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Numerical and Experimental Investigation of the Effect on Heat Transfer of Nanofluid Usage in Mini/Micro Channels

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ABSTRACT

In this study, the thermal performance of Al_2O_3, TiO_2 and ZnO nanofluid in horizontal microchannels was investigated experimentally and numerically. Al_2O_3 (13nm), TiO_2 (10-25nm) and ZnO (18nm) nanoparticles in water to prepare nano-powders with 0.5%, 0.7% and 1.0% volumetric concentration.A set of experiments was set up for experimentation. For this purpose, micro-channels of 20 cm in length were used at different surface temperatures (15, 25, 40 ° C) from different materials (400, 750, 1000 μm). In addition, nanofluids with different inlet temperatures, volumetric flow rates (20, 35, 50 mL/min) and concentration ratios are used using nanofluids. Temperature, flow and pressure measurements are based on heat transfer, heat transfer coefficient, Nusselt number, pressure drop and friction factor. The values required for the calculations are measured separately. The effects of parameters such as microchannel diameter, particle type, flow velocity and volumetric ratio on the friction factor, temperature distribution, pressure drop, Reynolds and Nusselt numbers with Taguchi method will be determined in the flow program and compared with the experimental study. In addition, this study will be a preliminary model for the design and analysis of new generation cooling radiators with nanofluid which are not used in diesel engines conforming to Euro 5/6 emissions norms.

Keywords:
Microchannel; Nanochannel; Reynolds Number; Nusselt Number; Numerical Analysis

INTRODUCTION

Nowadays, the cooling systems are used in various areas such as energy transfer, computer systems, electronic systems and heating. Cooling systems provide much more efficient results with recent technology. For decades, many studies include nanofluids that used as refrigerant for cooling systems.

The nanoparticle is a solution formed by the suspension of the nanoparticles in the liquid homogeneously and allowing the transport of the particles through the base liquid. Generally, metal particles and oxides are suspended and transported in pure water or ethylene glycol. We anticipated the heat transfer will be increase by the thermodynamic properties of nanoparticles.

In recent years there have been many studies on the use of nanofluids in cooling systems. Some of those; Bhattacharya et al. [10], using Al_2O_3-Water nano-fluid, studied numerically the heat transfer characteristics of laminar forced convection of the nano-fluid in their works. Chen et al. [9] quantitatively analyzed the heat transfer characteristics of a nanoparticle with different nanoparticle volume cross-sections. Lelea [13] determined the heat transfer performance numerically, taking into account the effect of viscous dispersion in the laminar flow regime. Heyhat [4] examined how the heat transfer coefficient and the friction factor change in a horizontal circular tube experimentally. Şahin et al. [2] examined the effects of volumetric concentration and Reynolds number on heat transfer and pressure drop performance experimentally. Karimzadehkhouei et al. [3] also studied TiO_2-Water nanofluids, differently from Al_2O_3-Water nanofluids. They have examined the pressure drop and heat transfer properties of neuroplates in horizontal smooth microtubes for thermally developing flows under constant heat flow conditions with using nanofluids. Ahmet et al. [11] who used the Cu-pure water in their studied examined the heat transfer gain and pressure drop characteristics of nanoparticles flowing through the isothermally heated curved canal path using numerical methods in their studies. Tsai-Chein et al. [12] also studied Carbon Nanotube-Water nano-fuel, which is different from Cu-Su nano-fuel. They examined the performance of the microchannel cooler using these two nanofluids.Azmi et al. [5], used TiO_2-Water nanofluid in their experiments, and examined the heat transfer coefficient and friction factor in turbulent flow at different volumetric concentrations, constant heat flow condition. Azmi et al. [5] experimentally investigated the heat transfer coefficient and friction factor of a copper circular tube using a SiO_2-water nanofluid in addition to the TiO_2-Water nanofluid in a different study. Bhanvase et al. [6] investigated the effects of the nano-flow rate and inlet temperature on the heat transfer performance in the case of constant heat flow experimentally. Haghigi et al. [7] examined the cooling performance of a small-diameter tube using Al_2O_3-Water and CeO_2-Water nanofluids, unlike TiO_2-Water nanofluids. Ho et al. [8] examined the results in different microchannels obtained for the maximum wall temperature, thermal resistance, mean heat transfer coefficient, pump power and friction factor with varying Reynolds in their work. Mohammed et al. [3] have applied three-dimensional simulations for varying Reynolds numbers at a constant volume for a triangular-shaped microchannel, a constant volume flow at the top plate, and evaluated the results.

