Diyala Journal of Engineering Sciences

Journal homepage: https://djes.info/index.php/djes

ISSN: 1999-8716 (Print); 2616-6909 (Online)

Design of Nanofluid-Based Spring Water/Tap Water and Nanoparticles of Fe_2O_3/ZnO as a Coolant for the Engines

Kaiwan Musleh Faisal*, Badiea Abdullah Mohammed

Department of Chemical Engineering, Faculty of Engineering, Soran University, Soran, Erbil, Kurdistan Region, Iraq

ARTICLE INFO

Article history:
Received March 24, 2023
Revised June 27, 2023,
Accepted July 1, 2023,
Available online September 1, 2023

Keywords:
Spring water
Fe2O3,-tap water
ZnO-Spring water
Heat transfer coefficient
Overall heat transfer coefficient

ABSTRACT

In this work, an experimental system was established to measure the heat transfer characteristics, including the heat transfer coefficient, overall heat transfer, Nusselt number, and thermal conductivity. The investigation focused on spring water and tap water-based nanofluids containing Fe_2O_3 and ZnO nanoparticles with particle sizes of 50 nm and 70 nm, respectively. The experiments were conducted inside an automobile engine, studying the effects of varying nanoparticle volume fractions at a constant temperature. Fe_2O_3 and ZnO concentration in the respective based fluids was verified between 0.02 % and 0.08 % v/v and 0.01 and 0.07 %, respectively. The spring water is not so far used in the previous studies and is much more available in Kurdistan region. Reynolds numbers of nanofluids inside the engine were considered between 1000 to 8000 in a different range as that of the literature review. Reynolds analogy for heat and momentum has been employed in this study. It was observed that the thermo-physio-mechanical properties of nanofluids increased with increase in the concentration of nanoparticles and Reynolds number. However, the friction factor decreased with increasing Reynolds number but increased with an increasing volume concentration of nanoparticles. Generally, the results showed that the enhancement of the effective heat transfer of the nanofluids reached 46%, the overall heat transfer coefficient reached 39%, thermal conductivity reached 21.35% and Nusselt number reached to 38%. at 0.08% volume fraction of Fe2O3/spring water nanofluid. Based on all previous parameters estimated, the designed nanofluids in this study could be classified as a workable nanofluid in many industry applications.

1. Introduction

In many engineering applications, increasing the temperature is not practical because it may cause premature damage. Therefore, developing effective cooling solutions to address these issues is critical, as they can have negative consequences for electronic devices, heat exchanger reliability, power and performance, and heat sinks [1]. Many researchers have reported the enhancement of effective heat transfer using nanofluids based on metal/oxide metal nanoparticles [2, 3]. Heat transfer is used in solar thermal collectors to convert solar energy to heat and power and used in thermal control elements in spacecraft. In many of these devices, heat needs to be dissipated at a rapid rate to ensure effective operation and maximum efficiency within the system [4, 5]. Since various remarkable technologies, including thermoelectric cooling, phase change material base cooling, heat pipe, and pump-based cooling, have been done in the last few years, still there are challenging issues in managing the electronic and electrical devices. Lower heat

* Corresponding author.
E-mail address: badiea.mahyoub@cheme.soran.edu.iq
DOI: 10.24237/djes.2023.16312

transferring capacity remains a limitation for these fluids. So, developing heat transfer fluids that possess better efficiency is the need of the hour to tackle thermal management in these devices [6]. In industrial and thermal applications such as cooling and heating systems, various types of fluids are typically used as heat providers, thus the alteration properties of the heat transfer fluids and the surface geometry have become a major concern that stirs the curiosity of academics. Multiple approaches have been adopted to develop advanced fluids in order to overcome the constraint of the poor thermophysical properties of the conventional heat transfer fluids and aim for considerable higher thermal conductivity, following a theoretical framework presented by Maxwell over a century ago that consists of solid-fluid dispersion [7]. The heat transfer coefficient can be increased by improving the coolant properties for a particular heat transfer method. Coolant in the heat transfer process is referred to as a cold fluid, water can act as a cooling fluid in the heat exchanger. Water is used as a cooling fluid because it has high specific heat properties with low viscosity and very low cost so that it brings advantages to the heat transfer application industry. Heating or cooling fluids are important for many industrial sectors, including transportation, energy supply, and production. The thermal conductivity of these fluids plays an important role in the development of energy-efficient heat transfer equipment [8].

Scientists tried various techniques to enhance the heat transfer [4]. However, modern technology makes it possible to avoid such obstacles by providing fluids with small enough-sized particles that can move freely in such passages, introducing the term “Nanofluids” that refers to fluids that have nanoscale particles dispersed throughout them. They can be produced by suspending nanoparticles sized less than 100 nm of metal components or oxide components and /or hybrids with conventional heat transfer fluids [7]. Even at low concentrations, nanoparticles can enhance the overall heat transfer significantly [9]. Most studies done on nanofluids in heat transfer systems such as heat exchangers recently have reported that the presence of nanoparticles in heat transfer fluids increased the effectiveness of thermal conductivity of the heat transfer fluids and consequently enhanced the heat transfer characteristics of the heat transfer system. Nanofluids with appropriate selection of the base fluid type, as well as appropriate selection of nanoparticles in terms of material, size, shape, and concentration in the base fluid, can perform much better coolant than the conventional heat transfer fluids. Hence, nanofluids are considered to have high suitability for the application in practical heat transfer processes [10]. Mixed convection heat transfer utilizing nanofluids, ionic nanofluids, and hybrid nanofluids in a horizontal tube has been reported by Ahmed *et al*. [9]. They found that the nanofluids achieved an enhancement reaching 15.5% for Al_2O_3 with a concentration of 2% at Richardson number of 0.016. However, no enhancement is noticed for hybrid nanofluids. G. Yalcın *et al.* [11] investigated the influence of particle size on the viscosity of water-based ZnO nanofluids. The results revealed the bigger-sized ZnO nanoparticles, higher viscosity than the smaller nanoparticles in aqueous nanofluids. The change of dynamic viscosity depends not only on nanoparticle size but also on nanoparticle shape.

Hussein [12] studied the effect of ZnO solid nanoparticles suspended in water on the double tube heat exchanger under turbulent flow. He obtained the friction factor decreased with increasing flow rate and is slightly increased with increasing concentration of nanofluid and the maximum heat transfer coefficient was %21. Nishant *et al.* [13] calculated the heat transfer characteristics of Fe_2O_3-water and Fe_2O_3-Ethylene glycol in a shell and tube heat exchanger under laminar to turbulent flow conditions. They observed an increase in thermal conductivity and heat transfer coefficient with the addition of particle volume fractions. The thermal behavior of water based nanofluids with ZnO, TiO_2, and Al_2O_3 as nanoparticles at different volume fractions in a heat pipe heat exchanger with constant temperature as the wall condition evaluated by Topuz *et al.* [14]. When compared to distilled water as the base fluid, Al_2O_3 nanofluid with 1.0 % concentration provided the best thermal enhancement of 15.3 % with no significant pressure drop. Experimental study on the forced convective heat transfer and flow characteristics of Al_2O_3/water nanofluid in horizontal shell and tube heat exchanger under turbulent flow conditions has been investigated by Jafaar *et al.* [15]. Hatami *et al.* [16] investigated the properties of nanofluids such as CuO/water, Fe_2O_3/water, TiO_2/water, and EG/water using computational fluid dynamics. When compared to EG/ water, they discovered that TiO_2/water nanofluid increased the heat recovery by 10% without any pressure drop. The investigative research of Al-damook *et al.* [1] includes numerical simulation to study the natural convection heat transfer in a concentric annular horizontal pipe for six different geometries using pure water. The results showed that the heat transfer rate of concentric elliptic and circular pipes is nearly 40% and 37% respectively greater than that of the other geometries. They examined two types of nanofluids Al_2O_3/H_2O and SiO_3/H_2O after adopted the optimum geometry they investigated the nanofluids has positive effects compared to pure water. The heat transfer coefficient was found to increase by 6% with a low pressure drop for the Al_2O_3/H_2O nanofluid at the volume fraction of 0.5% compared to the base fluid. Azzawi *et al.* [17] numerically investigated the effect of three different nanofluids Al_2O_3/water, CuO/water and SiO_2/water in the analysis and compared to pure water to enhance the convective heat transfer of the base fluid. Varying volumes of fraction flowing within different channel geometries, exposed to a uniform and different hot surface temperatures boundary condition, was successfully carried out in this study using a single-phase approach. The results showed that for the same hot surface temperature, elliptical cross-sectioned channel geometry offers up to twice compared to other type of geometries such that compared to airfoil pipe, square, circle and ellipse have 60%, 50% and 46% lower heat transfer coefficient, respectively. Moreover, Nanoparticle of Al_2O_3 dispersion to the base fluid enhances the heat transfer rate by 15%. Regarding to the fraction volumes, higher volumetric nanoparticle concentration of nanofluids have higher heat transfer rate with low pressure drop. Jafari *et al.* [18] reported the effect of alumina nanoparticle volume fraction on the overall heat processing of tomato juice in a shell and tube heat exchanger. The heat transfer and friction factor of Al_2O_3/water flow in a double pipe heat exchanger has been examined by Prasad *et al.* [19]. It is observed a 25% increase in heat transfer at 0.03% volume concentration at Reynolds number of 22000. Hussein *et al.* [20] have researched the effect of nanoparticles suspended in palm oil, observing a decrease in friction factor with increasing Reynolds number and decreasing nanoparticle concentrations. Kumar *et al.* [21] noticed the efficiency of effective heat transfer could be enhanced using Al/water nanofluids. With increasing concentrations, they observed an increase in density, viscosity, and thermal conductivity.

