

Article

Experimental and Numerical Study of Forced Convection of Water/EG- Al_2O_3 Nanofluids

Przemysław Kozak ¹, Jacek Barański ² and Janusz T. Cieśliński ^{2,*} ¹ Independent Researcher, 83-034 Trąbki Wielkie, Poland; ozariasz@go2.pl² Institute of Energy, Gdańsk University of Technology, Narutowicza 11/12, 80-233 Gdańsk, Poland; jacek.baranski@pg.edu.pl

* Correspondence: jcieslin@pg.edu.pl

Abstract

This paper presents the results of numerical and experimental studies of forced convection of water/EG- Al_2O_3 nanofluids through a horizontal stainless steel tube (8 mm inner diameter; 2000 mm length). As a base fluid, distilled water/EG mixture of three volume ratios (90:10, 80:20, and 60:40) is used. Nanoparticle mass concentrations are 0.1%, 1%, and 5%. The tested nanofluids are prepared by use of the two-step method. No dispersant is used to stabilize the suspension. Transition and turbulent flow regimes are tested. The commercial code Ansys Fluent 19.3 is used to conduct numerical simulations. A $k-\epsilon$ turbulence model with an expanded boundary layer function is adopted. A homogeneous nanofluid model is assumed, with thermophysical properties depending on the mean fluid temperature and nanoparticle concentration. The nanofluids are treated as incompressible Newtonian fluids. Both experimental and numerical studies showed an increase in the average Nusselt number with the addition of Al_2O_3 nanoparticles to each of the water/EG mixtures. However, the experimental results indicated that, at the maximum mass nanoparticle concentration of 5%, the Nusselt number increased by 42%, whereas the numerical simulations showed an increase of only 16% compared with the base fluid. Both experimental studies and numerical simulations show the flow resistance of the nanofluid increases with increasing nanoparticle concentration. Similarly to heat transfer, the numerical calculations predict lower pressure drops than those observed experimentally. For the maximum nanoparticle mass concentration of 5%, the experimental results indicate an increase in nanofluid flow resistance of about 95%, while numerical simulations predict an increase of about 50%, compared to the base liquid. The generalized correlation equations are proposed to calculate the average Nusselt number and the friction factor valid for the turbulent flow of water-based nanofluids and water/EG mixtures with a volumetric water fraction above 60% and a mass concentration of nanoparticles in the range of $0.1\% \leq \varphi_m \leq 5\%$.



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1. Introduction

It is hard to imagine any energy system that is not equipped with heat exchangers. Despite considerable efforts by numerous research groups, the problem of proper heat exchanger design (PHExD) remains a significant challenge. By PHExD one should understand a process whose outcome is a heat exchanger characterized by low capital costs and, at the same time, the lowest possible operating costs. In order to achieve low capital costs, the heat transfer process in the heat exchanger should be intensified to the maximum extent

possible. The literature presents numerous methods—active and passive—for heat transfer enhancement. In turn, low operating costs mean that the heat exchanger is characterized by low flow resistance and thus low costs associated with pumping power. The problem is that most heat transfer enhancement methods lead to an increase in flow resistance. It is worth noting that the heat transfer surface and the fluid flowing over it form a thermal system, in which heat transfer enhancement can be achieved by modifying the surface structure, the fluid properties, or by influencing both factors simultaneously. Therefore, the practical application of a heat transfer enhancement technique requires costly, laborious, and time-consuming experimental studies. To accelerate PHExD, the use of numerical tools becomes essential.

Automotive radiators are among the most mass-produced heat exchangers; therefore, even a slight reduction in their dimensions and weight—resulting from heat transfer enhancement—would yield enormous savings through reduced material consumption and, consequently, reduced energy required for their manufacture. Commonly used coolants in automotive systems are mixtures of water and ethylene glycol (EG), because even a small addition of EG lowers the freezing point far below that of pure water. The problem is the low thermal conductivity of EG and therefore low heat transfer intensity. The solution is to add particles with a high thermal conductivity to the water/EG mixture. If the particles are less than 100 nm in size, the resulting mixture is called a nanofluid [1].

In view of the comprehensive literature reviews already available on forced convection of nanofluids, e.g., [2–9], Table 1 includes only studies on nanofluids based on a mixture of water and EG.

Table 1. Summary of studies on forced convection water/EG based nanofluids.

Authors	Water/EG Mixture	Nanoparticles	Flow Regime	Approach
Kulkarni et al. [10]	(40/60) _{wt}	SiO ₂	Turbulent	Experiment
Namburu et al. [11]	(40/60) _{wt}	Al ₂ O ₃ , SiO ₂ , CuO	Turbulent	Numerical
Vajjha et al. [12]	(40/60) _{wt}	Al ₂ O ₃ , SiO ₂ , CuO	Turbulent	Experiment
Timofeeva et al. [13]	(40/60) _{vol}	SiC	Turbulent	Experiment
Ebrahimnia-Bajestan et al. [14]	(40/60) _{wt}	Al ₂ O ₃ , CuO, CNT, TNT	Laminar	Numerical
Bayat and Nikseresht [15,16]	(40/60) _{wt}	Al ₂ O ₃	Laminar Turbulent	Numerical
Yu et al. [17]	(55/45) _{vol}	Al ₂ O ₃	Laminar	Experiment
Kumaresan et al. [18]	(70/30) _{vol}	CNT	Laminar/ Turbulent	Experiment
Feng and Li [19]	(50/50) _{vol}	SiO ₂	Laminar	Experiment
Mojarrad et al. [20]	(50/50) _{vol}	Al ₂ O ₃	Laminar	Experiment
Chiney et al. [21]	(50/50)	Al ₂ O ₃	Laminar	Experiment
Bubbico et al. [22]	(50/50)	Al ₂ O ₃	Laminar/ turbulent	Experiment
Usri et al. [23]	(60/40) _{wt}	Al ₂ O ₃	Turbulent	Experiment
Cabaleiro et al. [24]	(50/50) _{vol}	ZnO	Laminar	Experiment
Patel and Subhedar [25]	(50/50)	Al ₂ O ₃	Laminar	Experiment
Selvam et al. [26]	(70/30) _{vol}	Ag	Laminar Transition Turbulent	Experiment

Table 1. Cont.

Authors	Water/EG Mixture	Nanoparticles	Flow Regime	Approach
Azmi et al. [27]	(60/40) _{vol}	TiO ₂	Turbulent	Experiment
Hamid et al. [28]	(60/40) _{vol}	TiO ₂	Transition/ turbulent	Experiment
Selvam et al. [29]	(30/70) _{vol}	GnP	Laminar/ Transition/ Turbulent	Experiment
Azmi et al. [30]	(60/40) _{vol} (50/50) _{vol} (40/60) _{vol}	Al ₂ O ₃	Turbulent	Experiment
Singh et al. [31]	(40/60) _{wt}	Al ₂ O ₃	Laminar	Experiment
Boertz et al. [32]	(40/60) _{wt}	SiO ₂	Turbulent	Numerical
Sajjad et al. [33]	(40/60) _{wt}	GO	Laminar	Numerical
Krishnakumar et al. [34]	(40/60) _{vol}	TiO ₂	Laminar	Experiment
Choi et al. [35]	(50/50) _{vol}	Al ₂ O ₃	Turbulent	Experiment
Singh et al. [36]	(60/40) _{wt}	CuO	Laminar	Experiment
Boukerma and Kadja [37]	(50/50) _{vol}	Al ₂ O ₃	Laminar	Numerical
Tetik and Kargoz [38]	(70/30)	Al ₂ O ₃ –SiO ₂ –TiO ₂	—	Experiment
Gürsoy et al. [39]	(50/50) _{vol}	GO+MXene	Laminar	Numerical
Asirinaidu [40]	(80/20) _{vol}	MWCNT/Al ₂ O ₃	Laminar	Numerical/ Experiment
Minh [41]	(60/40)	Al ₂ O ₃ , CuO	Laminar	Numerical
Gupta et al. [42]	(0/100)	Al ₂ O ₃	Laminar	Numerical/ Experiment

As shown in Table 1, the published studies focus on nanofluids based on water/EG mixtures with EG content in the range of (30–70)%. In most studies, the EG fraction in the mixture does not exceed 60%. This is due to the fact that the freezing point of the water/EG (40:60)_{wt} mixture is $-48.3\text{ }^{\circ}\text{C}$ [43]. It is worth noting that, for EG fraction greater than 70% and less than 60%, the freezing point temperature of the water/EG mixture is higher.

