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Article

Thermal Conductivity of Seminal Fluid in a Tube Equipped with a Torsion Bar

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Abstract: According to the studies conducted, forced convection heat transfer of nanofluid in curved tubes with different curvature ratios and constant surface temperature has not been fully investigated and more in-depth studies are needed in this regard in this experiment, water and water-alumina nanofluid with a volume percentage of 0.10 were used, and also three curved tubes with curvature ratios of 0.116, 1073 and 1022 and equal external surface areas and the same material were used. After measuring the inlet and outlet temperatures of the tube, the average Nusselt number and pressure drop in the tube are measured by repeating the experiment, the results obtained are displayed by statistical relations in the confidence interval Also, the theoretical relations available for curved tubes have been used to verify the experimental results of pressure drop. The results obtained show a maximum increase of 15% in the Nusselt number due to the use of water-alumina nanofluid with 0.1% by volume compared to the base fluid Also, the effect of curvature ratio on the heat transfer nanofluid of the working fluid was investigated and showed a significant increase in the convection heat transfer of the Hamidah tube with a smaller sludge ratio compared to the tube with a larger curvature ratio.

Keywords: Thermal conductivity of seminal fluid, tube flow, torsion bar, heat transfer, thermal properties, system thermal performance

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1. Introduction

Increasing efficiency and improving energy consumption in industries has always been of interest to researchers. Improving heat transfer in heating and cooling systems is no exception to this rule. The performance of thermal equipment can be improved by using specific methods. In general, these methods can be divided into two categories: active methods and passive methods. In active methods, an external force such as an electric field or a magnetic field is applied. In passive methods, special surfaces with additives are used the use of curved pipes is also a passive method of improving heat transfer curved pipes are essential components of almost all industrial process equipment, including power generation, chemical industries, heat exchangers, nuclear reactors, etc. The flow in a curved pipe is much more complex than the flow in a straight pipe in a curved pipe, secondary flows created by centrifugal force cause flow mixing and improve heat transfer many studies have been conducted on flow and heat transfer in various types of curved tubes, but due to the complexities of flow and heat transfer in these geometries, further investigations seem necessary [1,2].

On the other hand, the inherent poor thermal conductivity of fluids commonly used in transport Heat in industries such as water, oils, and ethylene glycol is a serious limitation in improving the performance and compactness of engineering equipment. One way to improve heat transfer is to use fine solid particles in the fluid. The use of these particles in nanometre dimensions in the fluid was first proposed by Choi in 1995 as

"nanofluids." Laboratory studies have shown that nanofluids not only increase the thermal conductivity but also increase the convection heat transfer coefficient compared to the base fluid [3-5]. One of the limiting factors resulting from the increase in the volume fraction of nanoparticles is the pressure drop inside the pipes and the increase in pump power. The increase in pressure drops due to the use of nanofluids, especially in the developing area, has been reported by various researchers [6].

In addition to laboratory studies, some have studied the theory and numerical simulation of the flow and heat transfer of nanofluids in different geometries [7]. Numerical simulations of convection heat transfer in different geometries and different boundary conditions are applicable to various types of nanofluids. In existing numerical simulations, nanofluids containing various nanoparticles such as alumina [8,9], copper oxide and carbon nanotubes have been studied. The flow geometry in most of these simulations is straight. Few studies are available on the flow inside curved tubes fully developed in Hamidah tubes [10-13].

Mullin et al. [14] conducted an experimental and numerical study on the flow in curved tubes and stated that the secondary flow has no significant effect at Reynolds numbers less than 20. The increase in the pressure drop of the flow inside curved tubes compared to the pressure drop of ordinary tubes was first proposed by Grindley and Gibson [15]. Kalb and Seder [16] and [2] studied the heat transfer of a steady viscous flow developed in a curved tube with a circular cross-section with a boundary condition of constant flux and constant wall temperature numerically and found a relationship for calculating the average Nusselt number in a certain range of Dean and Prandtl numbers.

Akbarinia and Laur [17], [11] and [12] have numerically simulated the laminar mixed convection of alumina nanofluid in water inside a 180-degree bend and investigated the effect of buoyancy and centrifugal force, concentration and diameter of solid particles on the convection heat transfer of nanofluid. They reported that at a given mass flow, the concentration of nanoparticles has a positive effect on the axial velocity and the buoyancy force has a negative effect on the Nusselt number and friction coefficient. Also, increasing the diameter of solid particles causes a decrease in the Nusselt number and secondary flow and an increase in the axial velocity.

Ebrahimia et al. [18, 19] Heat transfer of water-alumina nanofluid, whose thermophysical properties are a function of temperature and particle concentration, was considered for two straight and curved pipes with equal length and diameter, and the heat transfer of laminar flow of nanofluid-2 was numerically investigated by preparing and determining the nanofluid and its characteristics of a mixture of water and carbon nanotubes in a curved pipe with a 90-degree bend. They investigated the effect of curvature and nanoparticles and found that due to the movement of the secondary flow caused by the curvature effects, the heat transfer rate was significantly improved and was accompanied by an increase in pressure drop. A numerical investigation of forced convection heat transfer of alumina-water nanofluid in a curved pipe was carried out by Choi and Zhang [20].

The results show that with increasing Reynolds and Prandtl numbers, the Nusselt number should increase, and increasing the specific heat capacity and increasing the concentration of nanoparticles improves heat transfer and increases the pressure drop in the tube. A numerical study of the effects of applying a magnetic field to water and iron oxide ferrofluids in curved and straight horizontal tubes was carried out by Aminfar et al. [21].

Their results indicate that the use of an external magnetic field increases the heat transfer coefficient in a straight tube. However, in a curved tube, the heat transfer coefficient decreases due to the interaction between the stronger centrifugal force and the Kelvin force.

Liberto et al. [22] studied the interfacial flow and heat transfer in a curved tube by numerical simulation. Ciofalo et al. [23] studied the effects of gravitational and centrifugal buoyancy in laminar flow and heat transfer in curved and spiral tubes by numerical simulation.

In this research, the effect of using new methods such as nanofluids and geometric deformation in improving heat transfer systems has been investigated. Research shows that there are limited studies in the field of heat transfer.

Forced heat transfer of nanofluid inside the curved tube and the effect of geometric parameters on improving their performance. Therefore, this research is one of the first laboratory researches in this field. In most of the researches, the comparison of heat transfer between curved and straight tubes has been investigated, but in this research, considering the application of curved tubes in various engineering devices such as piping systems of industrial plants, turbo machines, and this simultaneous comparison between three curved tubes with 180 degree bends with equal material and external surface area and different base ratios, considering the pressure drop, was carried out and the effect of curvature ratio and the presence of nanoparticles in the base fluid on heat transfer and pressure drop was studied. Nanopowder with an average size of 15 nm was used to make 0.1% by volume nanofluid. To increase the accuracy of the experiments, each was performed at least three times and the results were displayed as a confidence interval.