The novelty of this work is that no so far research has been done by using a spring water as a base fluid for nanofluids and Reynolds analogy for heat and momentum is not used so far. However, this research on the design of nanofluid-based spring water/tap water and the utilization of Fe_2O_3/ZnO nanoparticles as a coolant for engines introduces several novel aspects to the field. Firstly, while previous studies have investigated the use of nanofluids as coolants, our work specifically focuses on the application of nanofluid-based spring water/tap water, which offers a more sustainable and readily available alternatively compared to traditional coolants. These nanoparticles possess enhanced thermophysical properties, such as high thermal conductivity and heat transfer efficiency, which can significantly improve the cooling performance of the engine. By addressing these various aspects, our work provides valuable insights into the development of advanced coolants for engines, emphasizing the potential for improved engine performance, reduced energy consumption, and environmental sustainability.

In this work, the characteristics of the nanofluids such as heat transfer coefficient, overall heat transfer coefficient, pressure drop, friction factor, and thermal conductivity in tube heat exchanger for automobile engines under laminar and turbulent flow conditions with five different Reynolds numbers of each nanofluid at different concentrations of nanoparticles at constant temperature have been investigated experimentally.

2. Experimental work

2.1 Preparation of nanofluids

The first critical step in nanofluid experimental studies is nanofluid preparation. Nanofluids are more than just liquid-solid mixtures. Some special requirements must be met, such as even and stable suspension, durable suspension, neglible particle agglomeration, and no chemical change in the fluid [22]. In general, two methods for producing nanofluids are used: single-step and two-step. In the former, nanoparticles are produced using a liquid chemical or physical vapor deposition technique while the nanofluid is being created [23]. Because of processes such as drying and dispersion are avoided in this method, the agglomeration of nanoparticles in the nanofluid is minimal, and as a result, the fluid is more stable. The disadvantage of the one-step technique is that it is limited to low vapor pressure fluids. In the latter, two-step method, nanoparticles are synthesized separately as dry powder and dispersed in the base fluids. This technique has the advantage of being able to use a wide variety of nanoparticles and base fluids without the limitations of the previous method. However, the agglomeration and stability of nanofluids are issues that must be addressed [24, 25]. In the present work, the nanofluid was prepared by the two-step method. Extensively, the two-step method is the most widely used because it is the most economical process to synthesize nanofluids. In this work, Fe_2O_3-tap water and Fe_2O_3- spring water, also ZnO - tap water and ZnO-spring water nanofluids were synthesized by dispersing Fe_2O_3 and ZnO nanoparticles in, both base fluids, tap water and spring water and the analyzing of base fluids were obtained from K. M. Shareef and S. G. Muhamad [26]. The desired particles as volume concentrations of Fe_2O_3 and ZnO nanoparticles were 0.02%, 0.03%, 0.05%, 0.06%, and 0.08%; and 0.01%, 0.03%, 0.04%, 0.06% and 0.07%, respectively, mixed into 3 liters for both the base fluids. The Fe_2O_3 nanoparticles were obtained from Skyspring Nanomaterials (Houston, Texas, USA) and the ZnO nanoparticles were obtained from Hongwu Inter National Group Ltd.-China. The volume fraction of nanoparticles required in nanofluids was estimated using the following formula [27].

$$\emptyset\ (\%) = \frac{m_p/\rho_p}{m_p/\rho_p + m_{bf}/\rho_{bf}} \times 100 \qquad (1)$$

Where $\emptyset$ is the volume fraction, m_p is the mass of nanoparticles, m_{bf} is the mass of base fluids, ρ_p is the density of nanoparticles, and ρ_b is the density of base fluids.

Properties of the base fluids and nanoparticles applied, some of them were tested in the chemical engineering department lab at 323 K, are depicted in Table 1. In this research, the nanofluids have been prepared by dispersing a specific amount of nanoparticles in the base fluids by using a magnetic stirrer before starting the experiment stirring nanofluids with a magnetic stirrer purposed to blend nanoparticles into the base fluids within 30 minutes. During the experiment, the stirrer was fixed on the nanofluid tank for preventing agglomeration and settling down nanoparticles and in this work no surfactant was used.

Table 1: Properties of nanoparticles and base fluids at 323 K average temperature (some of them were measured in the lab, and the resets are referenced)

Specification	Tap water	Spring water	Fe_2O_3	ZnO
Density (Kg/m^3)	998.2	999	5,240 [28]	5,460 [29]
Viscosity (mPa.s)	1.0005	1.108	N/A	N/A
Thermal conductivity (W/m.K)	0.6435 [30]	0.8259 [30]	13.55 [31]	23.73 [28]
Specific heat (J/Kg.K)	4,181 [32]	4,181.80 [32]	628.3 [29]	495.20 [28]

2.2 Experiment setup and procedure

The schematic picture and diagram of the experimental setup is shown in Fig.1.and 2. The test section consists of a shell and tube heat exchanger. The tube with an inner diameter of 0.013 m and outer diameter of 0.016 m, which is made of stainless-steel material, a digital display screen, a nanofluid cooling system and a heating water tank to maintain the temperature at a desired value, a set of thermocouples, flow meters for both hot and cold flow to fix Reynold number and U-tube manometer for the pressure drop inside the engine. Four resistance temperature detectors type PT-100 were installed to measure the inlet and outlet temperatures of the hot and cold nanofluids. Two of the thermocouples, 1 and 2, measure the fluid temperatures at the inlet and outlet of heat exchanger shell side, and the other two thermocouples, 3 and 4, measure the fluid temperatures at the inlet and outlet of heat exchanger tube side. At the entrance of the shell and tube heat exchanger, two rotameters with full-scale accuracy of ± 5% to measure the flow rates inside the engine and shell in order to specify Reynold number, since the Fe_2O_3 and ZnO nanofluids flow rates were 50, 100, 150, 200 and 250 L/h and the flow rate of side shell was kept at 150 L/h. Reynolds number based on the previous flow rate altered between 1334-7621 for nanofluids-based Fe_2O_3 and 1359-7524 for nanofluids-based ZnO. All readings were recorded steady state. The nanofluids was flowing through the tube side as a coolant fluid, while the hot water was flowing through the shell side as a hot side with the engine maintained at a temperature of 323 K. The paths of the two working fluids were arranged in co-current. The thermophysical properties of the nanofluids were calculated at mean temperature. The logarithmic mean temperature different method is used to calculate the inside heat transfer coefficient of the nanofluid. The mass of the nanoparticles was measured by a precise electronic balance with the accuracy of ± 0.001 g.