Generalizing measurement results in the form of correlations or conducting numerical simulations requires knowledge of the thermophysical properties of nanofluids, including the base fluids. Therefore, in parallel with experimental studies and numerical simulations, intensive research is ongoing to precisely determine the thermophysical properties of nanofluids and base fluids, which are mixtures of water and EG. Correlations for calculating thermophysical properties of water/EG mixtures, including thermal conductivity, can be found for example in [44–55], viscosity in [56–60], specific heat [61], density [62], surface tension [63], and electrical conductivity [64].

This paper investigates the single-phase convection process in a straight, horizontal nanofluid tube based on three water/EG mixtures with varying proportions and the addition of Al₂O₃. The novelty of this work is the use of an integrated empirical–analytical–numerical approach to study the process. The results of experimental investigations and numerical simulations of heat transfer and flow resistance for nine nanofluids are presented. The nanofluids were prepared using exactly the same method, and the experimental tests were carried out following an identical measurement procedure. The experimental and numerical results were processed using the same correlations for the thermophysical properties of the nanofluids. Particular attention was paid to viscosity and thermal conductivity as parameters of crucial importance in convective processes. Commonly accepted literature correlations were selected, and they were verified by our own measurements of viscosity and thermal conductivity. Original empirical correlations were proposed for calculating

the heat transfer coefficient and the friction factor for nanofluids based on three water–EG mixtures under turbulent conditions.

2. Materials and Methods

The stand for determining the thermal and flow characteristics of nanofluids consists of a heating section, an electrical power supply system, a circulation system for the tested fluid, a reservoir, and a cooling system. The run-in sections were selected to ensure undisturbed flow at the inlet and outlet of the measurement section. To reduce heat loss to the environment, the heating section was insulated with a 2 cm thick layer of mineral wool. The heat flux transferred to the tested liquid was determined as the product of the electric current flowing through the heating tube and the voltage drop across the tube. Current and voltage drop measurements were performed using an electric meter MT8045 (MCP, Shanghai, China) with True RMS capability. A PMMA tank was used as a reservoir for the tested liquid. The material's transparency enabled observation of any nanoparticle deposition during the experiment. Furthermore, the tank was designed to be disassembled, allowing for thorough cleaning. The tank was filled through a filler neck located above, terminated with a ball valve. The flow of the test liquid was forced by a centrifugal pump PQAm60 (PEDROLLO, San Bonifacio, Italy). The mass flow rate of the tested nanofluids was measured by use of a mass flow meter MASSFLO MASS2100 (DANFOSS, Nordorg, Denmark). Flow resistance was measured by a differential pressure transducer DMD831 (SIMEX, Nowe Miasto Lubawskie, Poland). A plate heat exchanger connected to municipal cold-water supply was used to cool the test fluid after it passed through the heated tube. The coolant flow rate was regulated by a throttle valve. A turbine flowmeter mounted between the throttle valve and the plate heat exchanger allowed for the measurement of the coolant flow rate. Figure 1 shows a diagram of the measurement system used to determine the thermal and flow characteristics of the tested nanofluids.

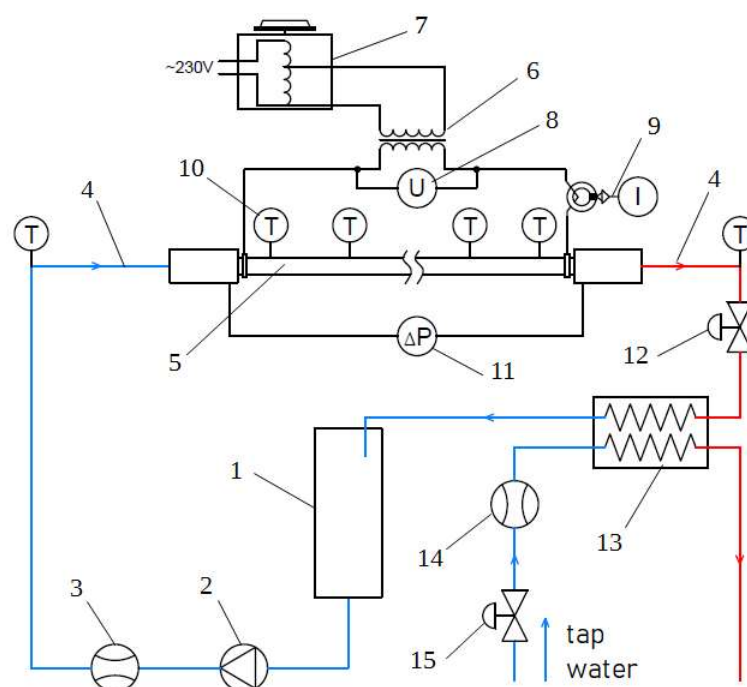


Figure 1. Scheme of the test stand; 1—tank, 2—centrifugal pump, 3—flow meter, 4—run-up sections, 5—test tube, 6—transformer, 7—autotransformer, 8—voltmeter, 9—clamp ammeter, 10—temperature sensors, 11—differential pressure transducer, 12—control valve, 13—plate heat exchanger, 14—flow meter, 15—cooling water control valve.

2.1. Heating Tube

The 2000 mm long, 8 mm internal diameter, and 10 mm external diameter heating tube was made of 304L stainless steel. The heating tube was connected to the transformer bank via copper terminals and functioned as an electrical resistor. The heating tube was thermally and electrically isolated from the system using PTFE mounting sleeves. A clamp allowed the mounting element to be tightened onto the tube, ensuring a tight seal. Sheathed Pt100 class A resistance temperature sensors were used to measure the liquid temperature. Six thin-film Pt100 class A resistance temperature sensors (CZAH-POMIAR, Chorzów, Poland), attached to the tube with thermally conductive adhesive, were used to measure the tube surface temperature. All temperature sensors were connected to ER303 displays (EDO, Prudnik, Poland). Figure 2 shows details of the heating section.

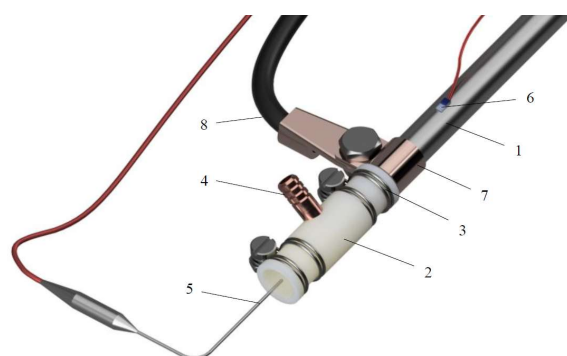


Figure 2. Heating section: 1—heating tube, 2—fastening and insulating element, 3—clamps, 4—connector, 5—sheathed resistance temperature sensor, 6—thin-film resistance temperature sensor, 7—connection terminal, 8—connection cable.

2.2. Materials

Table 2 presents a summary of the produced nanofluids used to determine thermo-physical properties and thermal-flow tests.

Table 2. Tested nanofluids.

Base Fluid	Nanoparticles	Mass Concentration [%]
water/EG (90:10) _{vol}	Al ₂ O ₃	0.1; 1.0; 5.0
water/EG (80:20) _{vol}		
water/EG (60:40) _{vol}		

For the nanoparticles, alumina was used. The nanoparticles had a spherical form and their diameter was in a range from 5 to 250 nm, while their mean diameter was 47 nm according to the manufacturer Sigma Aldrich Ltd. (Munich, Germany). The properties of alumina (Al₂O₃) nanoparticles are shown in Table 3.

Table 3. The properties of alumina (Al₂O₃) nanoparticles.