In this study, the heat conductive coefficient, heating performance and Nusselt numbers of water based nanofluids that have different temperatures(50–60°C) flowing on three different flow rates in the horizontal circular microchannels that are at various surface temperatures (10, 25, 40°C), materials (400, 750, 1000µm) and diameters are

Table 1. Properties of nanoparticles.

Nano Particle	*Avarage Diameters (nm)*	*Density (kg/m³)*	*Specific Heat (J/kg.K)*	*Thermal Conductivity Coefficient (W/m.K)*
Al_2O_3	13	3890	778	46
TiO_2	25	3900	710	10
ZnO	18	5606	500	54

examined by using Taguchi method experimentally. This study examined many different parameters in the same experimental setup and obtained the results that shown on the graphics unlike other studies in the literature. These results that obtained is modeling numerically(CFD) and compare with experimental results.

MATERIAL AND METHODS

Properties of Nanoparticles

In this study, Al2O3, TiO2 and ZnO, used as nanoparticles and incorporated in to water as the base fluid were. Table 1 shows the nanoparticle properties.

Preparation of Nanofluids

The nanofluids were prepared using an ultrasonic homogenizer(Characteristics of the ultrasonic homogenizer: Optics Ivymen System, CY-500, Power: 500W, Frequency: 20kHz, Probe Diameter / Length: Ø5.6 / 60mm). Al_2O_3, TiO_2 and ZnO nanoparticles were mixed with pure water, and they were set to volumetric concentration of 0.5%, 0.7% and 1%. The mass quantities of the nanoparticles and pure water used in the nanoparticle solution were measured using a precision scale based on the required amounts for volumetric concentration of the nanoparticles. Solubility has been proven by looking at the SEM images provided with homogeneity.

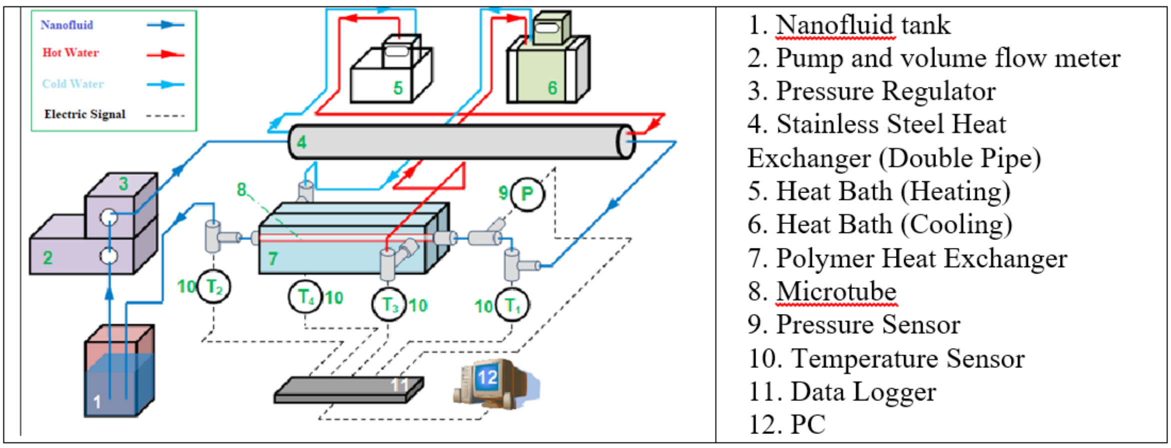

Figure 1. Schematic display of the test set.