The objectives of this research can be Summarized as follows: Comparison of heat transfer of nanofluid and base fluid in curved tubes.

Investigation of the effect of curvature on heat transfer and fluid pressure drop inside curved tubes Preparation of nanofluids is the first step in increasing the heat transfer of nanofluids.

1.1 Preparation and determination of nanofluid and its characteristics

Two common methods for producing nanofluids are the single-step method and the two-step method. In the two-step method, the ultrasonically prepared nanopowder is stabilized in the base fluid. Wang et al. [24] were among those who used the two-step method to produce water-alumina nanofluid.

In this paper, a two-step method was used to prepare nanofluids. Thus, alumina nanopowder with an average size of 15 nm prepared by the Spanish company Teknan was stabilized in the base fluid of distilled water for 3 hours by an ultrasonic device with a power of 200 W and 30 kHz.

The prepared nanofluid remained stable for at least 48 hours without any sedimentation, agglomeration, color change and remained completely uniform in color. It should be noted that no additional stabilizer was added to the fluid to prevent changes in the thermal properties of the nanofluid. The nanofluid was prepared and used at 0.1% by volume. The three main parameters in calculating the heat transfer rate of nanofluids, including viscosity, thermal conductivity, and heat capacity, may differ from the parameters of the base fluid. Einstein [25] has provided equation (1) to calculate the viscosity of nanofluids with a concentration of less than 5%.

$$\mu_{nf} = \mu_w \ (1+2.5\varphi) \quad (1)$$

In this relation, and is the volume percentage and with the viscosity

The density and specific heat of nanofluid are shown in equations (2) and (3), which were investigated with experimental data by Yek and Chu [26] and Xuan and Rotzel [27], respectively.

$$\varrho_{nf} = (1-\varphi)\ \varrho_w + \varphi\varrho_{nf}$$

$$C_{\varrho nf} = \varphi\varrho_{nf}\, C_{\varrho.np}+(1-\varphi)\ \varrho_w + c_{p.w} / \varrho nf$$

In this relation, ϱ_{nf} and ϱ_w are the densities of water and nanoparticles, respectively, and $C_{\varrho.np}$ and $c_{p.w}$ han are the specific heats of water and nanoparticles, respectively. One of the first mathematical models for the thermal conductivity of macro-suspensions is the Maxwell model [28].

In this model, shown in relation (4), the suspension is a function only of the particle volume fraction and the thermal conductivity of the fluid and the particle.

$$K_{nf} / K_w = K_{np} + 2K_w + 2\varphi(K_{np}-K_w) \ / \ K_{np} + 2K_w - \varphi(K_{np}-K_w)$$

In this equation, K and K are the thermal conductivity in nanoparticles and water, respectively.

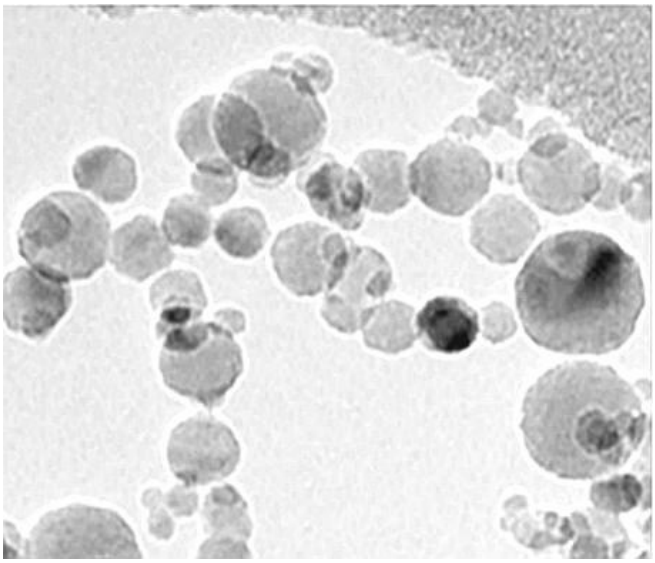


Figure 1. TEM image of alumina nanopowder

2. Materials and Methods

2.1. Experimental Setup

The experimental apparatus was designed to investigate forced convection heat transfer and pressure drop characteristics of water and Al_2O_3–water nanofluid flowing through curved tubes under controlled thermal boundary conditions.

The experimental system consisted of a heated water tank, a circulating pump, a cooling heat exchanger, a flow-rate measurement unit, a pressure-drop measurement system, and calibrated temperature sensors. Three curved tubes with curvature ratios of 0.042, 0.074, and 0.116 were investigated.

The geometrical dimensions, tube material, internal diameter, external diameter, and effective heat transfer area should be reported for each test section.

2.2 Preparation of Al_2O_3–Water Nanofluid

The Al_2O_3–water nanofluid was prepared using the two-step method. Alumina nanoparticles with an average nominal diameter of 15 nm were dispersed in distilled water at a volume concentration of 0.1%. The suspension was subjected to ultrasonic treatment for three hours using an ultrasonic device operating at 200 W and 30 kHz. The stability of the prepared nanofluid was evaluated over a period of 48 hours. The nanoparticle concentration was determined based on the mass and density of the solid particles and the base fluid.

2.3 Experimental Procedure

Before each experimental run, the heating system was operated until the surrounding water reached a temperature of approximately 92°C. The working fluid was circulated through the cooling heat exchanger to maintain an inlet temperature of approximately 18°C.

After reaching steady-state conditions, the inlet temperature, outlet temperature, surrounding water temperature, volumetric flow rate, and pressure drop were recorded. Each experimental condition was repeated at least three times to improve measurement reliability.

2.4 Thermophysical Properties

The density, specific heat capacity, viscosity, and thermal conductivity of the nanofluid were evaluated using appropriate mixture models.

The effective thermophysical properties were calculated using the nanoparticle volume fraction and the corresponding properties of water and alumina.

2.5 Heat Transfer Calculations

The heat transfer rate was determined using the energy balance: $q = \dot{m} C_{p,nf} (T_{out} - T_{in})$ The logarithmic mean temperature difference was calculated to determine the average heat transfer coefficient. The average Nusselt number was subsequently evaluated using the effective thermal conductivity of the working fluid.

2.6 Dimension Less Parameters

The Reynolds number and Dean number were calculated to characterize the flow regime and the influence of tube curvature. The curvature ratio was defined consistently using the tube diameter and the radius of curvature of its centerline.