Density [65] ρ_p [kg/m ³]	Specific Heat [65] c_{pp} [J/(kgK)]	Thermal Conductivity [66] k_p [W/(mK)]
3600	765	35

The nanofluids were prepared using a two-step method. A SARTORIUS LP420 precision laboratory balance (SARTORIUS AG., Göttingen, Germany) with a weighing range of up to 420 g and an accuracy of ± 0.01 g was used to measure the mass of the nanoparticles, while a BONSO 323 balance (BONSO, Hongkong, China) with a weighing range of up to

5000 g and an accuracy of ± 1 g was used to weigh the base liquid. After weighing the appropriate amount, the nanoparticles and the base liquid were placed in a tank equipped with a coil. Next, a high-speed X1740 homogenizer (CAT, Ballrechten-Dottingen, Germany) with adjustable speeds ranging from 2500 to 23,500 rpm was placed in the vessel, and the nanofluid was then mixed for 30 min at 7000 rpm. A coil installed in the tank, connected to cold water, allowed the temperature of the prepared nanofluid to be maintained within the range of 20 ± 0.5 °C. The tank was then transferred to a UNITRA ultrasonic bath (UNITRA, Olsztyn, Poland) equipped with 12 piezoelectric transducers with an operating frequency of 35 kHz and a total power of 1000 W. The ultrasonication time for the prepared nanofluid was 30 min. A cooling system was also used to ensure a constant nanofluid temperature of 20 ± 0.5 °C. Figure 3 shows a view of the prepared nanofluids.

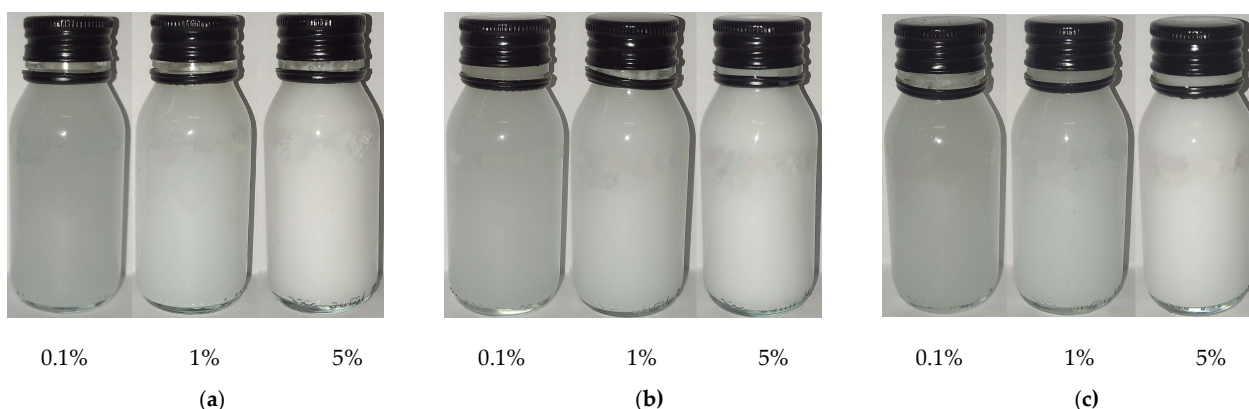


Figure 3. Tested nanofluids: (a) water/EG (90:10)_{vol}-Al₂O₃; (b) water/EG (80:20)_{vol}-Al₂O₃; (c) water/EG (60:40)_{vol}-Al₂O₃.

2.3. Stability of the Tested Nanofluids

Stability of the nanofluids is a crucial factor in the application of nanofluids that can alter not only the thermophysical properties of nanofluids but also the characteristics of the heating surface [67,68]. The fabricated nanofluids were subjected to experimental testing immediately after production to avoid potential sedimentation of the nanoparticles. An AL250T-IR laboratory turbidimeter (AQUALITYC, Dortmund, Germany) was used to determine the stability of the tested nanofluids. Because the turbidity meter's measurement range was 0.01–1000 NTU, it was possible to measure turbidity for nanofluids with a mass concentration of 0.1% and 1%. Measurements were taken daily over a one-week period. The results of the turbidity measurement of the tested nanofluids are shown in Figure 4.

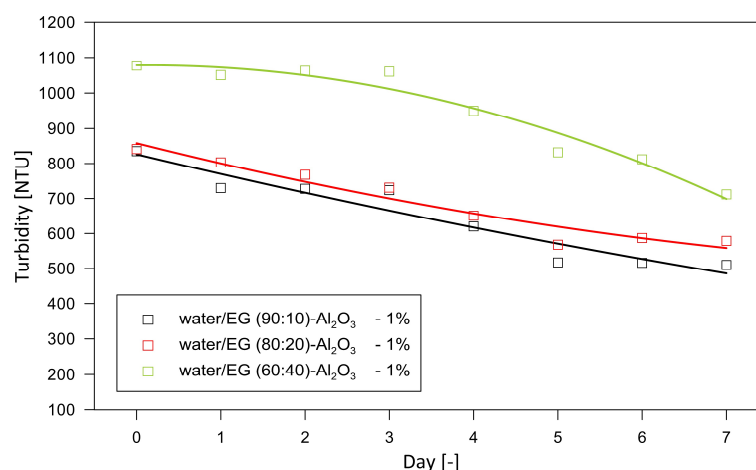


Figure 4. Turbidity of the tested nanofluids as a function of the days of the week.

The turbidity of the nanofluids with a mass concentration of 5% exceeded the device's measurement range. In these cases, direct observation of the produced samples was used as the method for assessing nanofluid stability. As an example, Figure 5 shows photographs of the water-EG (90:10)-Al₂O₃ (5%) samples taken immediately after preparation (Figure 5a), after 24 h (Figure 5b), and one week after preparation (Figure 5c). A comparison of the images indicates that the nanofluid sample became progressively lighter in color, which suggests partial sedimentation of the nanoparticles. However, if one takes into account that the total duration of a single measurement series was 3.5 h, it can be assumed that the prepared nanofluids were sufficiently stable for this not to affect the measurement results.

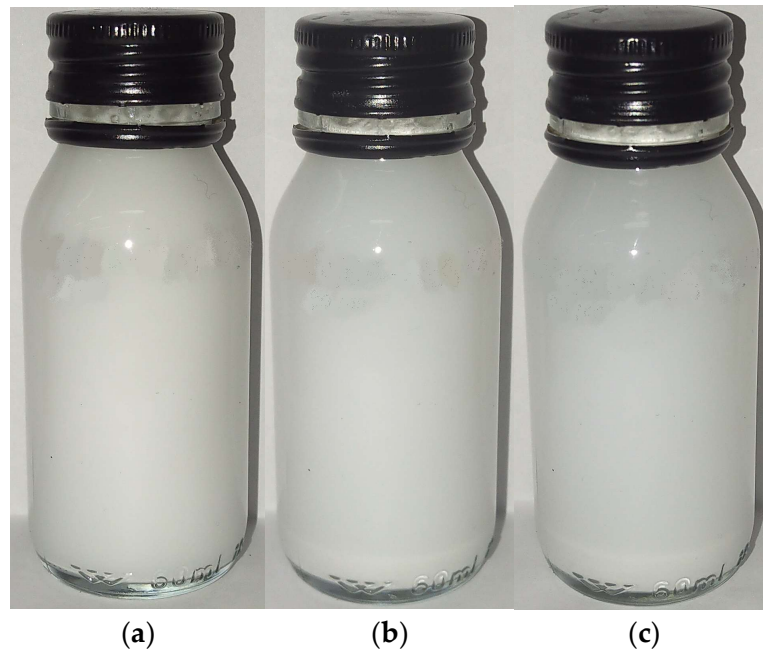


Figure 5. Photographs of the water/EG (90:10)-Al₂O₃ nanofluid with a nanoparticle mass concentration of 5%: (a) sample just after fabrication; (b) sample after 24 h; (c) sample after one week.