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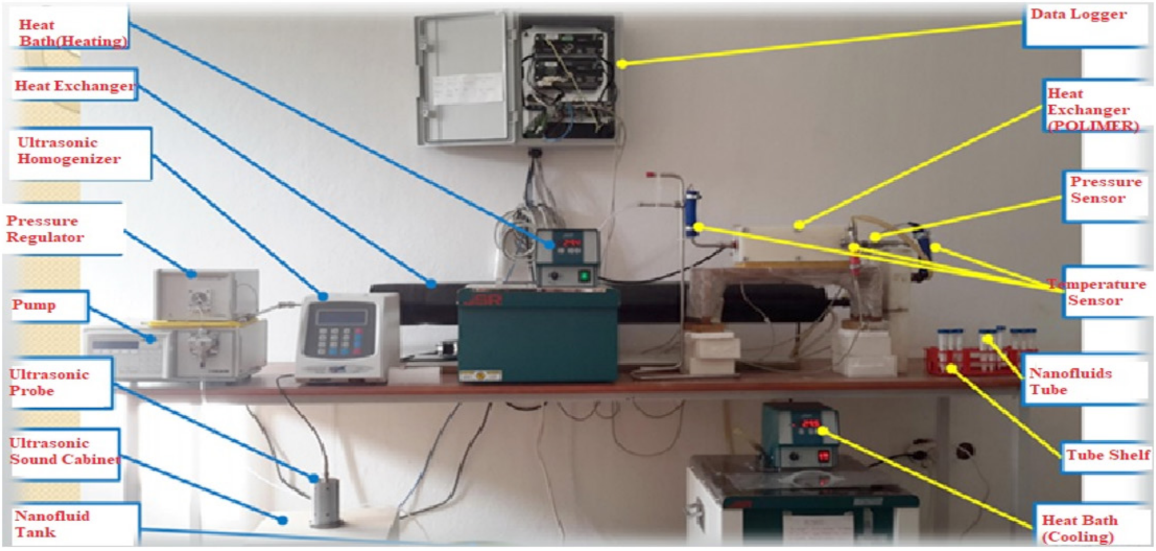

Figure 2. Test set.

Thermophysical Properties of Nanoparticles

The individual thermal conductivity coefficient for each volumetric concentration was measured with Decagon KD2-Pro (KS-1 Probe) and viscosity AND SV-10. The values obtained at the end of these measurements are transformed and plotted into a correlation which can give almost real results in the intermediate values by the curve fitting method. The specific heat and density values of the nanofluids are calculated and used from general equations.

Test Set

Experimental set include; the pump and regulator, heating bath, cooling bath, micropipes that working dimensions, heat exchanger made of polymer materials, insulating materials, heat exchanger made of stainless steel, temperature sensors, pressure sensor, data logger and PC. In Fig. 1 the test set is shown schematically, while in Fig. 2, the actual experiment set is given.

Table 2. Nusselt numbers as a result of verification experiments.

Volumetric Flow (mL/min)	10	15	17	20
T_{in} (°C)	44,8	44,0	44,4	44,8
T_{out} (°C)	16,2	19,2	19,9	21,3
$T_{surface,in}$ (°C)	10,1	10,1	10,1	10,1
$T_{surface,out}$ (°C)	9,9	9,9	10,0	10,0
Pressure Drop (bar)	1,150	1,680	1,900	2,300
Nusselt Number (Sieder-Tate)	3,342	3,809	3,964	4,171
Nusselt Number (Edwards)	4,066	4,244	4,311	4,409
Nusselt Number (Full Developed)	3,66	3,66	3,66	3,66
Nusselt Number (Experimentally)	3,081	3,496	3,785	4,011

Verification Experiments

Verification experiments have been conducted to check that the system is working properly before starting the experiments. In the verification experiments, hydrodynamic and thermally developed laminate flow condition in a circular cross-section with constant surface temperature limit were investigated. Nusselt numbers and heat transfer coefficients were found. The results of the experiments were compared with the Sieder-Tate and Edwards equations, which are valid in the literature with the selected conditions. Micropipes with a diameter of 400μm were used in verification experiments and pure water was used as a fluid. Table 2 and Table 3 show the experimental Nusselt numbers and heat transfer coefficients, respectively.

Table 3. Heat Convection Coefficient as a result of verification experiments.