2.7 Pressure Drop and Friction Factor

The pressure drop across each curved tube was measured experimentally. The Darcy friction factor was calculated using the Darcy–Weisbach equation and compared with an appropriate theoretical correlation for curved tubes.

2.8 Uncertainty Analysis

The uncertainty associated with the measured and calculated parameters was evaluated using the root-sum-square method and the propagation of measurement uncertainties.

The repeatability of the experimental measurements was also assessed using statistical analysis.

2.9 Laboratory system

In this paper, the forced convection heat transfer of the working fluid water and 0.10% water-alumina nanofluid in a curved tube passing through a rectangular cubic tank with a constant temperature boundary condition has been investigated. The tank body is made of soft Teflon with a length of 35 cm, a width of 22 cm, a height of 25 cm, and a thickness of 1 cm.

Also, three curved tubes with curvature ratios of 0.042, 0.074, and 0.116 and a surface area of The actual and schematic images of the system under test are shown in Figures 2(a) and 2(b), respectively, and the actual and schematic images of the top view of the fluid tank are shown in Figures 3(a) and 3(b), respectively. To start the test, the fluid flow rate must first be determined in each step to determine the flow velocity and then the Reynolds number.

In the first step, before starting the test, the heating element must be turned on until the temperature of the water tank, in which the test tube is completely placed, reaches 92°C with an accuracy of 0.5 and is fixed. To ensure that the temperature of the tank is stabilized, several temperature sensors are used near the wall and at different points inside the water tank.

For the constant temperature mode, the second step is to pour the working fluid into the fluid tank and turn on the pump. Then, this working fluid is directed to the heat exchanger. The heat exchanger is a shell-and-tube type that uses city water and ice to stabilize the inlet temperature at 18°C with an accuracy of 0.5. In each The system is allowed to operate at a flow rate of 10 to 20 minutes until the system reaches a steady state so that the fluid always enters the test section at the same temperature. When the system reaches a steady state, the temperature of the tank sensor, the temperature of the inlet and outlet sensors of the test tube are recorded at any time by the Adam 4015 device and transferred to the computer by a serial converter to the Adam 4561 port, and the average of the values is taken. With the above information, the heat transfer coefficient and the Nusselt number of this fluid flow can be determined. The pressure drop measuring device also shows the pressure changes on the display at each flow rate. The sensors used are PT 100 resistance sensors made by the German company Gemo, which are calibrated with an accuracy of 0.1 ° C. The results of each test are recorded after reaching a steady state and, to increase the accuracy of each test, are performed at least three times and the results obtained are displayed as a confidence interval with a statistical accuracy of 97%.

2.10 Data analysis

2.10.1. Formulation

One of the best ways to evaluate the thermal performance of a system is to examine the convection heat transfer coefficient and the Nusselt number. The convection coefficient is calculated from equation (5) [29] $h = q / A\Delta T_b$ (5)

where and the heat absorbed by the fluid along the test tube A area

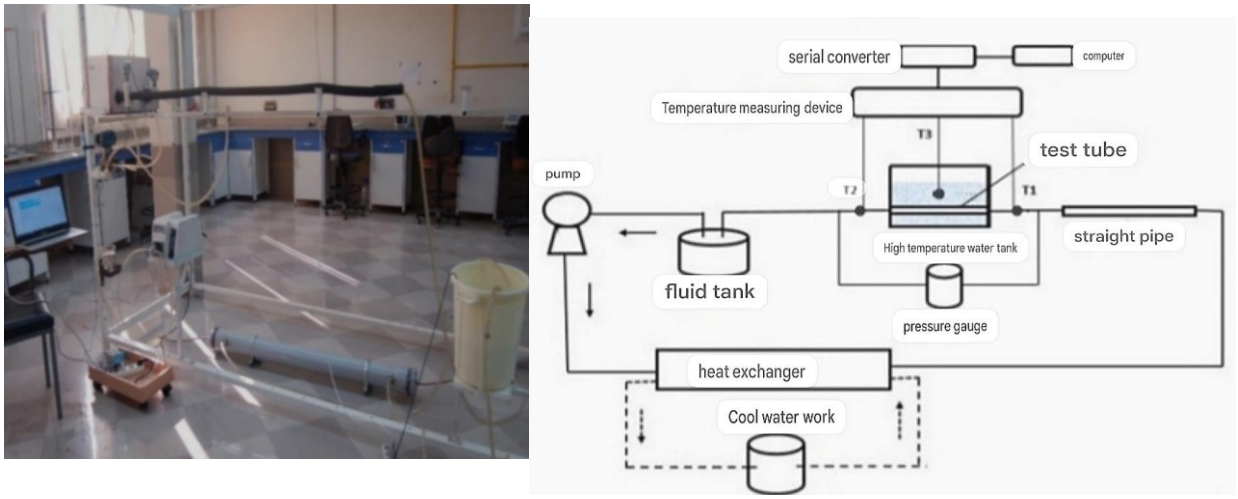


Figure 2. a) A picture of experimental system, b) Schematic of experimen-of system

2.10.2. Laboratory

The wall of the tube and is the average difference between the wall temperature and the centre of the tube between the inlet and outlet. The absorbed energy of the system can be defined as equation (6) [29]

$q = mC_{peff} (T_{out}-T_{in})$ (6)

where C_{peff} is the effective specific heat coefficient of the nanofluid calculated from equation (3) and the flow bulk temperature is also calculated using the LMTD[1] method [29]

$\Delta T_b = In\ T_w-T_{in} / T_w-T_{out}$ (7)

where T_w and T_{in} are T_{out} the inlet fluid temperatures, respectively.