2.4. Properties of the Tested Nanofluids

The literature results show the fundamental role of the effective thermal conductivity and the effective viscosity of nanofluids in forced convection heat transfer. Therefore, both of these parameters were determined with special care. Finally, the Corcione formula [69] was used to calculate the thermal conductivity of the tested nanofluids, as it is the only one that takes into account the freezing temperature:

$$k_{nf} = k_{bf} \left(1 + 4.4 Re^{0.4} Pr^{0.66} \left(\frac{T}{T_{fr}} \right)^{10} \left(\frac{k_p}{k_{bf}} \right)^{0.03} \phi_v^{0.66} \right) \quad (1)$$

where $Re = \frac{2\rho_{bf}k_B T}{\pi\mu_{bf}^2 d_p}$ and $k_B = 1.3807 \cdot 10^{-23}$ J/K (Boltzmann constant).

To confirm the accuracy of the thermal conductivity calculations for the tested nanofluids using Equation (1), verification measurements were performed using a KD2 Thermal Properties Analyzer from Decagon Devices Inc. (Pullman, WA, USA). All calculated thermal conductivity values were within the meter's measurement error of $\pm 5\%$.

Consistently, the Corcione formula [69] was used to calculate the dynamic viscosity of the tested nanofluids:

$$\mu_{nf} = \mu_{bf} \left(\frac{1}{1 - 34.87 (d_p/d_m)^{-0.3} \phi_v^{1.03}} \right) \quad (2)$$

where $d_m = \left[\frac{6M}{\pi N \rho_{bf,0}} \right]^{1/3}$ —molecule diameter, $N = 6.02214 \times 10^{23}$ —Avogadro number, and $\rho_{bf,0}$ —density of the base fluid at 293 K.

To confirm the accuracy of the dynamic viscosity calculations of the tested nanofluids using Equation (2), verification measurements were performed using a capillary viscometer Rheotest LK 2.2 Medingen GmbH (Medingen, Germany) coupled with an Alpha A6 thermostat (Lauda-Brinkmann, Lauda-Königshofen, Germany).

Density and specific heat of the tested nanofluids were determined by use of Equations (3) and (4) proposed by Pak and Cho [70], respectively:

$$\rho_{nf} = \varphi \rho_p + (1 - \varphi) \rho_{bf} \quad (3)$$

$$c_{p,nf} = \varphi c_{p,p} + (1 - \varphi) c_{p,bf} \quad (4)$$

Thermophysical properties of the base fluids, i.e., water/EG mixtures, were obtained from the data provided in the ASHRAE Handbook [71]. The appropriate correlations are shown in Tables 4–7. Table 8 shows the Prandtl number for the studied temperature range.

Table 4. Thermal conductivity of the base fluids.

Liquid	Correlation	Equation Number
Water/EG (90:10)	$k_{bf} = 0.51118 + 1.8488095 \cdot 10^{-3}t - 8.3333 \cdot 10^{-6}t^2$	(5)
Water/EG (80:20)	$k_{bf} = 0.467143 + 1.645238 \cdot 10^{-3}t - 8.0952 \cdot 10^{-6}t^2$	(6)
Water/EG (60:40)	$k_{bf} = 0.39371 + 1.1714 \cdot 10^{-3}t - 5.7143 \cdot 10^{-6}t^2$	(7)

Table 5. Dynamic viscosity of the base fluids.

Liquid	Correlation	Equation Number
Water/EG (90:10)	$\mu_{bf} = 2.039762 - 0.0562t + 8.48485 \times 10^{-4}t^2 - 5.4545 \times 10^{-6}t^3$	(8)
Water/EG (80:20)	$\mu_{bf} = 2.90643 - 0.086077t + 13.4459 \times 10^{-4}t^2 - 8.6869 \times 10^{-6}t^3$	(9)
Water/EG (60:40)	$\mu_{bf} = 5.477857 - 0.1718658t - 26.3593 \times 10^{-4}t^2 - 16.3636 \times 10^{-6}t^3$	(10)

Table 6. Density of the base fluids.

Liquid	Correlation	Equation Number
Water/EG (90:10)	$\rho_{bf} = 1018.725 - 0.220512t - 0.002436t^2$	(11)
Water/EG (80:20)	$\rho_{bf} = 1035.666 - 0.248631t - 0.002431t^2$	(12)
Water/EG (60:40)	$\rho_{bf} = 1066.802 - 0.307179t - 0.002436t^2$	(13)

Table 7. Specific heat of the base fluids.

Liquid	Correlation	Equation Number
Water/EG (90:10)	$c_{p,bf} = 3936.554 + 1.782143t + 0.000714t^2$	(14)
Water/EG (80:20)	$c_{p,bf} = 3768.595 + 2.30476t$	(15)
Water/EG (60:40)	$c_{p,bf} = 3400.738 + 3.361905t$	(16)

Table 8. Prandtl number of the tested fluids.

Liquid	Pr
Water/EG (90:10)	7.2–7.4
Water/EG (80:20)	9.8–10.0
Water/EG (60:40)	19.8–20.2
Water/EG(90:10)-Al ₂ O ₃ (0.1%)	7.4–7.6
Water/EG(90:10)-Al ₂ O ₃ (1%)	7.8–7.9
Water/EG(90:10)-Al ₂ O ₃ (5%)	9.4–9.7
Water/EG(80:20)-Al ₂ O ₃ (0.1%)	9.9–10.1
Water/EG(80:20)-Al ₂ O ₃ (1%)	11.3–11.6
Water/EG(80:20)-Al ₂ O ₃ (5%)	12.5–12.8
Water/EG(60:40)-Al ₂ O ₃ (0.1%)	19.1–19.5
Water/EG(60:40)-Al ₂ O ₃ (1%)	20.7–21.2
Water/EG(60:40)-Al ₂ O ₃ (5%)	24.0–24.5

2.5. Measurement Uncertainty

The inaccuracy of determining the heat flux density $\Delta\dot{q}$ was estimated as the mean square error

$$\Delta\dot{q} = \sqrt{\left(\frac{\partial\dot{q}}{\partial U}\Delta U\right)^2 + \left(\frac{\partial\dot{q}}{\partial I}\Delta I\right)^2 + \left(\frac{\partial\dot{q}}{\partial d_i}\Delta d_i\right)^2 + \left(\frac{\partial\dot{q}}{\partial L}\Delta L\right)^2} \quad (17)$$

where the absolute errors of the voltage drop ΔU , the current ΔI , the tube inner diameter Δd_i , and the active tube length ΔL are 1.5% $\times$ ww, ± 0.02 mm, and ± 5 mm, respectively. “ww” denotes the value indicated by the meter. The mean relative error of the heat flux density determination $\Delta\dot{q}/\dot{q}$ is $\pm 3.6\%$.

The inaccuracy of determining the average heat transfer coefficient was estimated as the root mean square error

$$\Delta\bar{\alpha} = \sqrt{\left(\frac{\partial\bar{\alpha}}{\partial\dot{q}}\Delta\dot{q}\right)^2 + \left(\frac{\partial\bar{\alpha}}{\partial\Delta T}\delta\Delta T\right)^2} \quad (18)$$

where the absolute error of temperature measurement using class A Pt100 resistance sensors is $\delta\Delta T = \pm 0.1 + 0.0017t$; hence, the average relative error in determining the average heat transfer coefficient $\Delta\bar{\alpha}/\bar{\alpha}$ is $\pm 0.3\%$.

2.6. Experimental Procedure

Before each measurement series, the heating tube was cleaned using a cotton swab and rinsed repeatedly with running water. The entire system was then rinsed with distilled water. After emptying the system, it was filled with the previously prepared nanofluid. After starting the circulation pump and setting its speed to ensure the required flow rate of the tested liquid, the cooling water circuit and the electrical power supply were turned on. The electrical power supply parameters were set to achieve a heat flow of 1000 ± 50 W. The cooling liquid flow was then adjusted to maintain the temperature of the tested liquid at the inlet to the measuring section at 25 ± 0.1 °C. After achieving a steady state, i.e., one in which the resistance thermometer readings did not change by more than ± 0.01 K within 15 min, the measured values were read and recorded. After saving the data, the setting of the circulation pump was changed and then the steps were repeated for the next mass flow rate of the tested liquid.