Volumetric Flow (mL/min)	10	15	17	20
T_{in} (°C)	44,8	44,0	44,4	44,8
T_{out} (°C)	16,2	19,2	19,9	21,3
$T_{surface,in}$ (°C)	10,1	10,1	10,1	10,1
$T_{surface,out}$ (°C)	9,9	9,9	10,0	10,0
Pressure Drop (bar)	1,150	1,680	1,900	2,300
Heat Convection Coefficient (Sieder-Tate) (W/mK)	5404	6177	6436	6786
Heat Convection Coefficient (Edwards) (W/mK)	6574	6881	7000	7175
Heat Convection Coefficient (Full Developed) (W/mK)	5918	5934	5942	5955
Heat Convection Coefficient (Experimentally) (W/mK)	4982	5668	6146	6527

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Data Analysis and Important Formulas

The values of Nusselt number, heat transfer coefficient and heat transfer calculations are obtained at the end of this research. The general formula given below of cross-flow heat exchangers was used for calculation heat transfer.

$$Q = \dot{m} * C_p * (T_{out} - T_{in}) \quad (1)$$

$$\dot{m} = \rho * \dot{V} \quad (2)$$

Here $\dot{m}$ is flow rate, C_p is specific heat of nanofluid, T_{in} is the inlet temperature of nanofluid in the microchannel, T_{out} is the outlet temperature of the nanofluid in the microchannel, ρ is density of nanofluid and, $\dot{V}$ indicates the multiplication of nanofluid velocity and surface area at the inlet of microchannel. The general formula of cross-flow heat exchangers is used for calculation of convective heat transfer coefficient as given below.

$$Q = h * A * \Delta T_{ln} \quad (3)$$

$$A = \pi * D * L \quad (4)$$

$$\Delta T_{inlet} = T_{in} - T_{surface,in} \quad (5)$$

$$\Delta T_{out} = T_{out} - T_{surface,\ out} \quad (6)$$

$$\Delta T_{ln} = (\Delta T_{in} - \Delta T_{out}) / \ln(\Delta T_{in} - \Delta T_{out}) \quad (7)$$

In these formulas, A is inner surface area of microchannel, D is the inner diameter of microchannel, L is length of microchannel, $T_{surface,in}$ is the temperature of the inner microchannel surface, $T_{surface,out}$ is the temperature of the outlet surface of the microchannel, ΔT_{ln} is the logarithmic average temperature belonging to the nanofluids, Q is the amount of heat transfer, h is conductive heat transfer coefficient. The following equations were used while calculating Nusselt number. In this formulas, h_i is conductive heat transfer-coefficient of the inner surface of the pipe, Di is the inner diameters of pipe and k is the thermal conductivity coefficient.

$$Nu = (h * D) / k \quad (8)$$

Sieder-Tate(Re<2300)

$$Nu_{the} = 1{,}86 Gz^{1/3} (\mu_b / \mu_s)^{0{,}14} \quad (9)$$

Edwards(Re<2300)

$$Nu_{the} = 3{,}66 + 0{,}065 Gz / (1 + 0{,}04 Gz^{2/3}) \quad (10)$$

Heat Convection Coefficient

$$h_{the} = Nu_{the} k / D_{in} (W / m^2 K) \quad (11)$$

The Principle of the Working System

The piston pump, which draws fluid from the nanofluid tank, was set from the digital indicator. In order to bring the nanofluid to the desired temperature, hot water was supplied through a heat exchanger made of stainless steel material. In the other heat exchanger chamber made of polymer material, in which the micro-tube is located, cold water was simultaneously supplied from the cooling chamber to cool the nanofluid. The pressure regulator, which was connected to the pump, regulates the flow while the pump delivering the nano-fuel from the tank to the system. The nanofluid coming out of the regulator that entering the double tube heat exchanger made of stainless steel material. The nanofluid at the desired temperature that coming out from dual tube heat exchanger enters the micro pipe. The temperature of the nanofluid flowing through the micropipeis reduced with the cold water circulating in the cross flow heat exchanger. is the temperature of it was measured by another temperature sensor located at the outlet of the micro channel. The heat transfer state was examined in terms of the temperature. The nanofluid coming out from the micro-pipe is again poured into the nanofluid tank with the used hoses. This ensures continuity in the system.