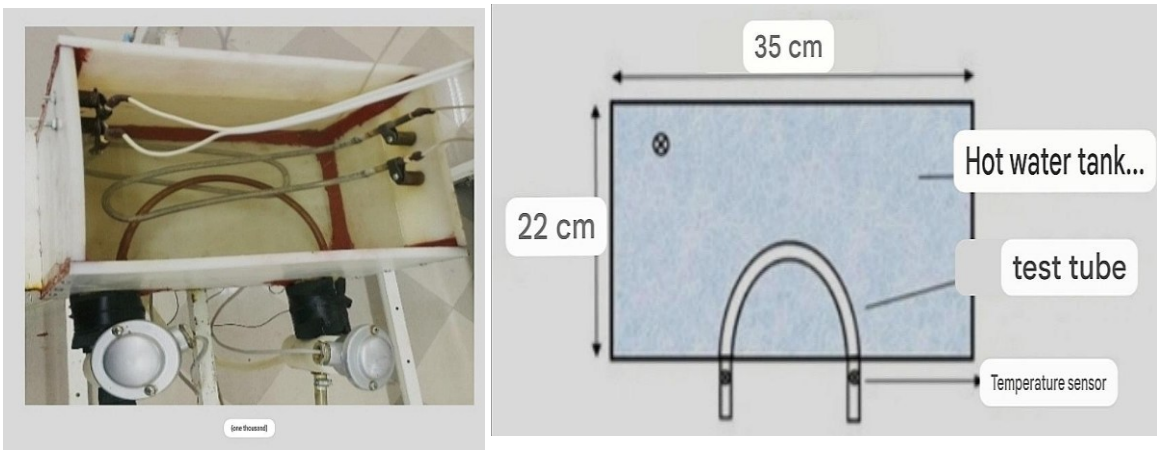


Figure 3. (a) Actual image of the top view of the tank, (b) Schematic of the top view tank and the outlet of the pipe, so the displacement coefficient is defined as equation (8)

will be :

$h = mC_{peff} (T_{out}-T_{in}) / \Delta In\ T_w-T_{in} / T_w-T_{out}$ (8)

Finally, the Nusselt number of the flow can be calculated as equation (9)

$Nu = hD / K_{eff}$ (9)

D is the pipe diameter and Kar is the effective conductivity of the fluid, which is calculated for nanofluids from equation (4). Equation (10) is used to calculate the Reynolds number , It becomes [29]

$Re = (P/\mu)_{eff} UD\ Jeff\ \mu$ (10)

M is the density and viscosity of the fluid and U is the average velocity of the fluid in the pipe. Equation (11) is used to calculate the Dean number [6]

$De = Re(r / R)_{0.5}$ (11)

Where 2/D is the radius of the pipe, R is the radius of curvature, and (r/R) is the curvature ratio of the curved pipe.

3. Results

In this project, the forced convection heat transfer of a fluid inside a curved pipe passing through a horizontal rectangular cubic tank has been investigated experimentally in the range of 81.98 to 749.29 DIN. In these experiments, water and alumina nanofluid at 0.1% by volume have been used as the working fluid in the test tube. The main objective of this project is to experimentally compare three curved pipes with the same conditions of constant external surface area and different material and curvature ratio. The experiments were performed under the boundary condition of constant temperature and the results are reported. To increase the accuracy of the results at each flow rate, the experiments were performed at least three times and displayed in the measured confidence interval. The acceptable error of these experiments in this range is shown in the figures.

Table 1 shows the accuracy and range of variation of the measuring instruments used. Using Table 1 and performing calculations, the maximum percentage uncertainty for temperature, pressure drop, flow rate, heat absorbed by the fluid, and Nusselt number is reported to be 0.5, 5.5, 5600, 06500, 0016, and 4.7 percent, respectively [30 and 31].

Table 1. Accuracy and range of variation of measuring instruments

precision	Interval of changes	Measuring tools
±۰/۱ degrees centigrade	100 to 100 degrees centigrade	Temperature sensor
±۰/۱ milliliters per minute	171/4 to 1714/3 milliliters per minute	pump

One of the important parameters in heat transfer is the Nusselt number. The Nusselt number of the flow is a function of the Dean number, which is shown in Figure 4 for a curved tube with a curvature ratio of 0.116, 0.074, and 0.042. As can be seen, the Nusselt number increases with increasing Dean number, and this increase is greater in a curved tube with a lower curvature ratio. To show the extent of this increase, Figure 5 uses a tube with a curvature ratio of 0.116 as a reference is selected and the Nusselt number of the other two tubes is measured relative to this tube.

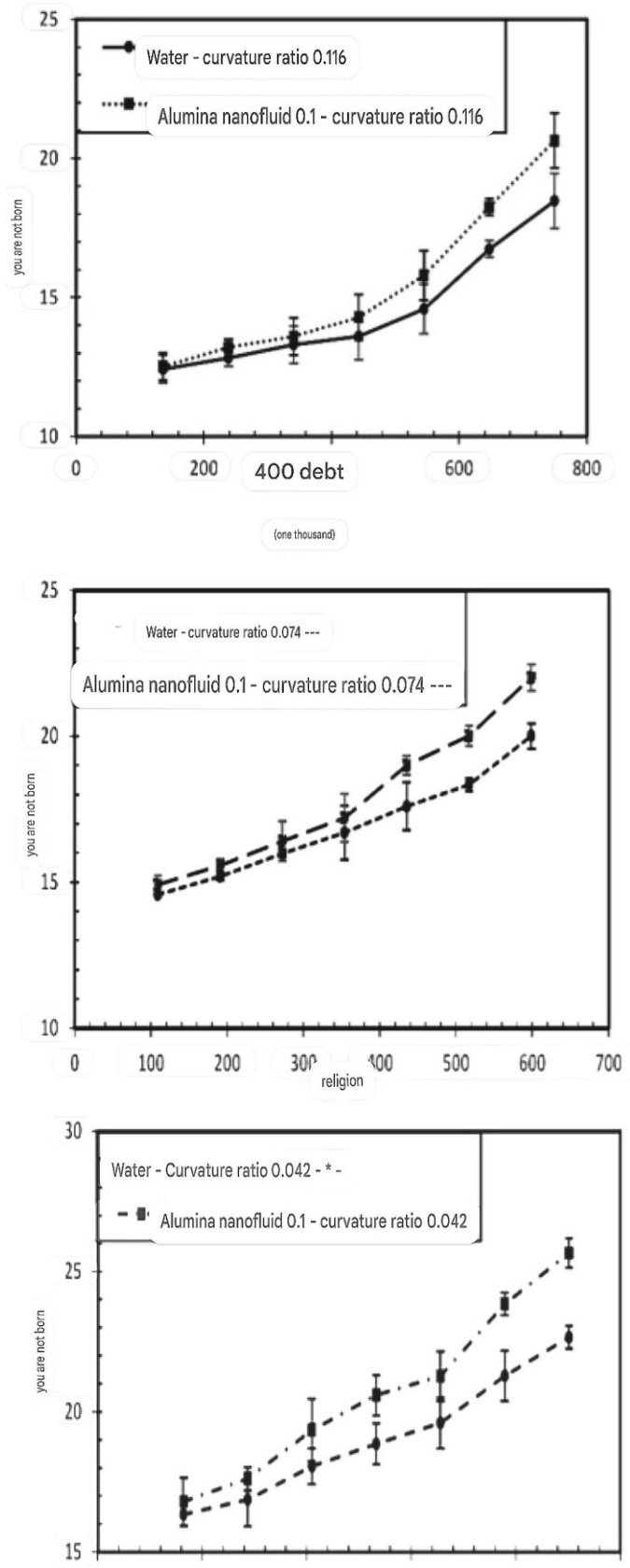


Figure 4. Nusselt number of the water and nano-fluid as functions of Dean number for curved tubes, with curvatures of: a) 0.116, b) 0.074 and c) 0.042