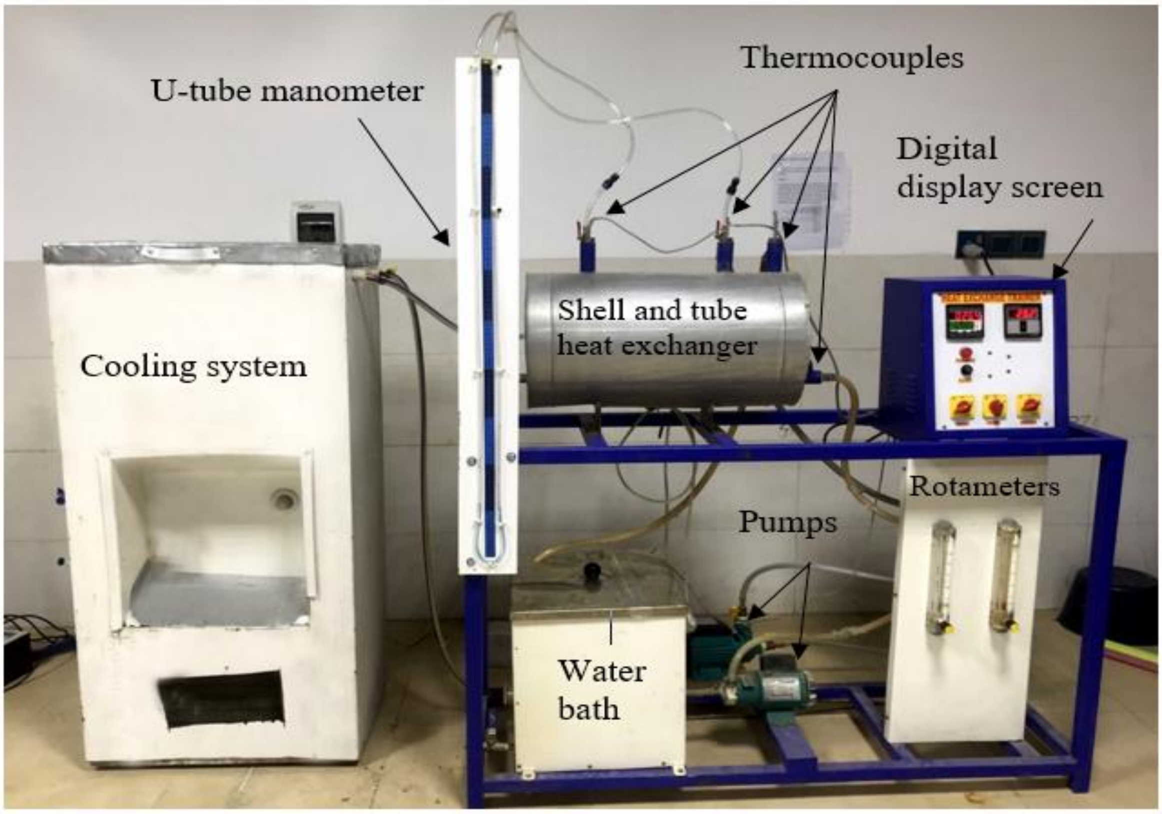

Figure 1. Experimental setup of shell and tube heat exchanger

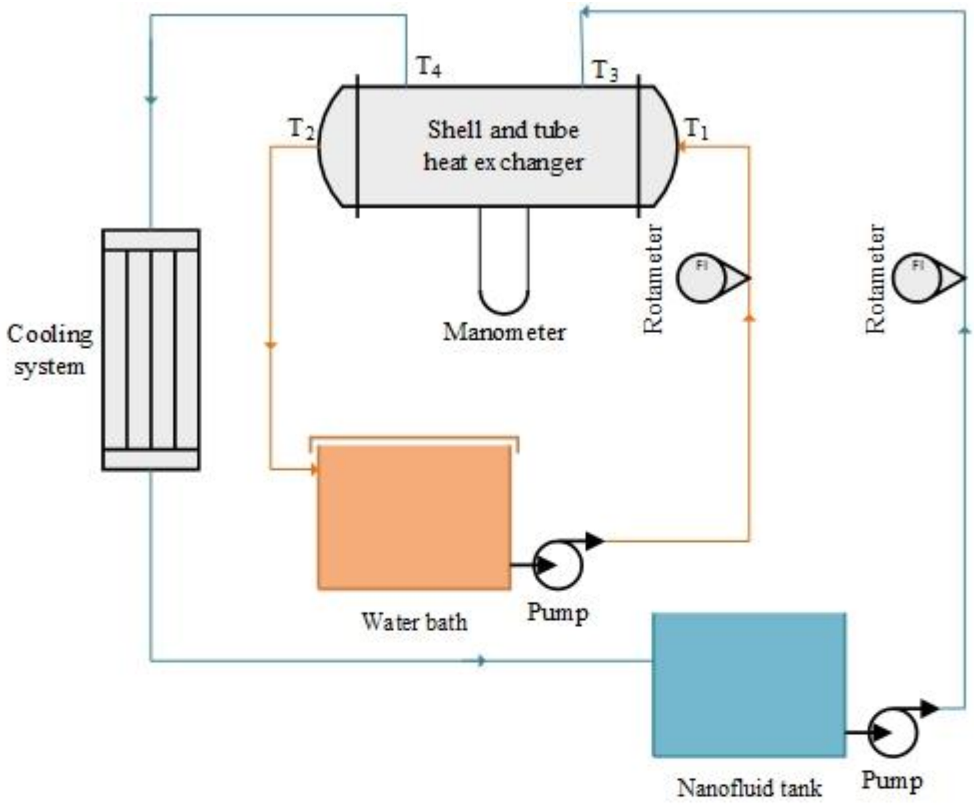

Figure 2. Schematic diagram of shell and tube heat exchanger

2.3. Thermo-physi-mechanical properties

An addition of nanoparticles into the base fluid changes the thermophysical properties of the base fluid, which are heat transfer coefficient, thermal conductivity, overall heat transfer coefficient, specific heat, density, viscosity, friction factor and pressure drop. Several theoretical formulas have been suggested to calculate the aforementioned properties of the nanofluids prepared.

2.3.1. Heat transfer characteristics

In this work, the convective heat transfer coefficient of the proposed nanofluids inside the tube experimentally has been calculated by Eq.(2) [33]:

$$h_i = \frac{Q_h}{A_i(T_w - T_b)} \tag{2}$$

Where h_i (W/m^2.K) is the convective heat transfer coefficient of the nanofluid, Q_h (W) is the heat rate of the hot side, A_i (m^2) is surface area of the inside tube, T_w (K) is temperature of the wall and T_b is bulk temperature of nanofluid. Related to the effective heat transfer, Nusselt number experimentally can be estimated using Eq.(3) [33]:

$$Nu = \frac{h_i\, d_i}{k} \tag{3}$$

Where Nu is Nusselt number, d_i (m) is the inside diameter of the tube, and k (W/m.K) is the thermal conductivity of the nanofluid. For comparing the experimental and theoretical results, the equations of Sieder and Tate for laminar flow and Gnielinski equation for turbulent flow might be used for calculating Nusselt number of the nanofluids [29, 31]:

$$Nu = 1.86(RePr)^{1/3}\left(\frac{d_i}{L}\right)^{1/3}\left(\frac{\mu_{nf}}{\mu_w}\right)^{0.14} \tag{4}$$

(Laminar flow)

$$Nu = 0.012(Re^{0.87} - 280)\,Pr^{0.4} \tag{5}$$

(Turbulent flow)

Where Re is Reynolds number of the nanofluid, Pr is Prandtl number of the nanofluid, L (m) is the length of the tube, μ_{nf} (Pa.s) is the viscosity of the nanofluid in the the bulk and μ_w is the viscosity of the nanofluid at the wall. Reynolds number and Prandtl number can be expressed as follows [35]:

$$Re = \frac{\rho_{nf}\, d_i\, v}{\mu_{nf}} \tag{6}$$

$$Pr = \frac{\mu\, Cp}{k} \tag{7}$$

Where ρ_{nf} (kg/m^3) is the density of nanofluid, v (m/s) is the velocity of the nanofluid inside the tube, and C_p (J/kg.K) is the specific heat of the nanofluid.

Overall heat transfer coefficient (U) in the tube side of heat exchanger experimentally is calculated as in Eq.(8) [33]:

$$U = \frac{Q_{avg}}{A_o \Delta T_{LMTD}} \tag{8}$$

Where U (W/m^2.K) is the overall heat transfer coefficient, Q_{avg} (W) is the average heat transfer rate between cold and hot side, A_o (m^2) is the heat transfer surface area, ΔT_{LMTD} (K) is the logarithmic mean temperature difference.

Equations (9-10) used for calculating heat transfer rates for both of hot and cold sides [33]:

$$Q_h = m_h C_{p_h} (T_{hi} - T_{ho}) \tag{9}$$

$$Q_c = m_c C_{p_c} (T_{co} - T_{ci}) \tag{10}$$

$$Q_{avg} = \frac{Q_h + Q_c}{2} \tag{11}$$

Where Q_h (W) is the heat transfer rate of the hot fluid, m_h (kg/s) is the mass flow rate of the hot fluid, C_{p_h} is the specific heat of hot fluid (J/kg.K), T_{hi} is the inlet temperature of the hot fluid (K), T_{ho} is outlet temperature of the hot fluid (K), q_c is heat transfer rate of the cold fluid (W), T_{ci} is the inlet temperature of the cold fluid (K) and T_{co} is the outlet temperature of the cold fluid (K).

2.3.2. Thermal conductivity

The cooling process in various engineering and industrial devices is one of the most important challenges. Heat is generated in various devices because of motion, ignition, chemical reactions, etc. These devices are cooled using a variety of fluids. These fluids commonly have low thermal conductivity, which tends to slow the cooling of these devices. The thermal conductivity of the fluids can be enhanced by adding metal and / or oxide metal solids in the nanoscale into the base fluid. Many researchers have been trying to improve their thermal performance by adding different nanofluids to various heat exchangers [22]. In this work, the theoretical model to predict the thermal conductivity of nanofluids was proposed. A Maxwell model is used to obtain the thermal conductivity of nanofluids as follows [33, 34]:

$$k_{nf} = k_{bf} \left[\frac{k_p + 2k_{bf} + 2\emptyset\,(k_{bf} - k_p)}{k_p + 2k_{bf} - \emptyset\,(k_{bf} - k_p)} \right] \tag{12}$$

Where k_{nf} is the thermal conductivity of nanofluid (W/m.K), k_{bf} is the thermal conductivity of the base fluid (W/m.K), k_p is the thermal conductivity of nanoparticle (W/m.K) and $\emptyset$ is the volume fraction of the nanoparticle (%).

2.3.3. Viscosity

The viscosity of nanofluid is another important property indicator. Viscosity is a fluid friction criterion that indicates the fluids resistance to flowing. Viscosity changes can have a significant impact on the amount of pumping power. As the viscosity increases, so does the power require for pumping, and thus the pumps energy consumption. To perform simulations in heat exchangers, the viscosity must also be known. Here the viscosity test was measured by Ostwald viscometer as well the viscosity of nanofluids can be estimated by using Eq.(13) [38]:

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\emptyset)^{2.5}} \tag{13}$$

Where μ_{nf} is the viscosity of the nanofluid (Pa.s), μ_{bf} is the viscosity of base fluid (Pa.s) and and $\emptyset$ is the volume fraction of nanoparticle.

2.3.4. Pressure drop

The pressure drop in this work was measured using manometer and calculated by Eq.(14):

$$\Delta p = (\rho - \rho_{nf}) g \Delta h \tag{14}$$

Where Δp is pressure difference or pressure drop (Pa), ρ stands for manometer fluid density of mercury (kg/m^3), g is gravitational acceleration (m/s^2), ρ_{nf} is density of the nanofluid (kg/m^3) and Δh is the height difference of manometer fluid (mercury) (m) which is obtained due to the manometer reading.

2.3.5. Friction factor

After measuring the pressure drop, the friction factor can be estimated by Eq.(15) [39]:

$$f_{exp} = \frac{\Delta p}{\left(\frac{L}{d_i}\right)\left(\rho_{nf}\frac{v^2}{2}\right)} \tag{15}$$

Where f_{exp} is the experimental friction factor, Δp is the pressure drop (Pa), L is the length of the tube (m), d_i is the inner diameter of the tube (m), ρ_{nf} is the density of the nanofluid (kg/m^3) and v is the velocity of nanofluid (m/s).

Comparison between the results of Eq. (15) and Eq. (16 and 17), the experimental and theoretical friction factor of the nanofluid inside the tube might be determined [37, 38]:

$$f = 0.316\, Re^{-0.25} \tag{16}$$

(Turbulent flow-smooth pipe)

$$f = 64\, Re^{-1} \text{ (Laminar flow)} \tag{17}$$

2.3.6. Density

Another important property of nanofluids is density. However, because the volume of a fluid changes with temperature, the definition of density for fluids differs from that for solids. In this study, the density of nanofluids experimentally was measured by the Eq.(18) [42]:

$$\rho_{nf} = \emptyset\rho_p + (1-\emptyset)\rho_{bf} \tag{18}$$

Where ρ_{nf} is the density of nanofluid (kg/m^3), $\emptyset$ is the volume fraction of the particles, ρ_p is the density of nanoparticles (kg/m^3) and ρ_{bf} is the density of the base fluid (kg/m^3).