3. Experimental Results

3.1. Validation of the Research Methods

Figure 6 shows a comparison of the average Nusselt number against the Reynolds number for distilled water determined experimentally and calculated from the Dittus–Boelter correlation [72]

$$\overline{Nu} = 0.23Re^{0.8}Pr^{0.4} \quad (19)$$

and Kraussold correlation [73]

$$\overline{Nu} = 0.032Re^{0.8}Pr^{0.37}\left(\frac{L}{d}\right)^{-0.054} \quad (20)$$

Both correlations reflect the experimental results within $\pm 5\%$ over the entire Reynolds number range, which may indicate the proper selection of the measuring equipment and the correctness of the applied measurement procedure and allow for conclusions about the influence of nanoparticles on heat transfer in turbulent flow conditions.

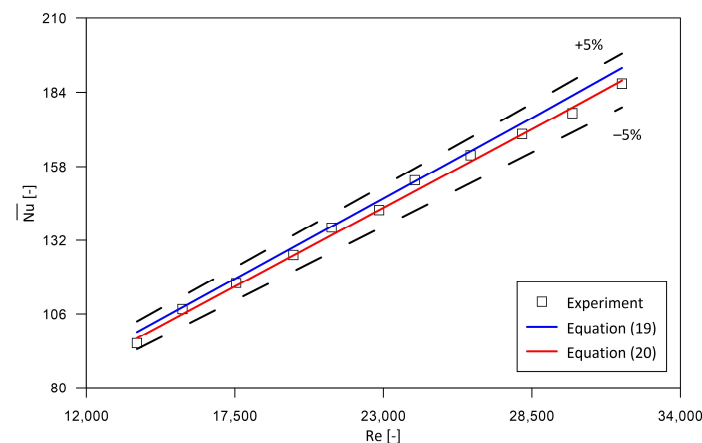


Figure 6. Experimental procedure validation results.

3.2. Experimental Results for the Nanofluids

For all three tested water/EG- Al_2O_3 nanofluids, increase in the average Nusselt number was observed with increasing nanoparticle concentration. As an example, Figure 7 shows the dependence of the average Nusselt number versus the Reynolds number for the water/EG (60:40)- Al_2O_3 nanofluid. The maximum increase in the average Nusselt number for the nanofluid was about 40% compared to the base fluid for the same Reynolds number.

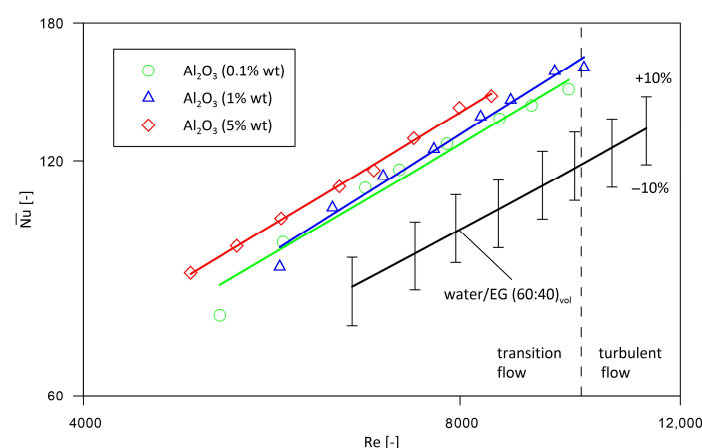


Figure 7. Relationship $\overline{Nu}$ – Re for water/EG (60:40)_{vol}- Al_2O_3 nanofluid.

Regardless of the tested nanofluid, water/EG- Al_2O_3 increase in the pressure drop was observed with increasing nanoparticle concentration. As an example, Figure 8 shows the relationship between pressure drop against Reynolds number for water/EG (90:10)- Al_2O_3 nanofluid. The addition of nanoparticles increases flow resistance, and this resistance increases with nanoparticle concentration. The maximum increase in the pressure drop for the nanofluid was about 95% compared to the base fluid for the same Reynolds number. This is due to the nanofluid having a higher viscosity than the base fluid, with viscosity increasing as nanoparticle concentration increases.

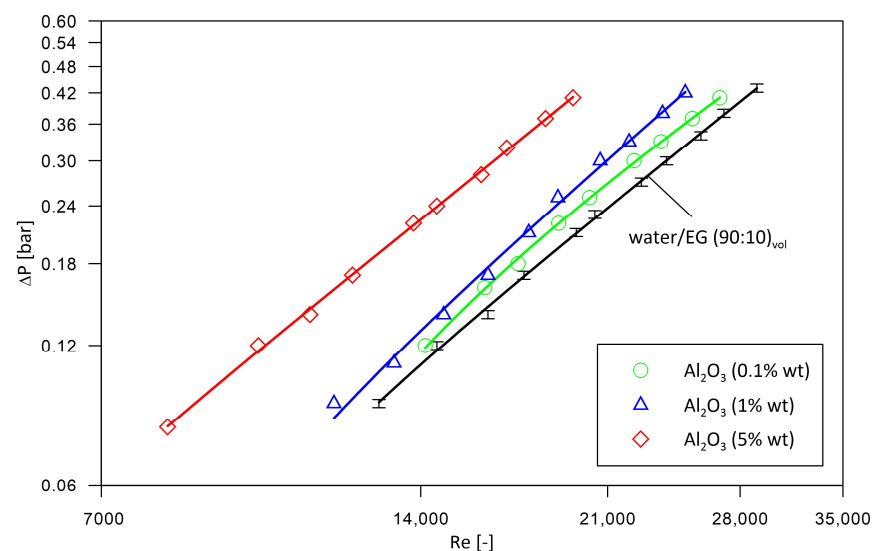


Figure 8. Flow resistance for water/EG (90:10)_{vol}- Al_2O_3 nanofluid.

Figure 9 presents the relationship between the average Nusselt number and the Reynolds number developed for the three nanofluids tested. It is evident that, at a given Reynolds number, the average Nusselt number increases with the EG fraction in the water–EG mixture. However, maintaining the same Reynolds number for a fluid with higher viscosity requires increasing the flow velocity in proportion to the increase in viscosity. This leads to higher flow resistance and, consequently, greater pumping power.

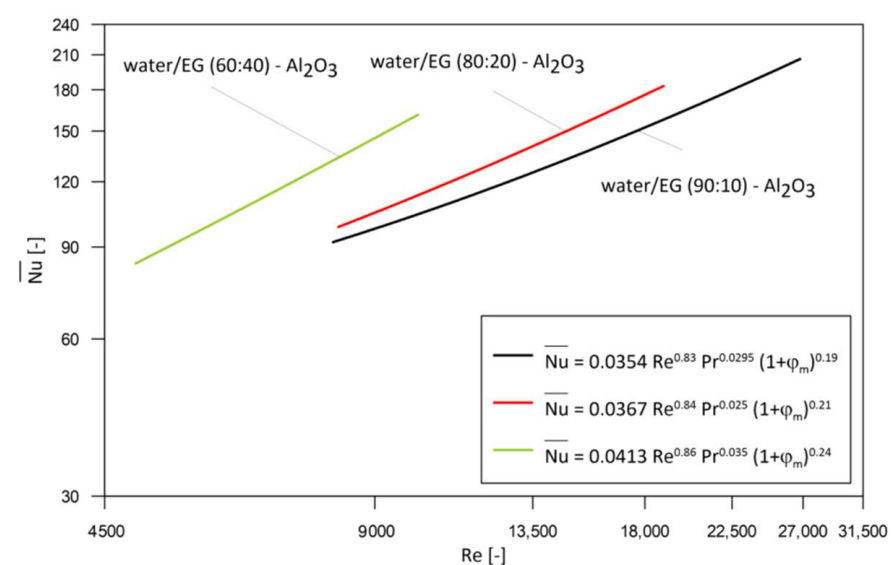


Figure 9. Influence of EG content in the base mixture on the average Nusselt number of nanofluids.