Figure 4 Nusselt number of water and nanofluid in terms of Dean number for (a) curved tube with curvature ratio 0.116, (b) curved tube with curvature ratio 0.074, (c) curved tube with curvature ratio 0.042

The results indicate that the maximum increase in the Nusselt number of the tube with a curvature ratio of 0.074 compared to the reference tube is 22% and for the tube with a curvature ratio of 0.042 it is 45%. Also, the use of nanofluid in the tube with curvature ratios of 0.116, 0.074 and 0.042 has caused a maximum increase of 12%, 13% and 15% in heat transfer compared to the base fluid (water), respectively.

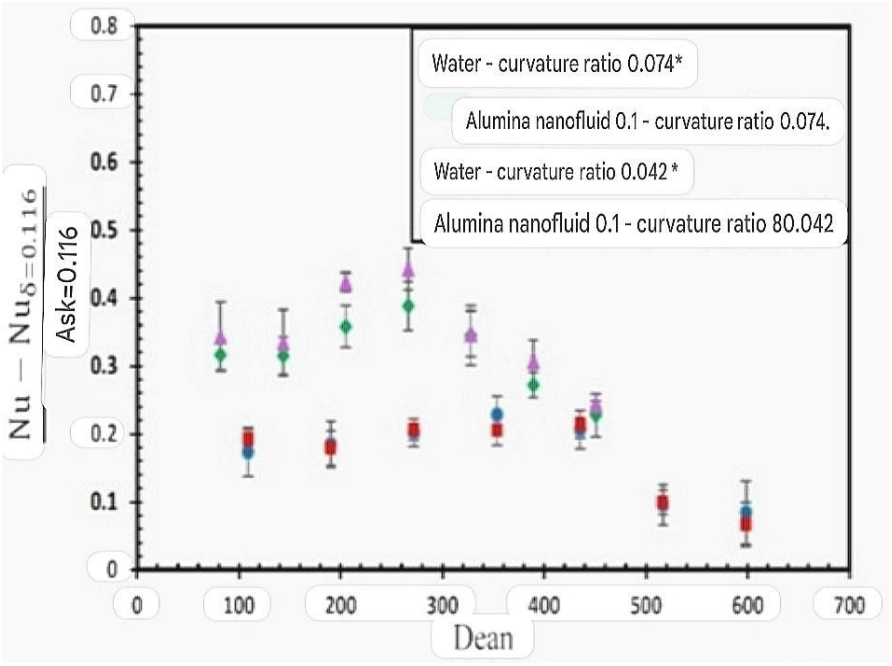


Figure 5. Enhancement of heat transfer in curved tubes with curvatures of 0.042 and 0.074 in comparison to the curved tube with the curvature of 0.116

In Figure 6, the heat transfer rate transferred from the wall of the curved tube to the working fluid inside it, calculated from equation (6), is shown in terms of the Dean number.

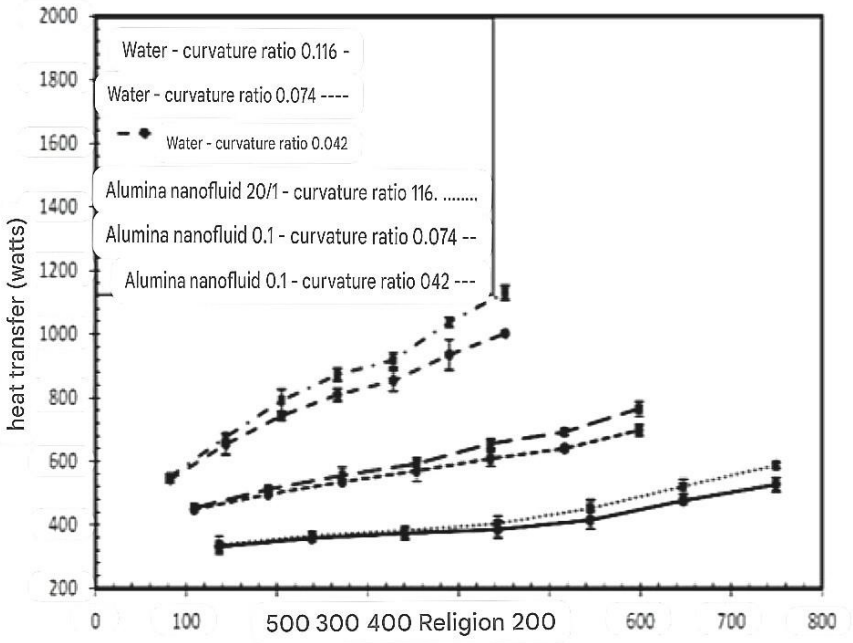


Figure 6. Heat transfer of water and Alumina nano-fluid as functions of Dean number, for curved tubes with different curvatures

The results show that with increasing Dean number and decreasing curvature ratio, the heat transfer rate increases. This increase is greater for pipes with curvature ratio , For a tube with a curvature ratio of 0.074, the maximum increase in heat transfer is 470 times, and for a tube with a curvature ratio of 0.042, the maximum increase is 1.15 times. For a tube with a curvature ratio of 0.116, the maximum increase in heat transfer is 1.15 times.

By examining the centripetal acceleration (R/) for both curved pipes, it can be said that by decreasing the curvature ratio, the centripetal acceleration of the fluid particles increases, which in turn increases heat transfer.

According to the graphs shown, it can be concluded that increasing the Dean number and adding nanofluid to the system increases the heat transfer rate, which results in a further decrease in the fluid outlet temperature and consequently an increase in the heat transfer of the fluid inside the tube. Suspension of nanoparticles can change the viscosity and thermal conductivity of the base fluid.

On the other hand, the movement of nanoparticles leads to an acceleration of the energy transfer process. Also, the penetration and dispersion of nano particles, especially metallic nanofluid particles, along the wall leads to a rapid increase in heat transfer from the wall to the fluid mass, and as a result, an increase in the heat transfer of the nanofluid compared to the base fluid. Researchers have identified factors such as the Brownian motion of nanoparticles, thermophysical properties, and the diffusion mechanism of nanoparticles as factors affecting the increase in heat transfer in nanofluid suspensions. [32] On the other hand, with increasing Reynolds number, the temperature at the outlet of the pipe decreases because the fluid has less opportunity to transfer heat. However, at a given Reynolds number, the use of nanofluid increases the heat transfer rate of the absorbed thermal energy of the fluid and, as a result, increases the outlet temperature.