Experimental Study

The nano-powders (Al_2O_3-pure water, TiO_2-pure water and ZnO-pure water) initially prepared at volumetric concentrations are also poured into the nanofluid tank at the desired amount. This amount is set with a precision scale. The metal pipes in the system are covered with insulating materials against any heat loss. The connection points on the system are connected with fasteners for preventing any leakage. In the heat chamber, the heated water is heated to a stable temperature value at the nanoparticle inlet temperature of the micro-tube. This stable temperature is monitored from the computer through the data logger located in the system. In the same way, if it is desired to circulate a few degrees of cold water in the heat exchanger reservoir surrounding the micro-pipe, the cooling bath is cooled until the stable temperature condition was obtained. This stable temperature value similarly controlledfrom the computer. By setting the desired flow rate from the flow rate indicator on the pump, nanofluid transfer is started in the system. From this point, the microchannel inlet temperature of the nanofluid and the temperature of the cold water circulating outside the micro tube are expected until the desired value was stabilized. When the required conditions were met, the amount of heat transfer was calculated by the obtained data.

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Table 4. Taguchi Experimental Values.

Test	Factors						
	A	B	C	D	E	F	G
	Tube Material	Tube Diameter µm	Fluid Type	Fluid Volume Concentration	Fluid Temperature °C	Heat Bath Temperature °C	Fluid Flow mL/min
1	SS	381	Al_2O_3	0.5	52.8	11.9	20
2	SS	381	TiO_2	0.7	58.4	24.3	35
3	SS	381	ZnO	1.0	67.0	40.6	50
4	SS	762	Al_2O_3	0.5	56.8	24.2	50
5	SS	762	TiO_2	0.7	72.6	38.9	20
6	SS	762	ZnO	1.0	50.8	9.1	35
7	SS	1026	Al_2O_3	0.7	49.2	38.6	35
8	SS	1026	TiO_2	1.0	58.6	10.4	50
9	SS	1026	ZnO	0.5	73.9	20.0	20
10	PEEK	381	Al_2O_3	1.0	64.6	24.6	35
11	PEEK	381	TiO_2	0.5	47.4	39.9	50
12	PEEK	381	ZnO	0.7	63.8	9.8	20
13	PEEK	762	Al_2O_3	0.7	65.7	10.6	50
14	PEEK	762	TiO_2	1.0	51.6	24.9	20
15	PEEK	762	ZnO	0.5	59.0	40.0	35
16	PEEK	1026	Al_2O_3	1.0	60.4	39.2	20
17	PEEK	1026	TiO_2	0.5	68.0	10.6	35
18	PEEK	1026	ZnO	0.7	47.9	23.7	50

Taguchi Method

The Taguchi method is a very effective method that is used to obtain the best results in long-term and highly variable experiments, which can accommodate many different parameters. Under normal conditions, without using this method, each nanofluid can be used at different concentrations, at different micropipe diameters, different micropipe materials, different flow rates, different temperature values, etc.The excessive number of experiments mustbe done in order to apply each condition. The Taguchi method suggests the optimum number of these parameters and instead of doing thousands of experiments for this study, we present the values that will give the best results in the 18 experiments shown in Table 2. This also saves cost and time.

Numerical Modeling

Numerical modeling analysis was performed with ANSYS CFD (computational fluid dynamics) program. The thermophysical properties of experimentally found nano-fluids were introduced to the program of equations belonging to the given data. The experimental data used

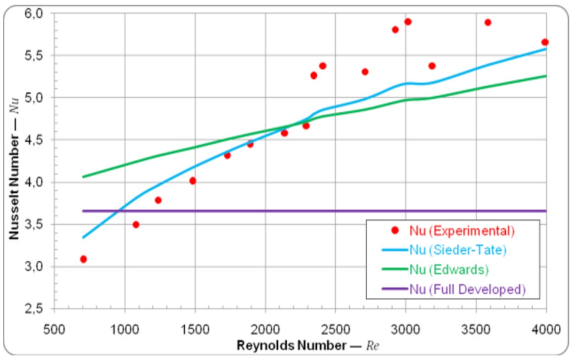

Figure 3. Verification experiments for Nusselt numbers.