2.3.7 Specific heat

Water processes high specific heat and is commonly used as a fluid for heat transfer in a variety of industries as well as it is readily available and inexpensive. Accordingly, the specific heat of nanofluid is an essential to be evaluated and to gain a comprehensive knowledge of the behavior of thermophysical parameters in terms of heat transfer characteristics. In most cases, however, the addition of nanoparticles has been reduced the specific heat of the fluid that added to. Eq. (19) can be used to determine the specific heat of nanofluids [42]:

$$C_{p_{nf}} = \emptyset\, C_{p_p} + (1-\emptyset)C_{p_{bf}} \tag{19}$$

Where $C_{p_{nf}}$ is the specific heat of nanofluids (J/kg.K), $C_{p_{bf}}$ is the specific heat of base fluid (J/kg.K), C_{p_p} is the specific heat of nanoparticle (J/kg.K) and $\emptyset$ is the concentration of nanoparticle (%).

2.4. Reynolds analogy for heat and momentum

It is the first time that Reynolds analogy for heat and momentum has been employed to comprehensively calculate the effective heat transfer. The three models suggested are as in the following equations [43]:

Simple Reynolds analogy:

$$\frac{h_i}{c_p\, \rho_{nf}\, u} = 0.032\, Re^{-0.25} \tag{20}$$

Taylor-Prandtl equation:

$$\frac{h_i}{c_p\, \rho_{nf}\, u} = \frac{0.032\, Re^{-0.25}}{1+2\, Re^{-0.125}\, (Pr-1)} \tag{21}$$

Universal velocity profile:

$$\frac{h_i}{c_p\, \rho_{nf}\, u} = \frac{0.032\, Re^{-0.25}}{1+0.82\, Re^{-0.125}\, [(Pr-1)+\ln(0.83\, Pr+0.17)]} \tag{22}$$

3. Results and discussion

3.1 Convective heat transfer

The effective heat transfer of the four nanofluids designed (spring water/Fe_2O_3, spring water/ZnO, tap water/Fe_2O_3, and tap water/ZnO) at different volume fraction of nanoparticles and at different Reynolds number at 323 K has been evaluated and depicted in Fig. 3. The heat transfer coefficient of nonfluids resulted from the aforementioned Reynolds analogy model for heat and momentum are close to each other, except that of simple Reynolds analogy have a deviation of 34%. It is observed that the addition of nanoparticles to the base fluid can remarkably have increased the heat transfer coefficient with increasing Reynolds number. The inertial forces, intermolecular forces, and the tendency of the fluid to resist separation play an important role. Consequently, the motion and incident of fluid molecules increase, which leads to higher heat transfer coefficient advantages [44]. The turbulent flow can play an important role in high volume concentration of nanoparticles to prevent the agglomeration. Generally, the enhancement of convective heat transfer coefficient is attributed to higher thermal conductivity of nanoparticles and decrease in the thermal boundary layer thickness leading to that the momentum of nanoparticles gets away from the wall to the center of the tube and makes a reduction in the viscosity at the wall region. Fig. 2.a shows the lowest and highest heat transfer coefficients which are 2450 and 3548 $W/m^2.K$, respectively, at Reynolds number of 7680. Giving the maximum enhancement of heat transfer coefficient is 44 % at 0.08% volume fraction of Fe_2O_3/tap water. It seems the enhancement in the presence of Fe_2O_3 is slightly increased than that of ZnO due to the higher specific surface area of Fe_2O_3 nanoparticles than ZnO nanoparticles and the reason of slightly increased due to the higher specific surface area for Fe_2O_3 nanoparticles and due to the higher thermal conductivity of ZnO nanoparticles. Fig 2.b indicates the lowest and highest heat transfer coefficients are 2550 and 3740 $W/m^2.K$, respectively at Reynolds number of 7680. The maximum enhancement of heat transfer coefficient is 46% with blank and 0.08% volume fraction of Fe_2O_3/spring water. Same trend in Fig 2.c, it illustrates a significant enhancement of ZnO/tap water reached to 40.6% at Reynolds number of 7680 and no more effect beyond. Slightly, the enhancement of the results illustrated in Fig. 2.d demonstrates the effect of nanofluid-based ZnO/spring water on the heat transfer coefficient at the concentration of 0.08%v is better than that of ZnO/tap water. It can be said that the specific surface area of Fe_2O_3 plays a significant rule since it is more than the specific surface area of ZnO. From Fig. 2.b and 2d, the specific surface area of Fe_2O_3 makes synergistic with spring water more than the thermal concavity of ZnO with spring water.

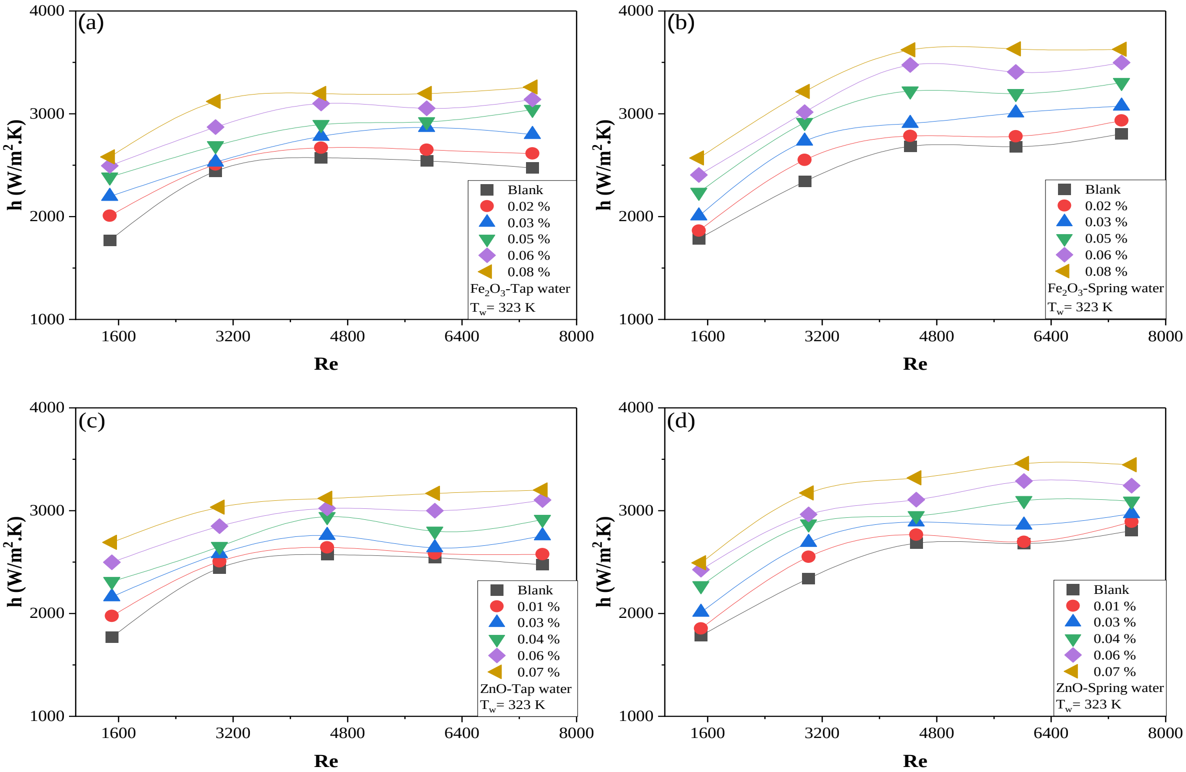

Figure 3. Heat transfer coefficient vs Reynold number at different concentration of nanoparticles at 323 K. (a) Fe_2O_3-Tap water nanofluid, (b) Fe_2O_3-Spring water nanofluid, (c) ZnO-Tap water nanofluid, (d) ZnO-Spring water nanofluid.

Comprehensively, the convective heat transfer has obvious enhancement in the presence of spring water/Fe_2O_3 more than others. This may be interpreted to the presence of Fe_2O_3 which possesses high surface area and smaller size. For this it can be said that, the little higher viscosity of spring water and higher thermal conductivity of ZnO is responsible to make unsynergetic between the advantage of higher thermal conductivity and higher viscosity of ZnO.

3.2 Overall heat transfer coefficient

The overall heat transfer coefficient of nanofluids depends on various factors such as the type of nanofluid, fluid of the shell, volume fraction of nanoparticles in nanofluids, temperature, inside and outside effective heat transfer, and mode of flow of the shell and tube fluids. Fig. 4.a and 4c state that the enhancement of the overall heat transfer coefficient is around 33% at over all Reynolds number. The maximum enhancement of overall heat transfer coefficient is 39 % at 0.08 %v for nanofluid -based Fe_2O_3 /spring water at Reynolds number range between 6400 and 8000 as shown in Fig. 4.b and 4d. This may be attributed to the increase of specific surface area of Fe_2O_3 and higher thermal conductivity of spring water because this type of water contains many species of metal sand metal oxides.