The results of the fluid outlet temperature at different Dean numbers for the case where the pipe passing through the tank has different curvature ratios are shown in Figure 7. As explained, the results indicate a decrease in fluid temperature with increasing Dean number and pipe curvature ratio.

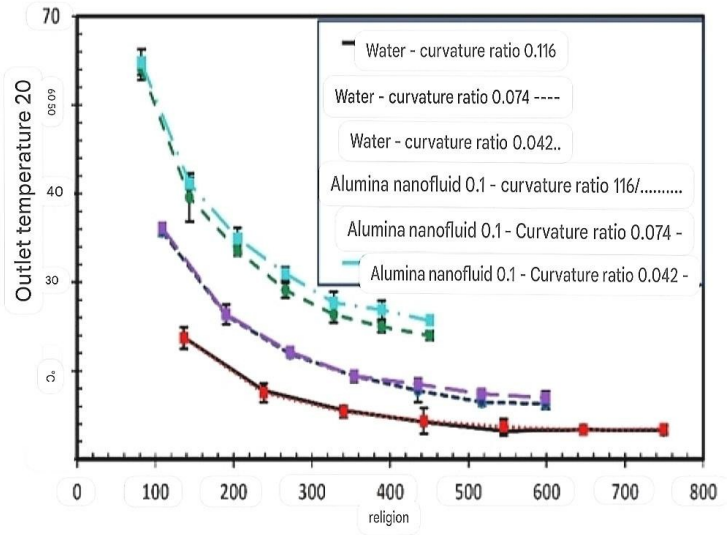


Figure 7. A comparison of the temperature of the fluid at exit versus Dean number, between curved tubes with different curvatures

Figure 8 shows the increase in the Nusselt number of alumina nanofluid compared to the base fluid (water) in a curved tube with different curvature ratios in terms of Dean number. As mentioned, adding a small amount of nanopowder changes the thermal properties of the fluid. It can be said that the increase in the Nusselt number is a function of the curvature ratio and increases with increasing Dean number. The highest increase in the Nusselt number was reported for a curved tube with a curvature ratio of 0.042 at Dean 450.87, by 15%.

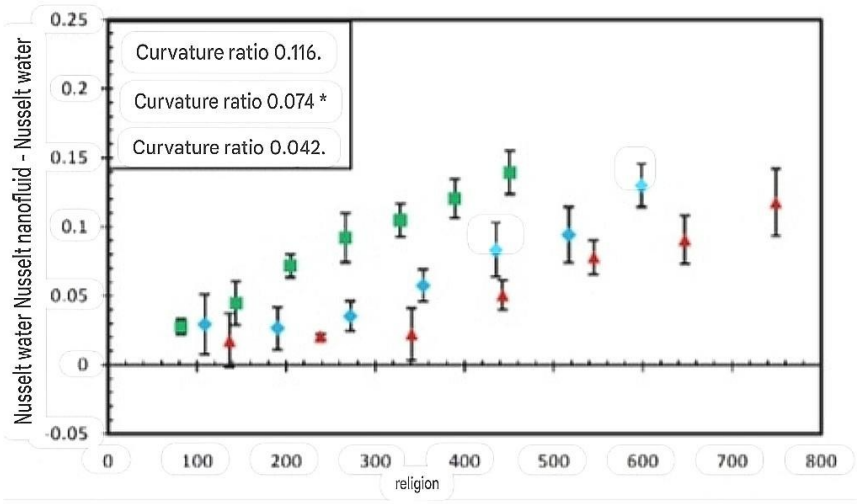


Figure 8. Enhancement percentage of Nusselt number of the Alumina nano-fluid versus Dean number for curved tubes with different curvatures

3.1 Pressure drop

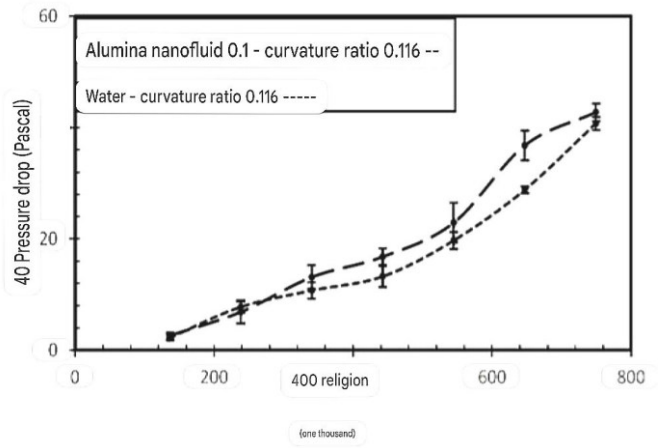
The study of pressure drop is one of the parameters that receives special attention in the industry due to its effect on energy consumption. Figure 9 shows the pressure drop created in a curved pipe with curvature ratios of 0.116, 0.074, and 0.042 as a function of the Dean number.

Experimental observations show that the presence of nanoparticles in the base fluid increases the pressure drop of the system. The increase in the viscosity of the nanofluid relative to water is one of the factors that leads to an increase in the pressure drop in the nanofluid relative to water. It has also been shown that the pressure drop in the pipe with a curvature ratio of 0.042 is greater than the other two pipes.

Figure 10 shows both the effects of heat transfer and pressure drop in a curved pipe. It is clearly seen that an optimum point with the highest value

Nur Nu)) can be calculated for any curved pipe with different curvature ratios ΔP/ΔP

It was extracted that values greater than one indicate that the increase in heat transfer dominates the increase in pressure drop of the nanofluid compared to water, and this indicates greater efficiency. For example, a pipe with a curvature ratio of 0.042 in the range of 450.87 Dean number shows the best efficiency in the graph. Efficiency refers to the simultaneous effects of heat transfer and pressure drop, which is shown in a dimensionless form on the vertical axis.



