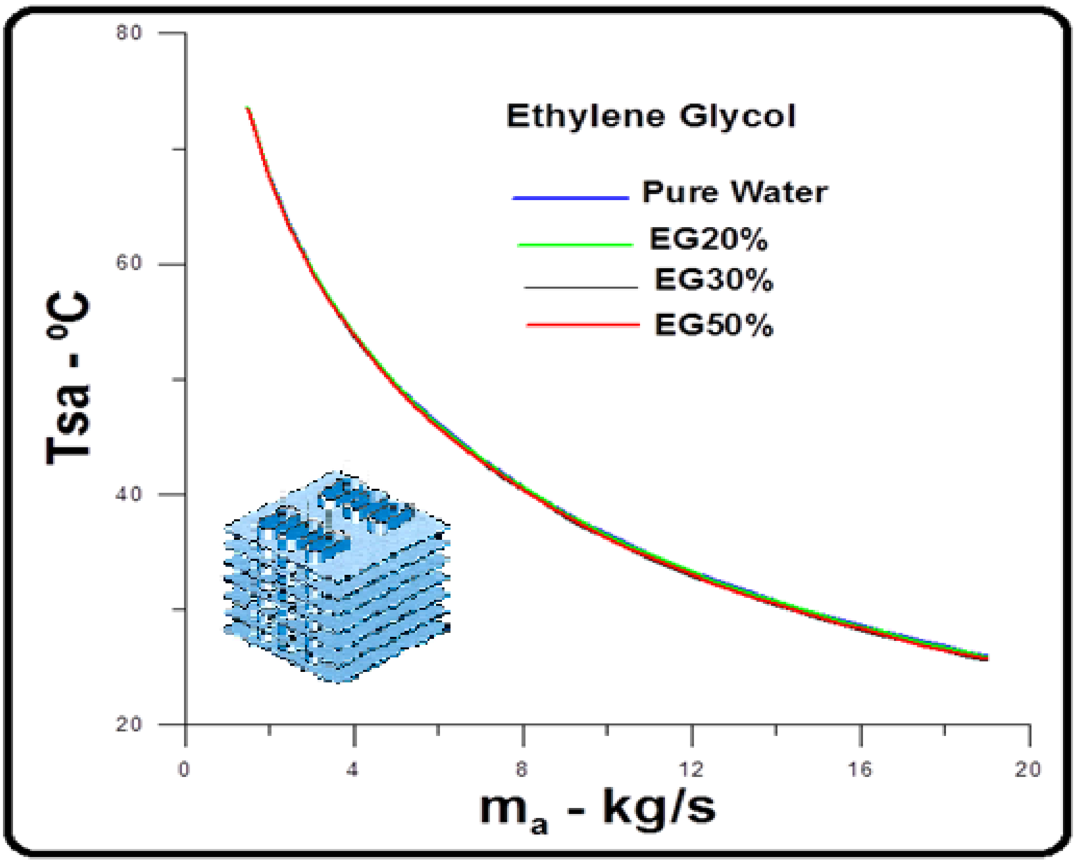

Figure 6 – Exit air temperature for Ethylene Glycol and water

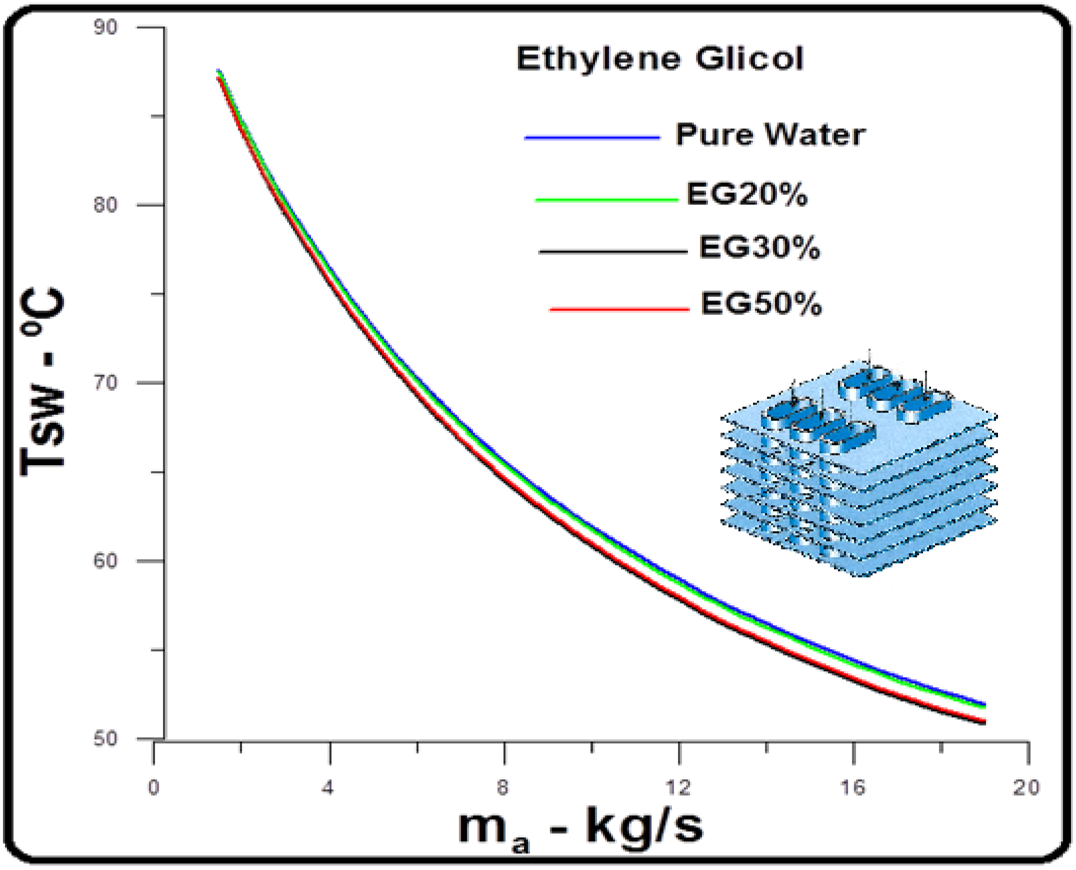

Figure 7 – Pipe outlet temperature for Ethylene Glycol and water

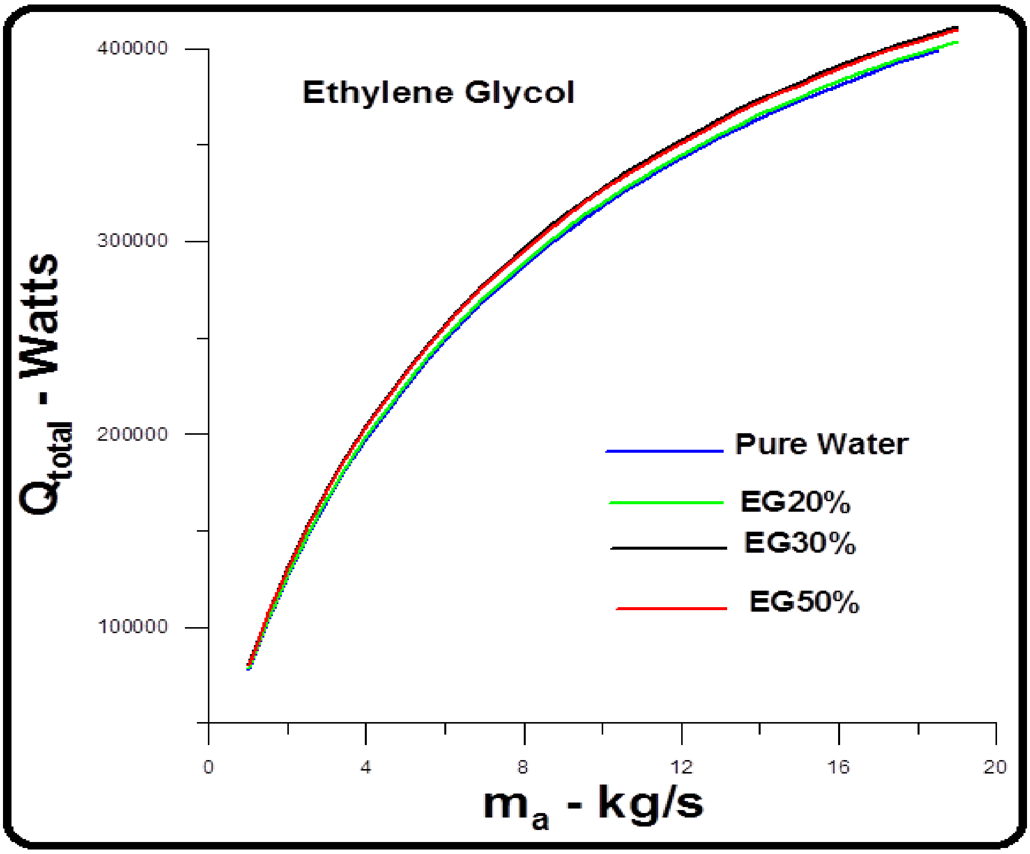

Figure 8 **– Heat transfer rate for Ethylene Glycol**

Figures 6, 7 and 8 show results for outlet temperatures and heat transfer rate to air and a mixture of ethylene glycol and pure water. It is evident that the addition of ethylene glycol does not significantly alter the results for pure water within the temperature ranges under analysis. In fact, the variations in the quantities analyzed, within the temperature range considered, show very poor performance in relation to water. However, as it is known, ethylene glycol is a fluid widely used as a refrigerant due to its low freezing point. Of course, in situations where the external temperature is very low, it should be considered in relation to pure water. For places where the external temperature is always high, it is evident that pure water is the most suitable refrigerant.

Thermophysical characterization of Ethylene Glycol (EG50%) with nanoparticles

Figure 9 shows the result of the average fluid temperature associated with nanoparticles. The relatively high ethylene glycol fractions do not significantly affect heat exchange, as shown in Figures 6, 7 and 8 above, however, by incorporating nanoparticle fractions, the result demonstrates significant changes.With respect to aluminum oxide (Al_2O_3), titanium dioxide (TiO_2) and copper oxide (CuO) nanoparticles, the thermal performance presented are relevant to, since there is a significant decrease in the average temperature of the base fluid. As can be seen, silver (Ag) has the best performance, closely followed by copper oxide.