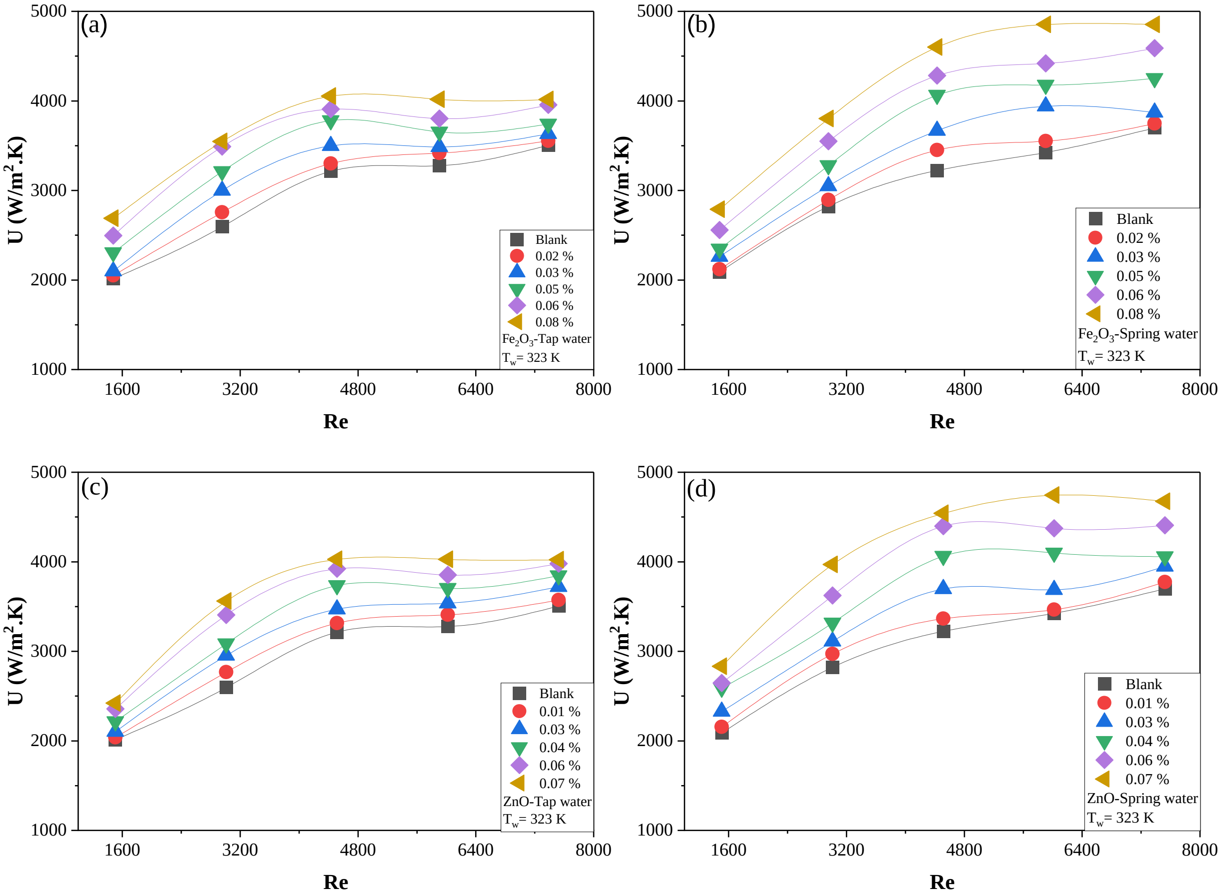

Figure 4. The overall heat transfer coefficient of vs Reynolds number for four types of nanofluids at different nanoparticles concentrations at 323 K

3.3 Nusselt number

The Nusselt number of nanofluids is obtained using Eqs. (3, 4 and 5) and the results are represented in Fig. 4. The comparison between the experimental results and those obtained from Gnielinski equation for laminar and turbulent mode of nanofluids is illustrated in Fig. 5. Nusselt number remarkably is more than 32 for nanofluids indicating that the heat transfer is coeffective mode, and the experimental results reflects good enhancement of nanofluids. To our knowledge, if the Nusselt number is between 1 and 10, it is a laminar flow with coeffective heat transfer [45]. However, the flow is laminar, it is observed that the Nusselt number is more than 32 in the presence and absence of nanoparticles, interpreting that the nanofluids highly work as a successful coolant in terms of convection.

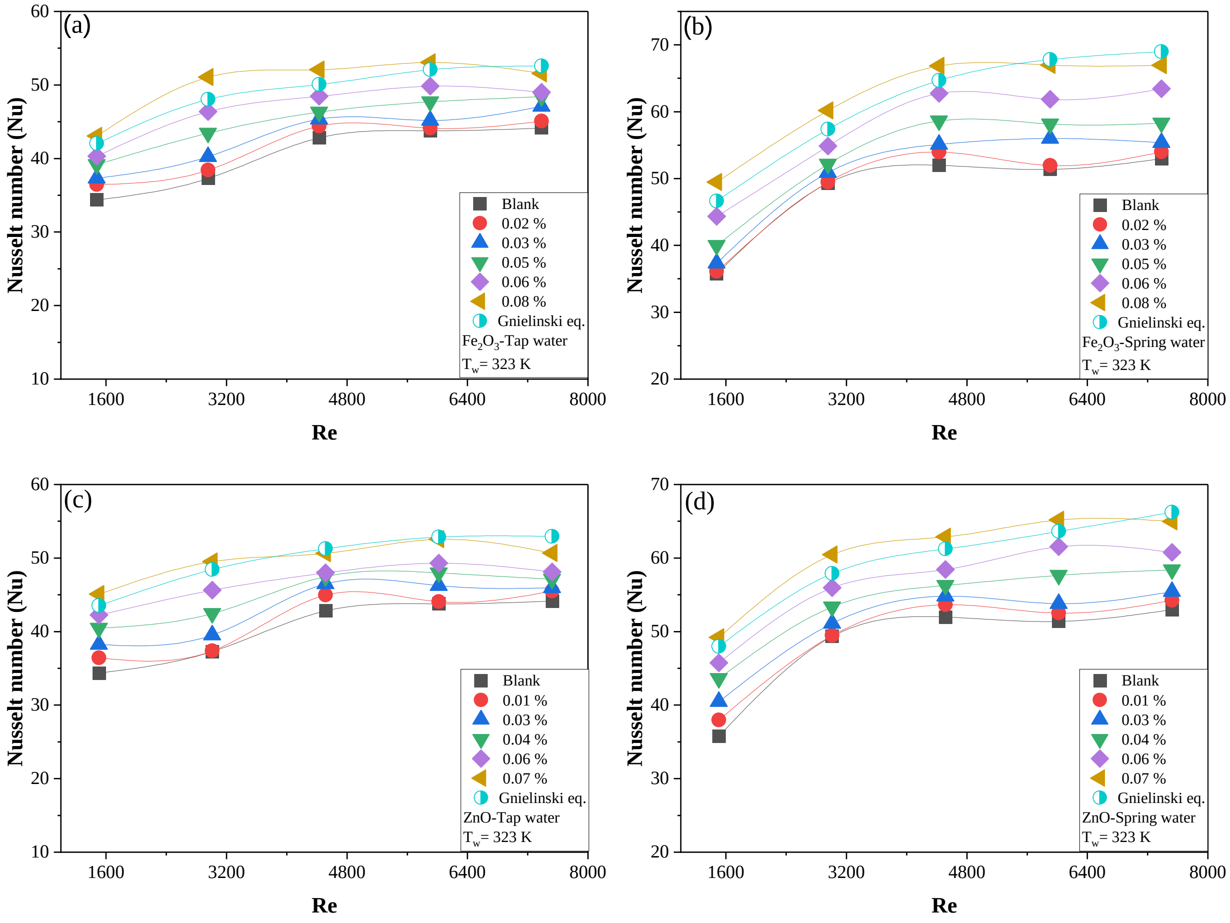

Figure 5. Nusselt number of different nanofluids with different nanoparticles concentration vs Reynolds number

The maximum deviation observed between the present experimental results and the theoretical value obtained by using Gnielinski formula is not exceeded ± 4.7%. Simply it is noticed the higher Nusselt number is for nanofluids -based Fe_2O_3/Spring water as shown in Fig.4b. Moreover, Nusselt number of the nanofluids in the presence of spring water for both nanoparticles is higher than tap water. Fig.4a, 4c point out the slight stability of the nanofluid -based tap water. It seems the effect of nanoparticles volume fraction reflects more attention than the effect of Reynolds number. The maximum enhancement of Nusselt number was 38% at 0.08% volume fraction at the Reynolds number between 2750 and 7600. The lower Nusselt number of the nanofluids-based spring water at Reynolds number between 1000 and 3200 may be attributed to the agglomeration of nanoparticles due to the little bit higher viscosity of spring water than of tap water and due to the low flow rate, settle down of particles occurred.

3.4 Thermal conductivity

Thermal conductivity is an important property of nanofluids for studying the convective heat transfer because it determines how well the fluid can transfer the heat. In addition, the thermal conductivity is the most important in the term of the nanofluids. Because thermal conductivity of nanoparticles is more than the base fluids. The heat transfer can't take a place between the fluid and nanoparticle unless the thermal conductivity of the nanoparticles exists. Without existing the thermal conductivity not have any transporting of the heat. The result obtained by using Eq. (12), remarkably, the thermal conductivity of the nanofluids of tap water and spring water based on nanoparticles of metal oxides of Fe_2O_3 and ZnO as noticed in Figs 6.