3.3. Correlation Equations

Based on multivariate regression analysis, an own correlation equation was developed to determine the average Nusselt number for nanofluids based on water–EG mixtures with a water volume content (WVC) in the range of $0.6 \leq \text{WVC} \leq 0.9$ in the form:

$$\overline{Nu} = 0.0374 Re^{0.81} Pr^{0.0294} WVC^{-1.1} (1 + \varphi_m)^{0.19} \quad (21)$$

Figure 10 shows a comparison of experimental results for the tested nanofluids based on water–EG mixtures, with calculations performed using the proposed correlation (Equation (21)). As shown in Figure 10, for 93.5% of the points, the difference between the measured and calculated values does not exceed $\pm 15\%$. Given the complexity of the process under investigation, the achieved result can be considered as satisfactory.

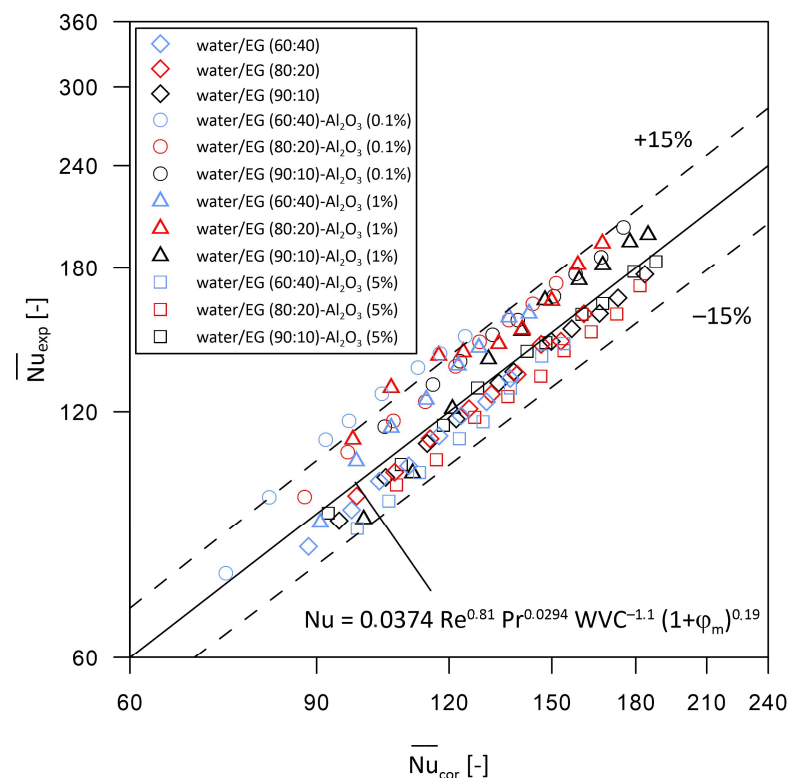


Figure 10. Comparison of experimental and correlation-based average Nusselt number.

Based on multivariate regression analysis, a correlation equation was developed to determine the friction factor for nanofluids based on water–EG mixtures with a water volume content in the range of $0.6 \leq \text{WVC} \leq 0.9$ in the form

$$f = \frac{0.311}{Re^{0.24}} WVC^{-0.08} (1 + \varphi_m)^{0.047} \quad (22)$$

Figure 11 shows a comparison of experimental results for the tested nanofluids based on water–ethylene glycol mixtures, with calculations performed using the proposed correlation (Equation (22)). As shown in Figure 11, the difference between the measured and calculated values does not exceed $\pm 15\%$ for any of the data points.

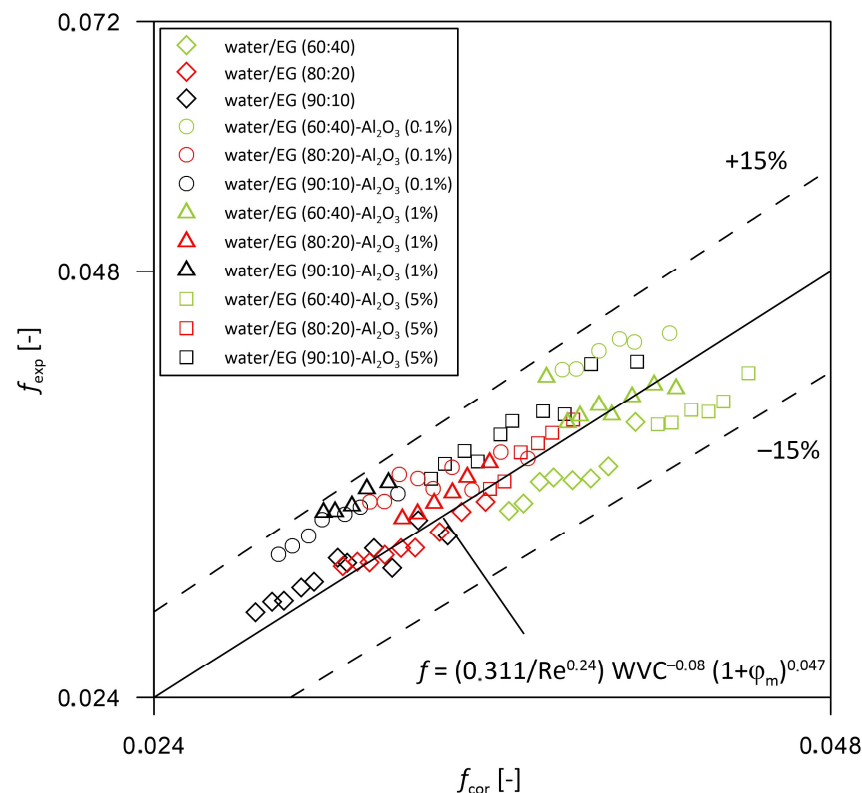


Figure 11. Comparison of experimental and correlation-based friction factor.

4. Numerical Simulations

To conduct numerical simulations, the commercial code ANSYS Fluent 19.3 was used. The $k-\epsilon$ turbulence model with an expanded boundary layer function and an enhanced wall treatment was adopted. The studied problem was solved using a 3D model. The structured mesh was used to discretize the model. Due to symmetry of the numerical domain (the tube), only half its volume was considered for the calculations. The nanofluid's model was assumed as homogeneous with thermophysical properties dependent on the mean fluid temperature and nanoparticle concentration. The nanofluids were treated as incompressible Newtonian fluids. The effect of gravity was neglected in the calculations.

4.1. Governing Equations

The governing equations consist of the continuity, momentum, and energy equations. The continuity equation is expressed as:

$$\nabla \cdot \mathbf{u} = 0 \quad (23)$$

while the momentum equation is given by:

$$\rho_{nf} \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu_{nf} \nabla^2 \mathbf{u} + \mathbf{F}_{body} \quad (24)$$

where $\mathbf{u}$ is the velocity vector, p is the pressure, ρ_{nf} and μ_{nf} are the density and dynamic viscosity of the nanofluid, and $\mathbf{F}_{body}$ represents body forces such as gravity. The energy equation is formulated as:

$$\rho_{nf} c_{p,nf} \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = k_{nf} \nabla^2 T \quad (25)$$

where T is the temperature and $c_{p,nf}$ and k_{nf} denote the specific heat capacity and thermal conductivity of the nanofluid. For steady-state conditions of simulations, the transient terms are neglected.

The effective thermophysical properties of the nanofluid (ρ_{nf} , μ_{nf} , $c_{p,nf}$, and k_{nf}) are calculated using classical mixture models as functions of the nanoparticle volume fraction ϕ and the corresponding properties of the base fluid.