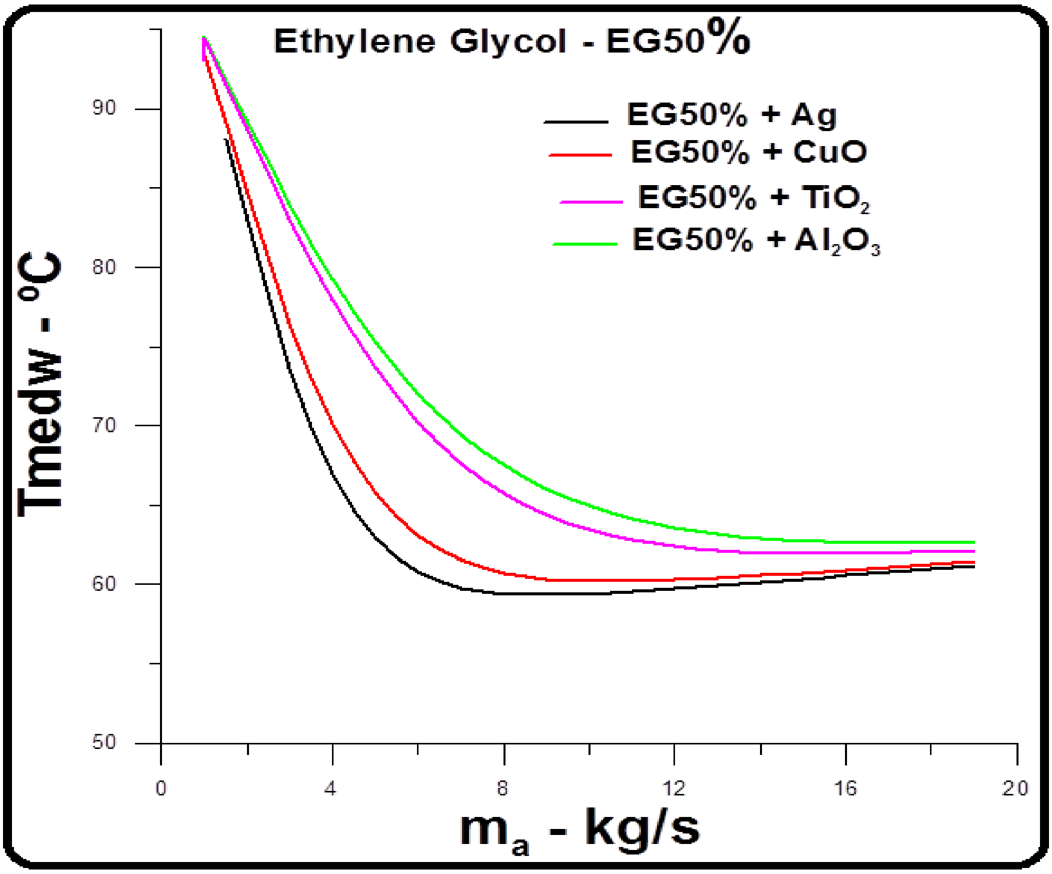

Figure 9 – Average Temperature for Ethylene Glycol with Nanoparticles

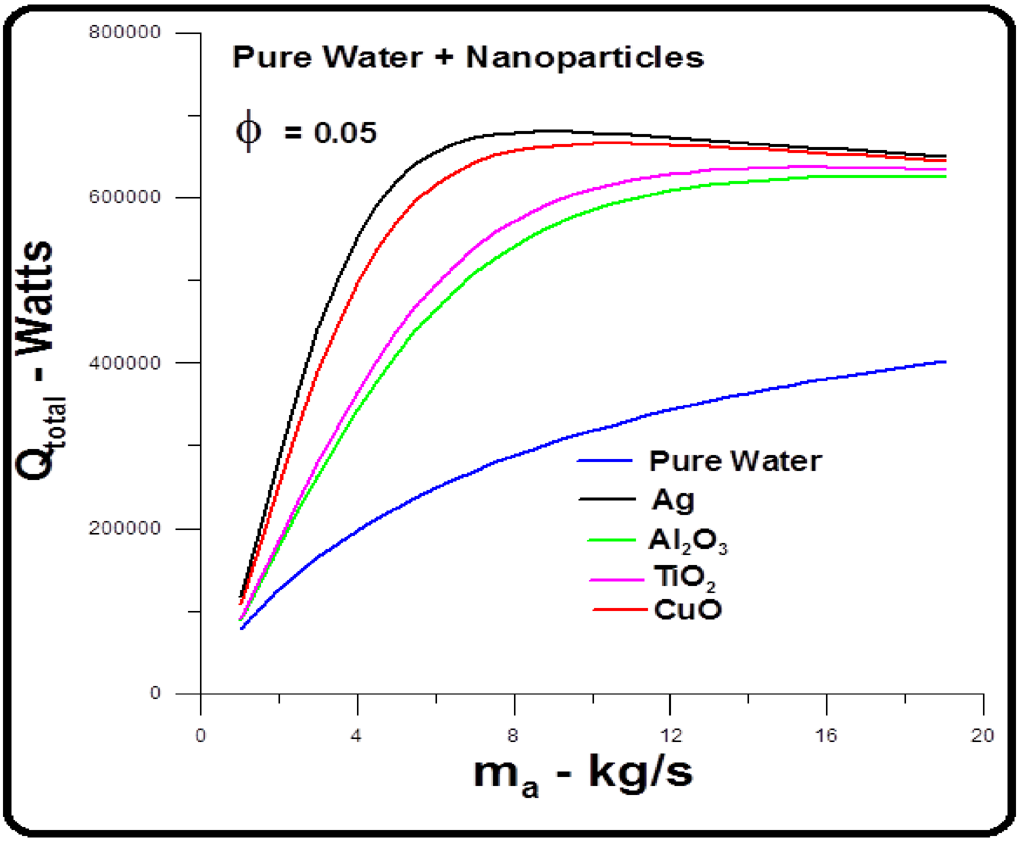

Figure 10 – Heat transfer rate for Ethylene Glycol with Nanoparticles

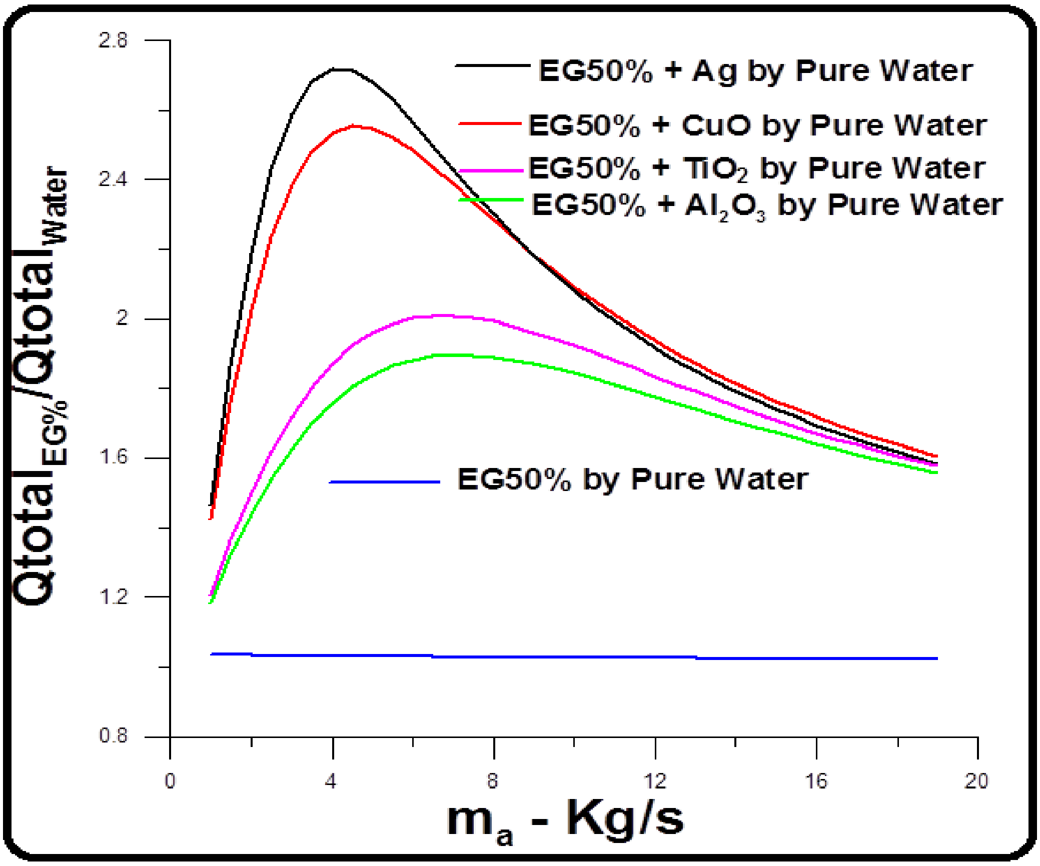

Figure 11 – Relationship for heat transfer rate between Ethylene Glycol with nanoparticles and pure water

Figure 10 shows the heat transfer rate exchanged between the compact finned flat tubes heat exchanger fluids with the addition of nanoparticles. Ethylene glycol does not significantly change the heat transfer rate, as already observed through Figure 09, with respect to pure water. However, silver, aluminum oxides, copper and titanium dioxide present high values for heat transfer rates. In fact, as can be seen from Figure 11 below in relation to pure water, pure ethylene glycol has results close to 1, and the addition of