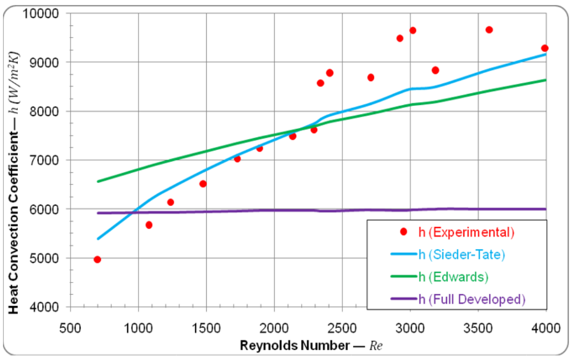

Figure 4. Verification experiments for heat convection coefficient.

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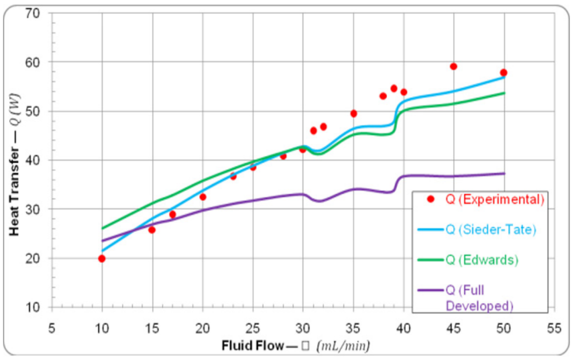

Figure 5. Verification experiments for heat transfer.

in Table 4 are compared with the numerical modeling.

RESULTS AND DISCUSSION

Verification Experiments Results

As shown in Fig. 3 and Fig. 4, Nusselt numbers and heat transfer coefficients are calculated using the Sieder-Tate and Edwards equations, and they were shown on the figure by curve fitting method. Fig. 5 shows the amount

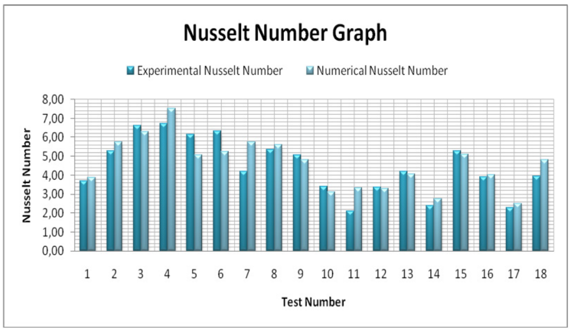

Figure 6. Nusselt number graphic.

of heat transfer obtained by using these results. Experimental Nusselt numbers and heat transfer coefficients obtained from the test results were also transferred by the curve fitting method and compared with the results calculated by formulas. Also in Figure 5, the calculated heat transfer amount from the experimental results was compared with the results found in the formulas. In these

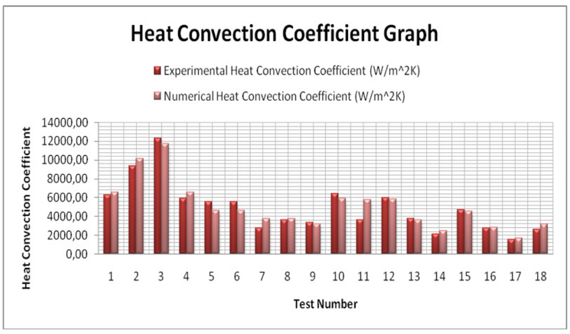

Figure 7. Heat convection coefficient graphic.

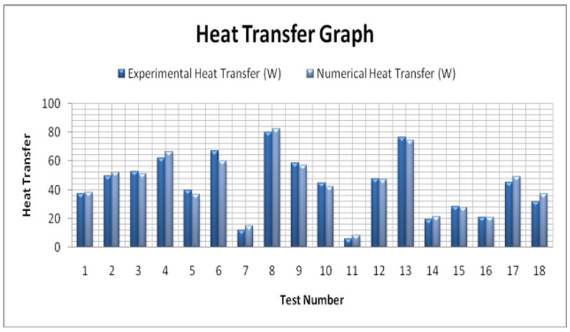

Figure 8. Heat transfer graphic.