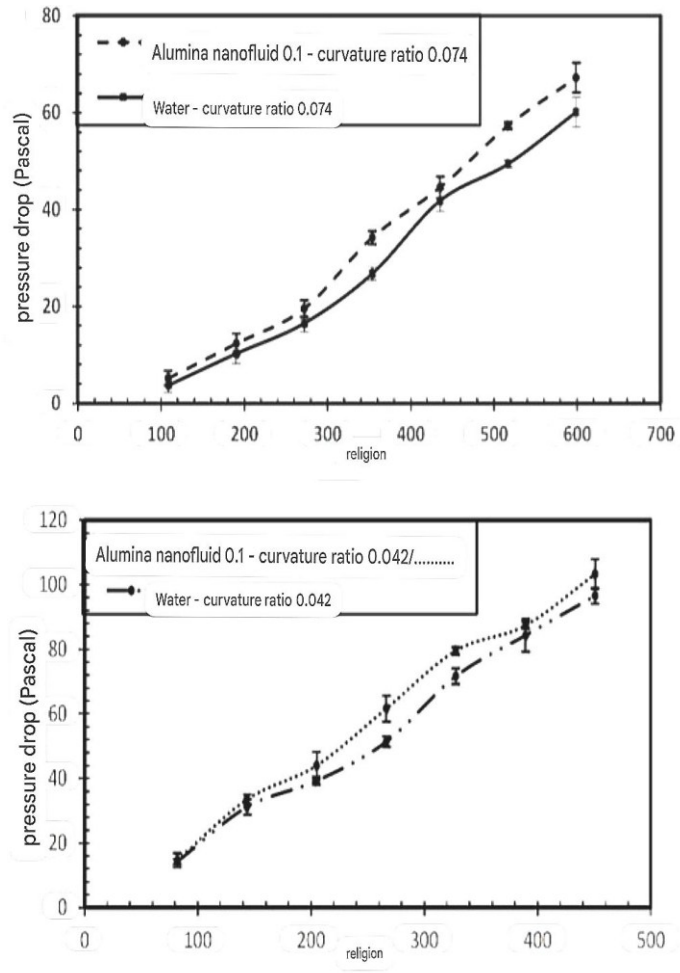


Figure 9. Pressure drop in different Dean numbers for curved tubes with curvatures of: a) 0.116, b) 0.074 and c) 0.042

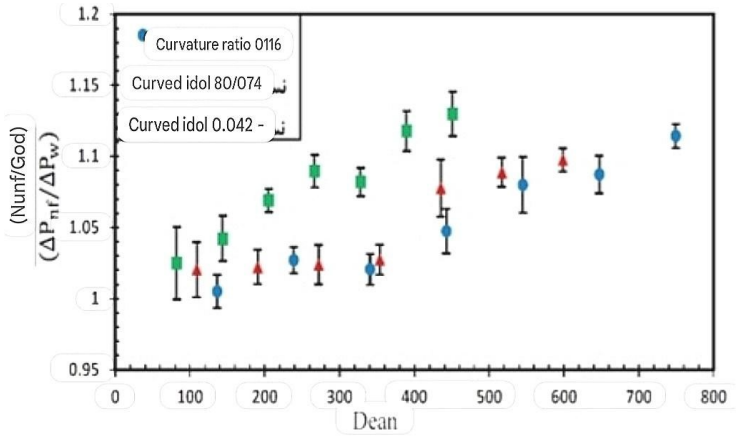


Figure 10. The increase in the Nusselt number on the rate of increase of pressure drop in terms of the Dean number

3.2 Verification of Darcy friction coefficien

Using the Blasius equation and the experimental pressure drop obtained from the experimental test, the friction coefficient of the curved pipe is calculated. To verify the friction coefficient obtained from the pressure drop at the two ends of the curved pipe for water and 0.10% volume alumina nanofluid, the theoretical Ito equation [33] defined for curved pipes was used for comparison. Equation (12) shows the Blasius equation and its corresponding friction coefficient.

$\Delta P=f_r\ (L/d)(Pv^2/2)\rightarrow f_r\ 2d\ \Delta P/LPv^2$

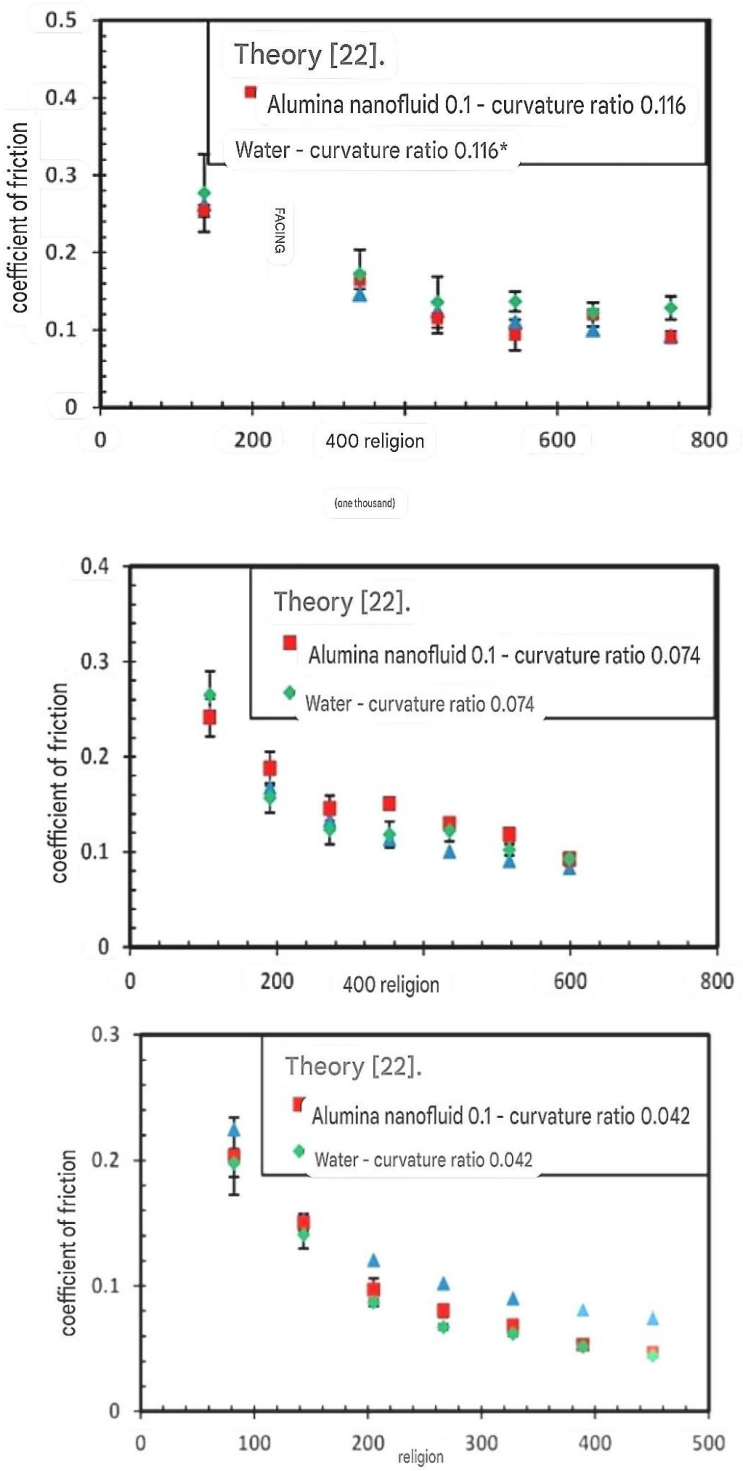


Figure 11. Compares the experimental results of the friction coefficient of water and alumina nanofluid in each of the two curved tubes with the theoretical results of the Ito relationship. The obtained results do not show much error from the theoretical relationship.