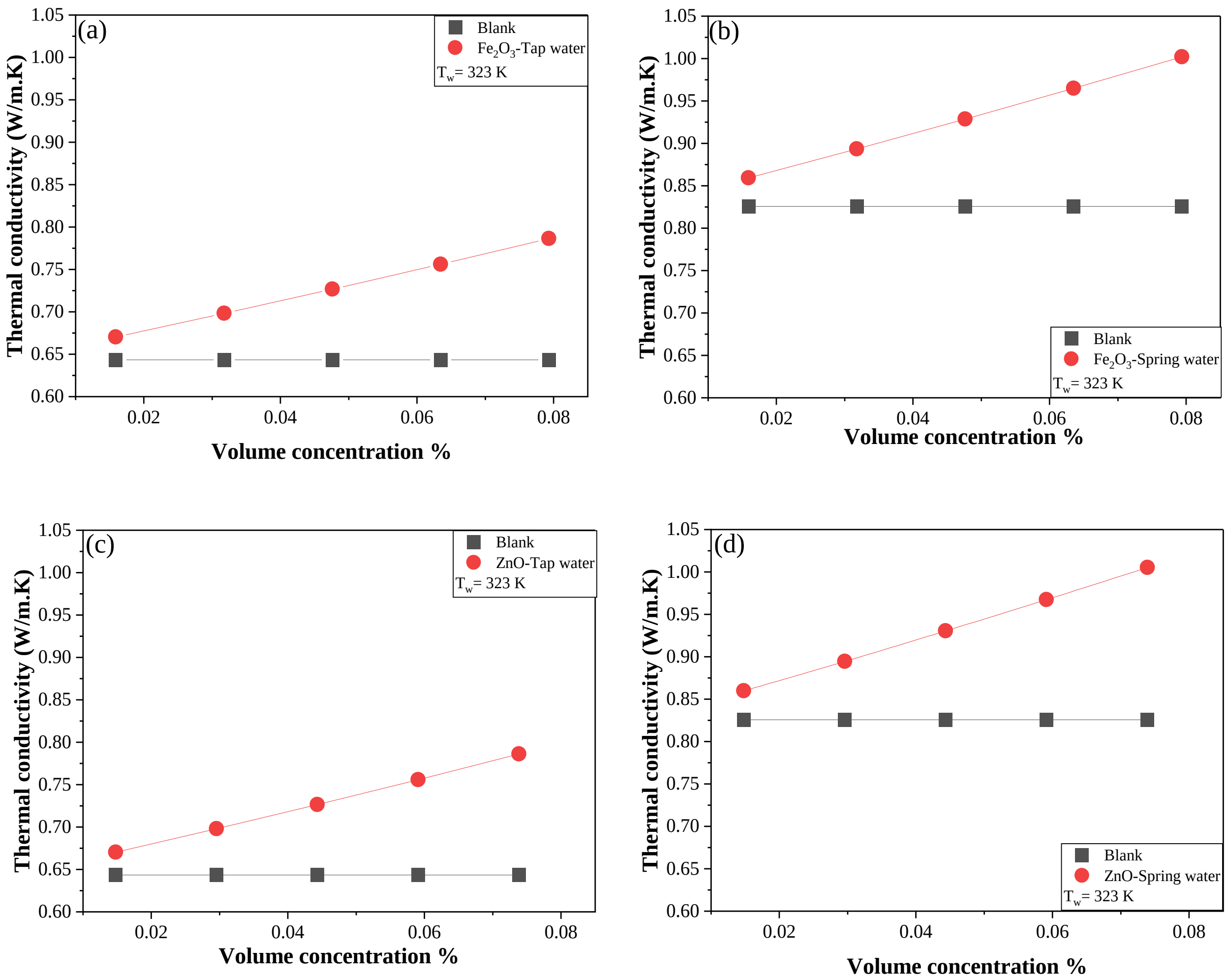

Figure 6. Thermal conductivity of nanofluids as a function of nanoparticle concentration.

Figs. 6b and 6.d point out the highest thermal conductivity for nanofluid -based Fe_2O_3/spring water and ZnO/spring water at different concentration of the nanoparticles. Without any doubt, this could be referred to the higher thermal conductivities for both ZnO and Fe_2O_3. The maximum enhancement of thermal conductivity approximately is 22.23% at 0.08% nanoparticles volume fraction based – Fe_2O_3/tap water, beyond this concentration there is no significant enhancement, as well the agglomeration and particles settle down may occur.

3.5 Pressure drop

In order to use nanofluids in industrial units, the pressure drop of the nanofluids must be measured in addition to the heat transfer performance. Fig. 7 shows the pressure drop of the base fluids and nanofluids proposed. It is observed that when nanoparticles are added at different concentration to the suggested base fluids, the pressure drop proportionally increases.

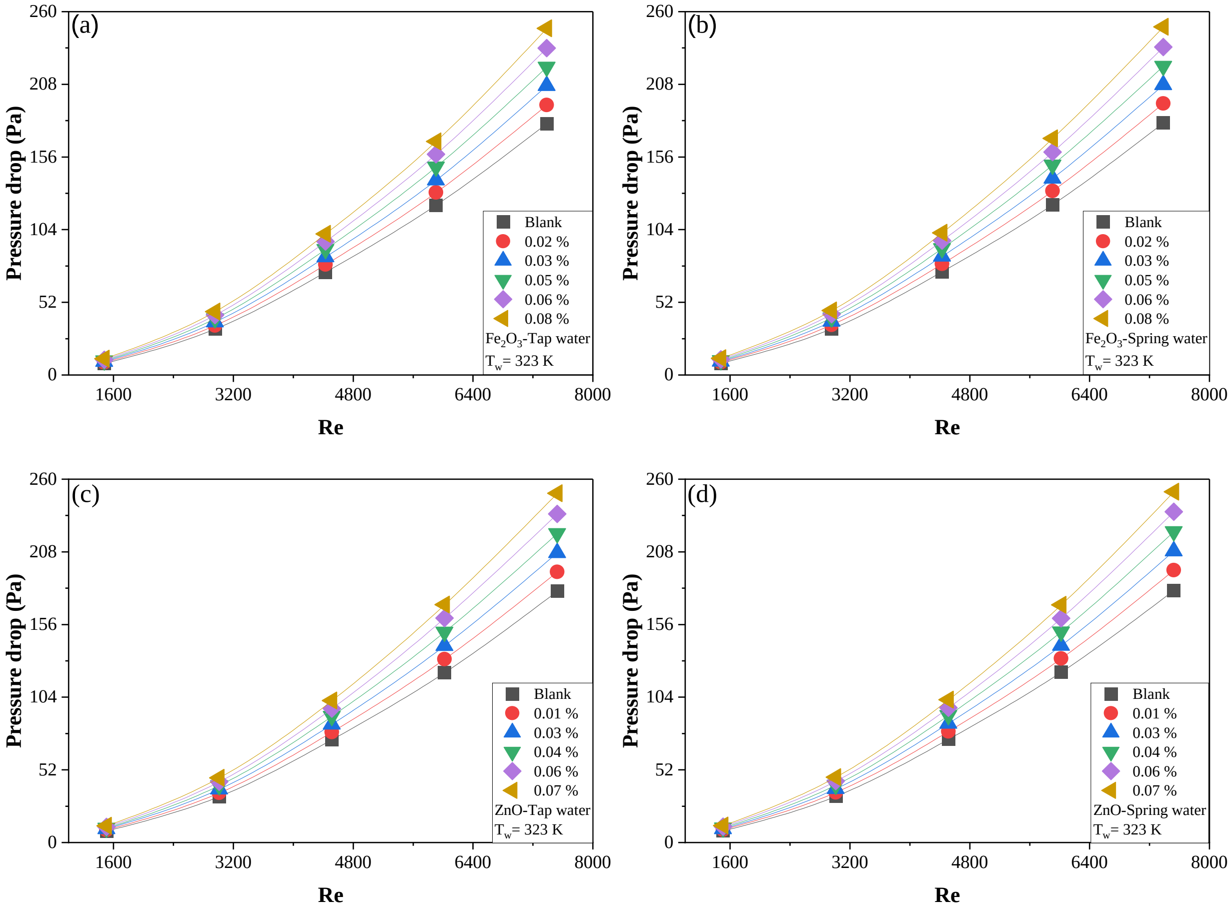

Figure 7. pressure drop vs Reynolds number of nanofluids at different concentration of nanoparticles at 323 K

Obviously, the pressure drop is highly affected by Reynolds number. This is due to the increase of the viscosity of the nanofluids and makes resistance to increase. Fig. 7 shows same trends for the lowest and highest pressure drop of tap water which is 8.27 Pa at Reynolds number of 1476 and 248.11 Pa at the Reynolds number of 7680. The highest-pressure drop was 251 Pa for ZnO/spring water nanofluid at the Reynolds number of 6798 (Fig. 7.d). The increase in viscosity and the bigger size of ZnO are responsible of a slight increase of pressure drop than that of Fe_2O_3/spring water.

3.6 Friction factor

The comparison of friction factor resulted from the experiments and friction factor estimated from Blasius equation Eq. (15, 16, and 17) of four nanofluids at different volume concentrations of nanoparticles as a function of Reynolds number is addressed in Fig. 8.