The boundary conditions used in this study reflect those typical of internal forced convection. At the inlet, the velocity and temperature are prescribed as:

$$\mathbf{u} = \mathbf{u}_{in}, \quad T = T_{in} \quad (26)$$

At the solid walls, a no-slip condition is applied for velocity ($\mathbf{u} = 0$), and the thermal boundary condition is a uniform heat flux:

$$-k_{nf} \frac{\partial T}{\partial n} = q'' \quad (27)$$

At the outlet, a fully developed condition is assumed:

$$\frac{\partial \mathbf{u}}{\partial x} = 0, \quad \frac{\partial T}{\partial x} = 0 \quad (28)$$

4.2. Mesh Parameters

In order to check the effect of mesh density on the achieved results, calculations were made for three values of the number of elements: 648,000, 2,058,000, and 4,920,000. The ANSYS Gambit 2.4.6 preprocessor was used to generate the 3D mesh model. Figure 12 shows sections of the generated meshes.

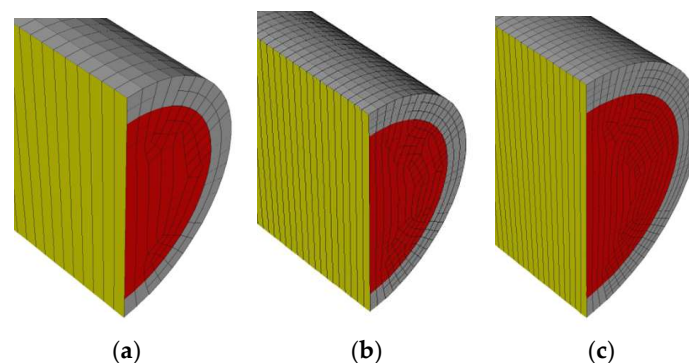


Figure 12. Mesh model: (a) 648,000 elements; (b) 2,058,000 elements; (c) 4,920,000 elements.

Figure 13 shows a comparison of the results of calculations of the average Nusselt number obtained for three mesh densities with the Dittus–Boelter correlation—Equation (19)—and the Kraussold correlation—Equation (20)—for $Re_{min} = 18,000$ and $Re_{max} = 40,000$. Figure 13 shows that the best fit, for both the lowest and highest Reynolds number, was obtained for the highest mesh density (4,058,000 elements). The largest differences between the calculated average Nusselt number and the Dittus–Boelter and Kraussold correlations were 1.5% and 1.4%, respectively, for the densest mesh. For the medium-density mesh (2,058,000 elements), the largest difference between the Dittus–Boelter correlation and the numerical calculations was 3.9%, while, compared to the Kraussold correlation, the largest difference was 2.3%. To shorten the simulation time, the numerical calculations were performed for the medium-density mesh.

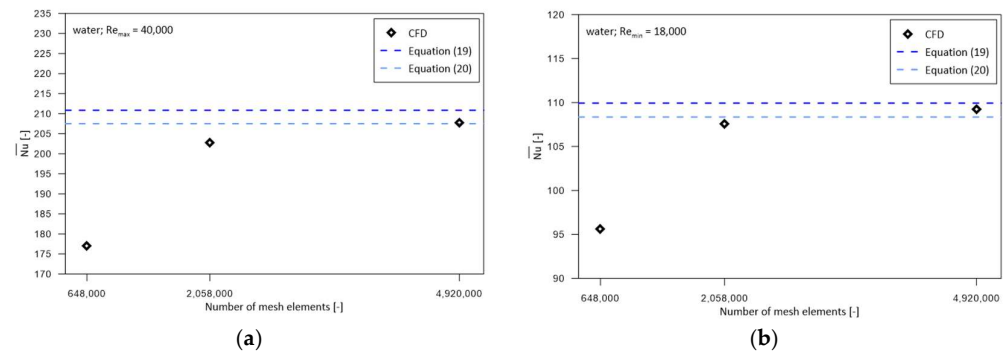


Figure 13. Mesh model vs. average Nusselt number for (a) $Re_{min} = 18,000$; (b) $Re_{max} = 40,000$.

4.3. Numerical Model Validation

Figure 14 presents the results of the numerical model validation for distilled water and the Reynolds number in the range of $14,000 < Re < 35,000$. The results of numerical calculations reflect the results of experimental studies and the results of calculations obtained from the Dittus–Boelter and Kraussold correlations within $\pm 5\%$, which should be considered a satisfactory result.

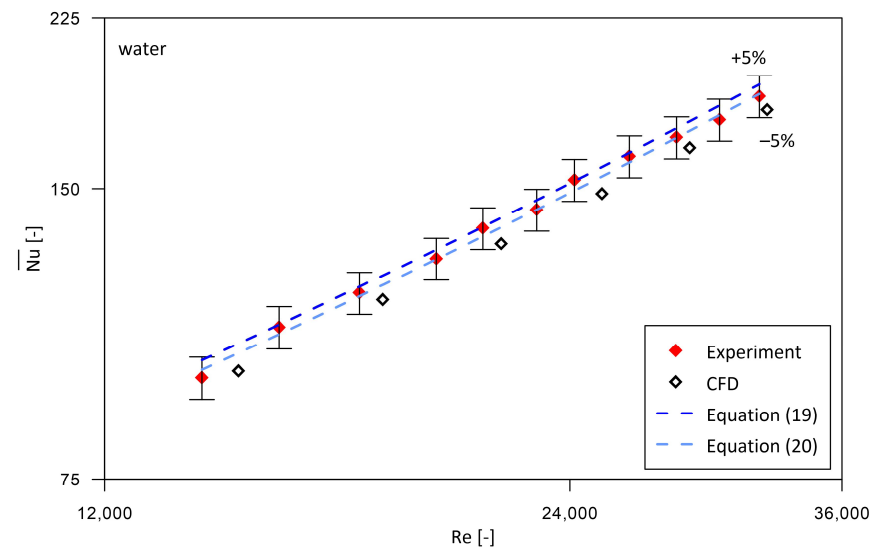


Figure 14. Numerical model validation results.

4.4. Results of Numerical Calculations

Figure 15 presents a comparison of the results of numerical calculations with experimental data for water/EG (90:10)- Al_2O_3 nanofluids. As shown in Figure 15, both the experimental results and the numerical calculations yield higher average Nusselt numbers than those measured for the base fluid (red line in Figure 15), regardless of nanoparticle concentration. Both the experimental results and the numerical calculations show an increase in the average Nusselt number as the nanoparticle concentration increases. However, while the increase in the average Nusselt number calculated numerically for a nanoparticle mass concentration of 5% was approximately 16% compared to the experimental values (red line in Figure 15), the increase in the average Nusselt number obtained experimentally for a nanoparticle mass concentration of 5% compared to the base fluid (red line in Figure 15) was as much as 42%.

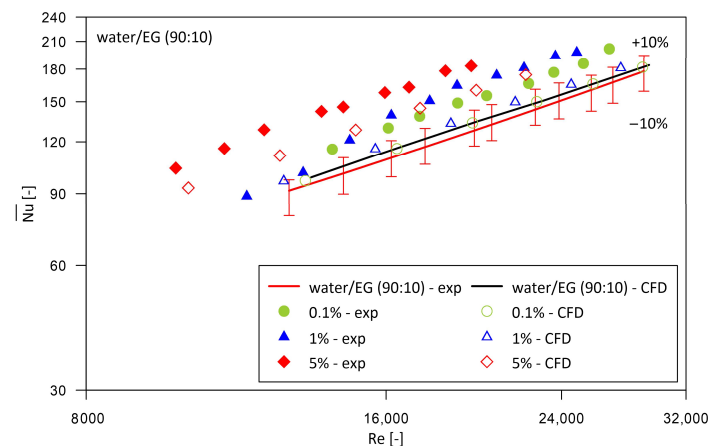


Figure 15. Comparison of numerical and experimental calculation results for water/EG (90:10) based nanofluids.

In the case of the water/EG (90:10)- Al_2O_3 nanofluid, such an increase in the average Nusselt number may result from a relatively small increase in the viscosity of the nanofluid (only 10% of the EG share in the mixture) and, at the same time, an increase in the thermal conductivity of the nanofluid.