graphs the relation between Nusselt numbers and heat transfer coefficients with Reynolds value are shown. The results that using the formulas in the literature obtained were close to the experimental results. Experiments have been carried out in a number of different ways to see the transition regime between the laminar flow and the turbulent flow. Fig. 6, 7, and 8 show the Nusselt numbers,

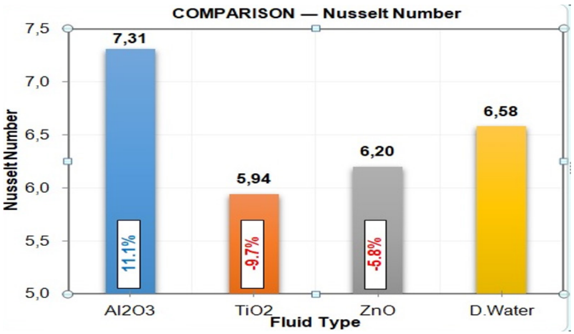

Figure 9. Comparison of Nusselt numbers compared to fluid types.

heat transfer coefficients and heat transfer quantities found in the experiments with the optimum experimental parameters presented by the Taguchi table, and the Nusselt numbers, heat transfer coefficients and heat transfer quantities found in the numerical studies in the same parameters. As can be seen in Fig. 11, the best thermal performance was achieved with the Al_2O_3-water nanofluid. Compared to pure water, 15.3% higher heat transfer was achieved. The second best performer is the nanofluid

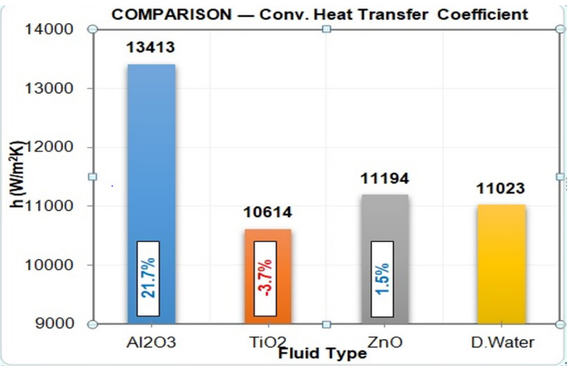

Figure 10. Comparison of heat convection coefficient compared to fluid types.

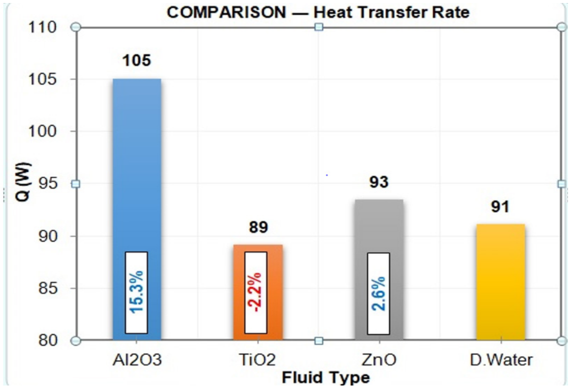

Figure 11. Comparison of heat transfer rate compared to fluid types.

ZnO-water nanofluid. 2.2% less heat transfer than water was obtained with TiO_2.

CONCLUSION

In this study, the Nusselt number, heat transfer coefficients and heat transfer amount of Al_2O_3-water, TiO_2-water and ZnO-water nanofluids flowing in a horizontal circular microchannel under constant surface temperature conditions were calculated experimentally and numerically. Pure waterwas used as the base liquid. The results can briefly given as follows:

1)The concentrations and waiting times of the nanoparticles should be well adjusted. If it's not set well, there might be crashes in the nanofluid and sedimentation may occur. Nanoparticles in the melt can cause plugging of the tubes. This can adversely affect both the operation of the system and the thermal performance.

2)The equations given in the literature used in the calculations should be chosen according to the ambient conditions used in the experiments.

3)When the pipe diameter is reduced, the heat transfer rate was increasing.

4) The best thermal performance was obtained with Al2O3-water nanofluid.

5) Nanoparticles with the highest thermal conductivity capacity may not provide the best value for heat transfer. The thermal conductivity of the ZnO nanoparticle was higher than that of the other nanoparticles, but the Al_2O_3-water nanofluid had the highest heat transfer value as a result of the experiments.

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