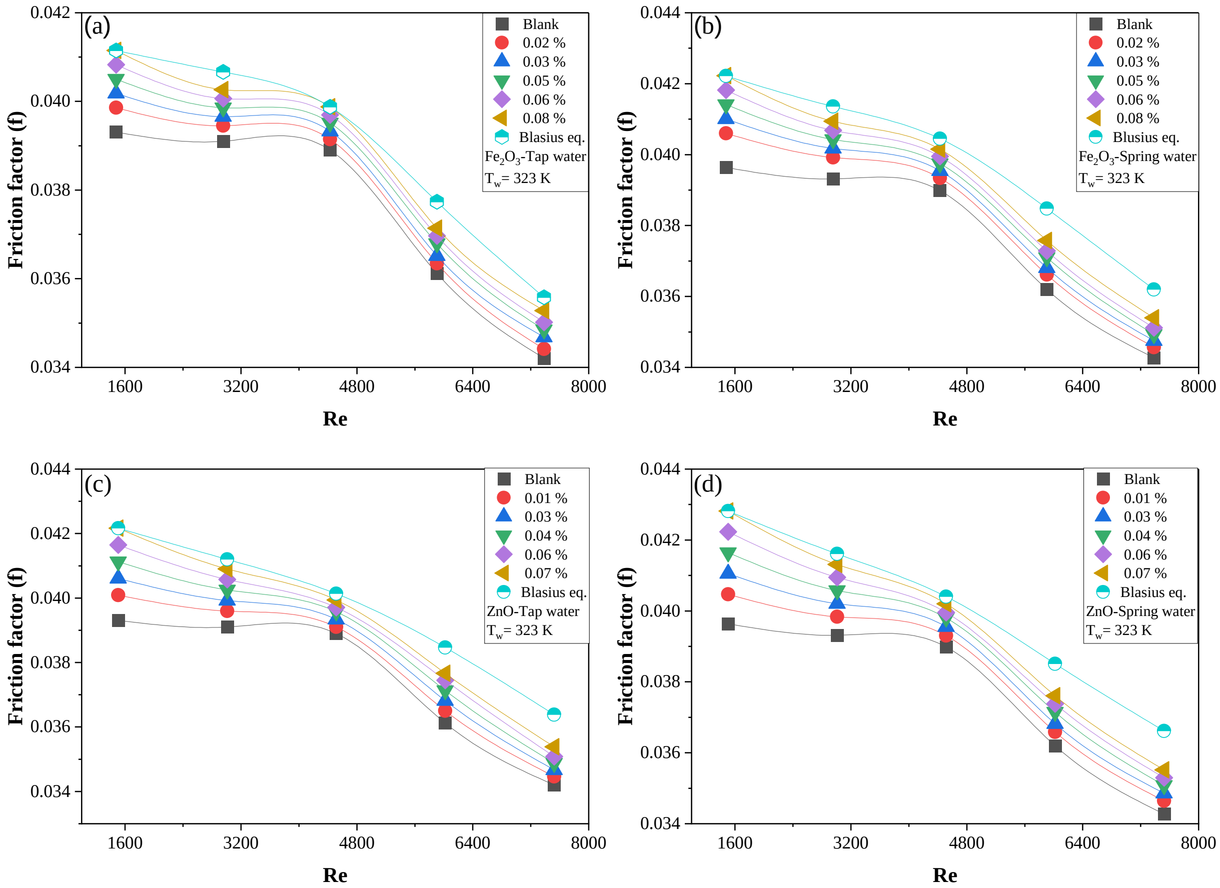

Figure 8: Friction factor vs Reynolds number of nanofluids at different concentration of nanoparticles at 323 K

It is noticed that the friction factor is very slightly increased with the increase of nanoparticles volume fraction, in contrary it decreases with increasing of Reynolds number. Meanwhile, with respect to Reynolds number, it is found that the diversity of experimental friction factor at different concentrations of nanoparticles in low Reynolds number is greater than that of high Reynolds number, this may be attributed to readily the particles to settle down and due to the increase the boundary layer thickness. Furthermore, the friction factors for spring water nanofluids revealed a very little bit change higher, it may be due to slightly higher viscosity. The highest friction factor for nanofluid based ZnO-tap water with the value of 0.0422 at Reynolds number of 1334, whereas the highest friction factor for nanofluid based ZnO-spring water is 0.0428 at Reynolds number of 1359. The maximum deviation observed between the present experimental data and the theoretical value and Balsius equation is 2.9%. Similarity, Figs. 7.c and 7.d indicate the lowest friction factor for the nanofluid -based ZnO/Tap water and ZnO/spring water is 0.0345 at Reynolds number of 7680. The maximum deviation observed between the present experimental data and theoretical value and Balsius equation is 3%.

4. Conclusion

In this paper, not so far studies have been conducted on spring water as a base fluid for nanofluids. Thermophysimechanical properties of Fe_2O_3 and ZnO as suspended nanoparticles with different volume concentration at 323 K in two base fluids of tap water and spring water experimentally is measured. The size of Fe_2O_3 nanoparticles was 50 nm and ZnO nanoparticles was 70nm. The shell heat exchanger is to maintain the temperature at a desired value and the tube heat exchanger is used as an engine. Nanofluids circulated inside the tube of the engine as a coolant by different volumetric flowrates (50, 100, 150, 200, and 250 L/h) and hot water passed through the shell side as a hot fluid at a constant volumetric flowrate with a value of 150 L/h. Reynolds numbers of nanofluids inside the engine were considered between of (1000 to 8000). The volume fraction of Fe_2O_3 and ZnO nanoparticles in the respective based fluids was verified between (0.02%, 0.03%, 0.05%, 0.06%, and 0.08%) and (0.01%, 0.03%, 0.04%, 0.06%, and 0.07 %). The effects of nanoparticles added to the chosen base fluids on the heat transfer coefficient, overall heat transfer coefficient, Nusselt number, thermal conductivity, pressure drop, and friction factor experimentally have been evaluated. The density and viscosity of the nanofluids during the experiments were investigated. As a result, the highest heat transfer coefficient obtained from Fe_2O_3/spring water nanofluid with a value of 3740 $W/m^2.K$, at the volume concentration of 0.08%, respectively at Reynolds number of 7680. The maximum enhancement was at the volume concentration 0.08% with the value of 46%. For overall heat transfer coefficient the highest has been obtained from Fe_2O_3/spring water nanofluid with a value of 4853 $W/m^2.K$ at Reynolds number 7680 at the volume concentration of 0.08% and the maximum enhancement of overall heat transfer coefficient was obtained 39% at the volume concentration of 0.08%. Based on the obtained results, the major conclusions and findings of the current work are as follows:

1. Heat transfer coefficient and overall heat transfer coefficient could be enhanced with increasing the volume fraction of nanoparticles and Reynolds number up to a specific amount, then the addition is non-significant.
2. The thermal conductivity and specific surface area of the nanoparticles are the main factors effecting the enhancement of effective heat transfer of the nanofluids. They took role-playing for enhancement the heat transfer coefficient. The higher thermal conductivity is not necessary, the higher heat transfer coefficient, when the lower the thermal conductivity particles possess higher specific surface area.
3. For the same conditions of velocity and volumetric flow rate, the power consumption of nanofluid-based spring water is 2% higher than the power consumption of nanofluid-based tap water.
4. The enhancement of the effective heat transfer using the designed nanofluids without straight forward side effect of friction factor over a wide range of Reynolds number, promotes the nanofluids as a coolant for the engine performance.

References

[1] A. Al-damook and I. D. J. Azzawi, “Multi-objective numerical optimum design of natural convection in different configurations of concentric horizontal annular pipes using different nanofluids,” *Heat Mass Transf. und Stoffuebertragung*, vol. 57, no. 9, pp. 1543–1557, 2021, doi: 10.1007/s00231-021-03051-8.

[2] B. Raei, F. Shahraki, M. Jamialahmadi, and S. M. Peyghambarzadeh, “Experimental study on the heat transfer and flow properties of γ-Al2O3/water nanofluid in a double-tube heat exchanger,” *J. Therm. Anal. Calorim.*, vol. 127, no. 3, pp. 2561–2575, 2017, doi: 10.1007/s10973-016-5868-x.

[3] I. M. Shahrul, I. M. Mahbubul, R. Saidur, S. S. Khaleduzzaman, and M. F. M. Sabri, “Performance evaluation of a shell and tube heat exchanger operated with oxide based nanofluids,” *Heat Mass Transf. und Stoffuebertragung*, vol. 52, no. 8, pp. 1425–1433, 2016, doi: 10.1007/s00231-015-1664-6.

[4] W. Ajeeb, R. R. S. Thieleke da Silva, and S. M. S. Murshed, “Experimental investigation of heat transfer performance of Al2O3 nanofluids in a compact plate heat exchanger,” *Appl. Therm. Eng.*, vol. 218, no. January 2022, p. 119321, 2023, doi: 10.1016/j.applthermaleng.2022.119321.

[5] E. C. Okonkwo, I. Wole-Osho, I. W. Almanassra, Y. M. Abdullatif, and T. Al-Ansari, *An updated review of nanofluids in various heat transfer devices*, vol. 145, no. 6. Springer International Publishing, 2021. doi: 10.1007/s10973-020-09760-2.

[6] V. Singh, M. Gupta, A. Kumar, S. Luthra, and A. Kumar, “Experimental Investigations of Thermophysical Properties and Convective Heat Transfer of Al2O3 and CuO Nanofluids in a Copper Tube: Proposing New Correlations,” *Biointerface Res. Appl. Chem.*, vol. 13, no. 3, pp.

0–15, 2023, doi: 10.33263/BRIAC133.229.

[7] F. Mebarek-Oudina and I. Chabani, "Review on Nano-Fluids Applications and Heat Transfer Enhancement Techniques in Different Enclosures," *J. Nanofluids*, vol. 11, no. 2, pp. 155–168, 2022, doi: 10.1166/jon.2022.1834.

[8] A. Klarasita, A. Bayu, D. Nandiyanto, R. Ragadhita, and T. Kurniawan, "Heat Exchanger Design for Cerium Oxide Nanoparticles Production," vol. 09, no. 2, pp. 206–217, 2022.

[9] A. H. Abdelaziz, W. M. El-Maghlany, A. Alaa El-Din, and M. A. Alnakeeb, "Mixed convection heat transfer utilizing Nanofluids, ionic Nanofluids, and hybrid nanofluids in a horizontal tube," *Alexandria Eng. J.*, vol. 61, no. 12, pp. 9495–9508, 2022, doi: 10.1016/j.aej.2022.03.001.

[10] Y. K. Lee, "Akademia Baru The Use of Nanofluids in Domestic Water Heat Exchanger Akademia Baru," *J. Adv. Res. Appl. Math.*, vol. 3, no. 1, pp. 9–24, 2014.

[11] G. Yalçın, S. Öztuna, A. S. Dalkılıç, and S. Wongwises, "The influence of particle size on the viscosity of water based ZnO nanofluid," *Alexandria Eng. J.*, vol. 68, pp. 561–576, 2023, doi: 10.1016/j.aej.2022.12.047.