silver, copper oxide, aluminum oxide, and titanium dioxide above 1.2 for all air flows under analysis. Silver has a maximum performance of 2.7 near airflow of 4.5 kg / s. The results show that the best performances occur for relatively low airflow rates and that for high flow rates the addition of nanoparticles of any kind results close to 1.6.

V. CONCLUSIONS

It was presented the thermophysical properties of ethylene glycol, density, viscosity, specific heat, and conductivity, which serve as the base fluid associated with water, for different weight and volume fractions.

It was demonstrated that heat transfer rate using nanofluids can be up to 2.7 times higher than the use of 50% ethylene glycol and water, or pure water, for relatively low airflow.

There is a maximum point of heat exchange in low airflow, where the properties of nanoparticles have a greater influence as a function of the high thermal diffusivity when compared to the water diffusivity.

The heat transfer rate for high airflows approaches a single value, whatever the type of nanoparticle used, at a volume fraction of 0.05, reflecting the greater influence of the convection process.

Ethylene glycol does not significantly change the heat transfer rate compared to pure water. However, nanoparticles of silver, aluminum oxides, copper oxides, and titanium dioxide have high values for heat transfer rates when added to the solution of aqueous ethylene glycol.

There is no definitive conclusion about the appropriateness of using ethylene glycol in relation to water within the temperature range analyzed. It would be interesting to perform a theoretical and experimental analysis at temperatures close to the cooling point of the water-ethylene glycol mixture.

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