Figure 16 shows the effect of nanoparticle mass concentration on the average Nusselt number for the tested base liquids and selected Reynolds numbers. As shown in Figure 15, for the water/EG (80:20)- Al_2O_3 nanofluid, both the experimental data and numerical results indicate that the average Nusselt number increases with increasing nanoparticle concentration, regardless of the Reynolds number. However, when the nanoparticle concentration increases from 0.1% to 1%, both the experimental measurements and the numerical simulations show an increase in the Nusselt number of about 15%. When the nanoparticle concentration increases from 1% to 5%, the increase in the Nusselt number is smaller, at around 8%. The experimental data for $\text{Re} = 10,000$ even show a decrease in the Nusselt number over the nanoparticle concentration range from 1% to 5%; however, this decrease falls within the measurement error.

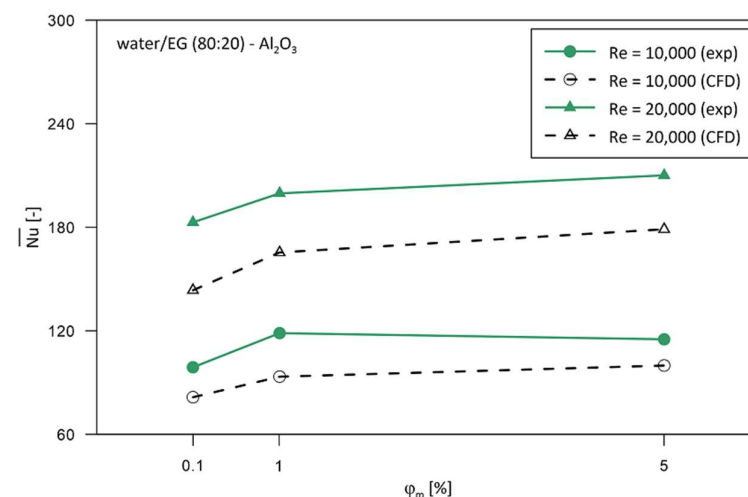


Figure 16. Impact of nanoparticle concentration on $\overline{\text{Nu}}$ for water/EG (80:20)- Al_2O_3 nanofluids.

4.5. Discussion of the Numerical Calculations

As the comparison of the experimental results and numerical simulations showed, the single-phase, homogeneous nanofluid model underpredicts heat transfer parameters such as the Nusselt number. At the same time, other thermal parameters—such as the outlet temperature and wall temperature—are overpredicted compared with the experimental results.

It should be emphasized that the single-phase homogeneous approach was deliberately selected as a compromise between the accuracy of the physical description and computational efficiency. This modeling framework captures the general trends in heat transfer enhancement and the influence of key flow parameters, which are qualitatively consistent with the experimental observations. The remaining discrepancies are likely associated with the neglect of mechanisms typical of multiphase descriptions, such as relative particle motion and particle–fluid slip effects.

For the present analysis, the one-phase homogeneous model provides an adequate representation of the problem, despite underestimating the Nusselt number by up to 22%. The model can be improved in a straightforward manner. In future work, more accurate modeling is planned, including multi-stage linear and polynomial approximations of the nanofluid thermophysical properties.

Nevertheless, the observed deviations, reaching a maximum of approximately 22%, fall within the typical range reported for this class of models and do not compromise its usefulness for qualitative analysis of the investigated phenomenon.

A single-phase approach inherently neglects several microscale mechanisms that may become increasingly important at higher nanoparticle concentrations. Therefore, the results should be interpreted primarily as a macroscopic assessment of the influence of changes in effective properties, rather than as a complete representation of all heat-transfer-enhancement mechanisms.

The single-phase model assumes a uniform dispersion of nanoparticles and treats the nanofluid as a continuous medium. In practice, particularly at higher concentrations, non-ideal effects may occur, including local particle accumulation, agglomeration, and concentration gradients in the near-wall region. Moreover, the model assumes no relative motion (no slip) between the particles and the base fluid. In real nanofluids, phenomena such as thermophoresis and migration induced by velocity and temperature gradients may arise, introducing additional energy-transport pathways that are not captured here.

Within the single-phase framework, any predicted increase in the Nusselt number results exclusively from variations in effective properties—namely thermal conductivity, viscosity, specific heat, and density. Consequently, the model cannot distinguish whether heat transfer intensification is driven by macroscopic changes in transport properties or by microscopic mechanisms associated with particle motion.

As nanoparticle loading increases, viscosity rises, particle–particle interactions become stronger, and the risk of suspension instability increases. Because these effects are not explicitly modeled, the single-phase approach may lead to under- or overestimation of Nusselt numbers and to inaccuracies in predicted pressure losses. In addition, the present model does not account for potential particle deposition on the walls, modifications of the near-wall layer, or changes in effective wall roughness.

Despite these limitations, the single-phase model offers a computationally efficient tool for predicting global trends and evaluating the impact of nanoparticle concentration on heat transfer performance. The presented results should therefore be regarded as a baseline estimate of heat transfer enhancement attributable to effective-property variations, while more advanced multiphase models are required to solve microscale transport in detail.

5. Conclusions

The research conducted allows the following conclusions to be drawn:

- Adding Al_2O_3 nanoparticles to water/EG mixtures with volume ratios of 90:10, 80:20 and 60:40 increased the average Nusselt number, with higher nanoparticle concentrations producing greater enhancements.

- For a given Reynolds number, increasing the EG content in the base mixture leads to a higher average Nusselt number.
- For all tested nanofluids, the pressure drop increased, and the increase became more pronounced as nanoparticle concentration rose.
- The experimentally determined thermo-hydraulic performance factor calculated as

$$\zeta_{exp} = \frac{\overline{Nu}_{nf} / \overline{Nu}_{bf}}{\Delta P_{nf} / \Delta P_{bf}}$$

was above unity for all tested nanofluids with nanoparticle concentrations of 0.1% and 1%, reaching a maximum $\zeta_{exp} = 1.29$ for the water/EG (80:20)-Al₂O₃ (1%) at Re = 10,500. For a nanoparticle mass concentration of 5%, the thermo-hydraulic performance factor was below unity for all tested nanofluids.

- For analytical and comparative purposes, generalized correlations were proposed for turbulent flow of water/EG mixtures to compute the average Nusselt number and the flow resistance coefficient, applicable for water volume fractions exceeding 60% and nanoparticle mass concentration of $0.1\% \leq \phi_m \leq 5\%$.
- The homogeneous nanofluid model adopted for the numerical calculations reproduces the results of experimental studies for water/EG-based nanofluids with moderate accuracy, regardless of nanoparticle concentration. The numerically predicted average Nusselt number was lower than the corresponding experimental value, with a maximum deviation of 22%. From a practical perspective, the numerical results can support the design of heat transfer equipment (e.g., heat exchangers or boilers) by reducing the risk of failing to meet the required thermal duty and, consequently, proper operation conditions.

Future work will focus on thermal and hydrodynamic studies of water/EG nanofluids in complex geometries, such as shell-and-tube heat exchangers with segmental baffles.

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Nomenclature

c_p	Specific heat	[J/(kgK)]
d	Diameter	[m]
f	Friction factor	[-]
I	Current	[A]
k	Thermal conductivity	[W/(mK)]
k_B	Boltzmann constant	[J/K]
L	Length	[m]
M	Molecular weight	[kg/kmol]
N	Avogadro number	[-]
$\overline{Nu}$	Average Nusselt number	[-]

Pr	Prandtl Number	[-]
ΔP	Pressure difference	[Pa]
Re	Reynolds number	[-]
t	Temperature	[°C]
T	Temperature	[K]
U	Voltage	[V]
WVC	Volume content of water	[-]
Greek letters		
φ	Concentration	[-]
ρ	Density	[kg/m ³]
μ	Dynamic viscosity	
Subscripts		
bf	Base fluid	
bf,o	Base fluid at T = 293 K	
cor	Correlation	
exp	Experiment	
fr	Freezing	
i	Inner	
m	Molecule	
nf	Nanofluid	
p	Particle	
t	Tube	
v	Volume	
wt	Mass	

Abbreviations

CNT	Carbon nanotube
EG	Ethylene glycol
GO	Graphene oxide nanotube
MWCNT	Multi-walled carbon nanotubes
NTU	Nephelometric Turbidity Unit
TNT	Titanate Nanotube
W	Water

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