[12] H. F. Kadhim, "Effectiveness Enhancement of the Double Tube Heat Exchanger Using ZnO Nanofluid," *J. Pet. Res. Stud.*, vol. 12, no. 2, pp. 97–109, 2022, doi: 10.52716/jprs.v12i2.660.

[13] N. Kumar and S. S. Sonawane, "Experimental study of Fe2O3/water and Fe2O3/ethylene glycol nanofluid heat transfer enhancement in a shell and tube heat exchanger," *Int. Commun. Heat Mass Transf.*, vol. 78, pp. 277–284, 2016, doi: 10.1016/j.icheatmasstransfer.2016.09.009.

[14] A. Topuz, T. Engin, A. Alper Özalp, B. Erdoğan, S. Mert, and A. Yeter, "Experimental investigation of optimum thermal performance and pressure drop of water-based Al2O3, TiO2 and ZnO nanofluids flowing inside a circular microchannel," *J. Therm. Anal. Calorim.*, vol. 131, no. 3, pp. 2843–2863, 2018, doi: 10.1007/s10973-017-6790-6.

[15] J. Albadr, S. Tayal, and M. Alasadi, "Heat transfer through heat exchanger using Al2O3 nanofluid at different concentrations," *Case Stud. Therm. Eng.*, vol. 1, no. 1, pp. 38–44, 2013, doi: 10.1016/j.csite.2013.08.004.

[16] M. Hatami, D. D. Ganji, and M. Gorji-Bandpy, "CFD simulation and optimization of ICEs exhaust heat recovery using different coolants and fin dimensions in heat exchanger," *Neural Comput. Appl.*, vol. 25, no. 7–8, pp. 2079–2090, 2014, doi: 10.1007/s00521-014-1695-9.

[17] I. D. J. Azzawi, S. G. Yahya, L. A. H. Al-Rubaye, and S. K. Ali, "Heat transfer enhancement of different channel geometries using nanofluids and porous media," *Int. J. Heat Technol.*, vol. 39, no. 4, pp. 1197–11206, 2021, doi: 10.18280/ijht.390417.

[18] S. M. Jafari, S. S. Jabari, D. Dehnad, and S. A. Shahidi, "Heat Transfer Enhancement in Thermal Processing of Tomato Juice by Application of Nanofluids," *Food Bioprocess Technol.*, vol. 10, no. 2, pp. 307–316, 2017, doi: 10.1007/s11947-016-1816-9.

[19] P. V. Durga Prasad, A. V. S. S. K. S. Gupta, M. Sreeramulu, L. S. Sundar, M. K. Singh, and A. C. M. Sousa, "Experimental study of heat transfer and friction factor of Al2O3 nanofluid in U-tube heat exchanger with helical tape inserts," *Exp. Therm. Fluid Sci.*, vol. 62, pp. 141–150, 2015, doi: 10.1016/j.expthermflusci.2014.12.006.

[20] A. M. Hussein, Lingenthiran, K. Kadirgamma, M. M. Noor, and L. K. Aik, "Palm oil based nanofluids for enhancing heat transfer and rheological properties," *Heat Mass Transf. und Stoffuebertragung*, vol. 54, no. 10, pp. 3163–3169, 2018, doi: 10.1007/s00231-018-2364-9.

[21] V. Kumar, N. Pandya, B. Pandya, and A. Joshi, "Synthesis of metal-based nanofluids and their thermo-hydraulic performance in compact heat exchanger with multi-louvered fins working under laminar conditions," *J. Therm. Anal. Calorim.*, vol. 135, no. 4, pp. 2221–2235, 2019, doi: 10.1007/s10973-018-7304-x.

[22] M. Zarringhalam, A. Karimipour, and D. Toghraie, "Experimental study of the effect of solid volume fraction and Reynolds number on heat transfer coefficient and pressure drop of CuO-Water nanofluid," *Exp. Therm. Fluid Sci.*, vol. 76, pp. 342–351, 2016, doi: 10.1016/j.expthermflusci.2016.03.026.

[23] E. A. Chavez Panduro, F. Finotti, G. Largiller, and K. Y. Lervåg, "A review of the use of nanofluids as heat-transfer fluids in parabolic-trough collectors," *Appl. Therm. Eng.*, vol. 211, no. March, p. 118346, 2022, doi: 10.1016/j.applthermaleng.2022.118346.

[24] R. Lotfi, A. M. Rashidi, and A. Amrollahi, "Experimental study on the heat transfer enhancement of MWNT-water nanofluid in a shell and tube heat exchanger," *Int. Commun. Heat Mass Transf.*, vol. 39, no. 1, pp. 108–111, 2012, doi: 10.1016/j.icheatmasstransfer.2011.10.002.

[25] A. Hajatzadeh Pordanjani, S. Aghakhani, M. Afrand, B. Mahmoudi, O. Mahian, and S. Wongwises, "An updated review on application of nanofluids in heat exchangers for saving

energy," *Energy Convers. Manag.*, vol. 198, no. July, p. 111886, 2019, doi: 10.1016/j.enconman.2019.111886.

[26] K. M. Shareef and S. G. Muhamad, "Natural and drinking water quality in Erbil, Kurdistan," *Curr. World Environ.*, vol. 3, no. 2, pp. 227–238, 2008, doi: 10.12944/cwe.3.2.04.

[27] L. S. Sundar, E. V. Ramana, M. K. Singh, J. Gracio, and A. C. M. Sousa, "Preparation, Thermal and Rheological Properties of Propylene Glycol and Water Mixture Based Fe3O4 Nanofluids," *J. Nanofluids*, vol. 3, no. 3, pp. 200–209, 2014, doi: 10.1166/jon.2014.1108.

[28] E. D. Bojesen, M. Sondergaard, M. Christensen, and B. B. Iversen, "Particle size effects on the thermal conductivity of ZnO," *AIP Conf. Proc.*, vol. 1449, pp. 335–338, 2012, doi: 10.1063/1.4731565.

[29] "National Instittue for Standards and Technology, US, NIST Chemistry WebBook (2023), https://webbook.nist.gov/cgi/cbook.cgi?ID=C1317608&Type=JANAFS&Table=on," p. 1317608, 2023.

[30] "Water - Thermal Conductivity vs. Temperature." https://www.engineeringtoolbox.com/water-liquid-gas-thermal-conductivity-temperature-pressure-d_2012.html.

[31] B. Adrian, *CONVECTION HEAT Other books by Adrian Bejan :* 2013.

[32] Engineering ToolBox, "Water - Specific Heat vs. Temperature," *Water - Specific Heat vs. Temperature*. p. online, 2004. [Online]. Available: https://www.engineeringtoolbox.com/specific-heat-capacity-water-d_660.html

[33] J. Saari, "Faculty of Technology LUT Energy HEAT EXCHANGER," pp. 1–101, 2011.

[34] R. S. Subramanian, "Heat transfer in Flow Through Conduits," *Dep. Chem. Biomol. Eng. Clarkson Univ.*, vol. 1, pp. 1–9, 2006.

[35] N. Kumar, S. S. Sonawane, and S. H. Sonawane, "Experimental study of thermal conductivity, heat transfer and friction factor of Al2O3 based nanofluid," *Int. Commun. Heat Mass Transf.*, vol. 90, no. January, pp. 1–10, 2018, doi: 10.1016/j.icheatmasstransfer.2017.10.001.

[36] Z. Haddad, H. F. Oztop, E. Abu-Nada, and A. Mataoui, "A review on natural convective heat transfer of nanofluids," *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 5363–5378, 2012, doi: 10.1016/j.rser.2012.04.003.

[37] X. Q. Wang and A. S. Mujumdar, "Heat transfer characteristics of nanofluids: a review," *Int. J. Therm. Sci.*, vol. 46, no. 1, pp. 1–19, 2007, doi: 10.1016/j.ijthermalsci.2006.06.010.

[38] K. Bashirnezhad *et al.*, "Viscosity of nanofluids: A review of recent experimental studies," *Int. Commun. Heat Mass Transf.*, vol. 73, pp. 114–123, 2016, doi: 10.1016/j.icheatmasstransfer.2016.02.005.

[39] V. Nageswara Rao and B. Ravi Sankar, "Heat transfer and friction factor investigations of CuO nanofluid flow in a double pipe U-bend heat exchanger," *Mater. Today Proc.*, vol. 18, pp. 207–218, 2019, doi: 10.1016/j.matpr.2019.06.294.

[40] P. K. Vijayan, A. K. Nayak, and N. Kumar, *Governing differential equations for natural circulation systems*. 2019. doi: 10.1016/b978-0-08-102486-7.00003-2.

[41] B. S. Petukhov, "Heat Transfer and Friction in Turbulent Pipe Flow with Variable Physical Properties," *Adv. Heat Transf.*, vol. 6, no. C, pp. 503–564, 1970, doi: 10.1016/S0065-2717(08)70153-9.

[42] L. Syam Sundar, M. K. Singh, and A. C. M. Sousa, "Investigation of thermal conductivity and viscosity of Fe3O4 nanofluid for heat transfer applications," *Int. Commun. Heat Mass Transf.*, vol. 44, pp. 7–14, 2013, doi: 10.1016/j.icheatmasstransfer.2013.02.014.

[43] F. Flow, H. Transfer, and M. Transfer, "Coulson & Richardson ' s".

[44] R. Aghayari, H. Maddah, F. Ashori, A. Hakiminejad, and M. Aghili, "Effect of nanoparticles on heat transfer in mini double-pipe heat exchangers in turbulent flow," *Heat Mass Transf. und Stoffuebertragung*, vol. 51, no. 3, pp. 301–306, 2015, doi: 10.1007/s00231-014-1415-0.

[45] U. Roy and P. K. Roy, *Advances in heat intensification techniques in shell and tube heat exchanger*. Elsevier Inc., 2020. doi: 10.1016/B978-0-12-819422-5.00007-4.