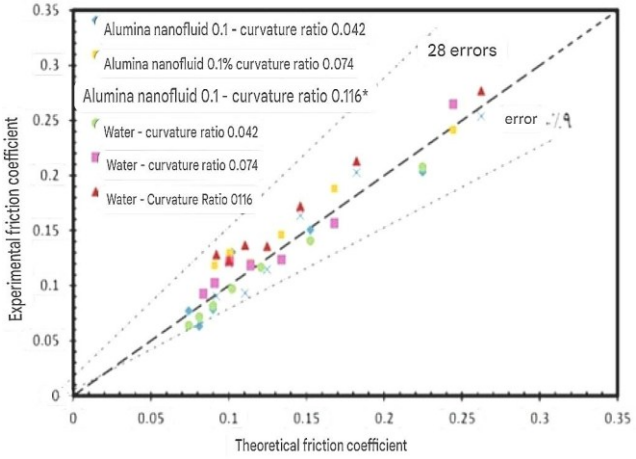


Figure 12. shows the experimental results of the friction coefficient of nanofluid and water against the theoretical results.

The middle line is the line of perfect agreement between the theoretical and experimental results, and the deviation from this line is considered as the experimental error. The maximum error of 28% and the minimum of 9% compared to the theoretical results are reported by this graph.

4. Discussion

The experimental findings demonstrate that the incorporation of Al_2O_3 nanoparticles into water improves forced convective heat transfer in curved tubes under constant wall temperature conditions. The results indicate that both the Dean number and tube curvature ratio significantly influence the thermal performance of the working fluid. As illustrated in Figure 4, the Nusselt number increases with increasing Dean number for both water and Al_2O_3–water nanofluid, indicating enhanced convective heat transfer as flow intensity increases. This behavior can be associated with secondary flow structures generated by centrifugal forces, which promote fluid mixing and thermal energy redistribution within curved geometries. The observed trend is consistent with the fundamental analysis of flow in heated curved pipes presented by Yao and Berger [2] and the numerical investigation conducted by Akbarinia [7]. Moreover, the addition of nanoparticles enhances the effective thermophysical properties of the base fluid, contributing to improved heat transfer performance. Similar enhancements in convective heat transfer have been reported by Wen and Ding [4] and Yang et al. [5] in their investigations of nanofluid flow under laminar conditions.

The influence of tube curvature ratio represents another important finding of the present investigation. The experimental results show that reducing the curvature ratio from 0.116 to 0.074 and 0.042 improves the Nusselt number under the investigated operating conditions. Specifically, the maximum increases in the Nusselt number were approximately 22% and 45% for curvature ratios of 0.074 and 0.042, respectively, compared with the reference tube having a curvature ratio of 0.116. These results suggest that the geometric configuration of the curved tube contributes substantially to the overall heat transfer characteristics. The observed differences may be associated with variations in flow development, secondary circulation, and the effective heat transfer path within the experimental configurations. Previous studies by Kalb and Seader [16] and Ciofalo et al. [23] have demonstrated that curved-tube geometry and centrifugal effects influence fluid motion and heat transfer distributions. However, because the compared tubes differ in curvature characteristics, the contribution of individual geometric factors cannot be completely isolated from the present experimental observations.

The addition of Al_2O_3 nanoparticles at a volume concentration of 0.1% further enhanced the thermal performance of the curved tubes. The maximum Nusselt number improvements relative to pure water were approximately 12%, 13%, and 15% for curvature ratios of 0.116, 0.074, and 0.042, respectively. The highest enhancement was

observed at a Dean number of approximately 450.87 for the tube with a curvature ratio of 0.042, as presented in Figure 8. These findings indicate that even a relatively low nanoparticle concentration can produce a measurable improvement in convective heat transfer. The enhancement may be attributed to changes in effective thermal conductivity, particle dispersion, and interactions between nanoparticle transport and fluid motion. Chandrasekar and Suresh [32] discussed several mechanisms associated with heat transfer enhancement in alumina-based nanofluids, while Rea et al. [3] experimentally demonstrated the thermal and hydrodynamic characteristics of oxide nanoparticle suspensions. Nevertheless, the present measurements do not independently quantify Brownian motion or particle migration, and their individual contributions should therefore be interpreted as possible mechanisms rather than directly verified effects.

The relationship between Dean number and heat transfer rate provides additional insight into the behavior of the investigated fluids. Figure 6 indicates that the overall heat transfer rate generally increases with increasing Dean number, although the magnitude of enhancement differs among the three curvature ratios. This trend reflects the combined influence of flow rate, fluid thermal properties, and heat exchange between the curved tube wall and the circulating fluid. Meanwhile, Figure 7 shows that the outlet fluid temperature generally decreases as the Dean number increases under the experimental conditions. This apparent difference can be explained by the reduced residence time of the fluid at higher flow rates, which may decrease the temperature rise per unit mass even when the total heat transfer rate increases. Consequently, outlet temperature alone should not be used as an indicator of overall thermal performance without considering mass flow rate and specific heat capacity. These observations emphasize the importance of evaluating the heat transfer rate and Nusselt number simultaneously when comparing the thermal behavior of water and nanofluids.

Despite the improvement in heat transfer characteristics, the introduction of nanoparticles also increases the hydraulic resistance of the system. As illustrated in Figure 9, the pressure drop generally increases with Dean number, and the Al_2O_3–water nanofluid exhibits a higher pressure drop than the base fluid under comparable experimental conditions. This behavior can be associated with changes in effective viscosity and the interaction between fluid motion and the curved tube geometry. The results also indicate that the tube with a curvature ratio of 0.042 produces a greater pressure drop than the other investigated configurations. Similar hydraulic penalties associated with nanofluid applications have been reported by Rea et al. [3] and Mirmasoumi and Behzadmehr [6]. Therefore, although nanoparticle addition and geometric modification improve convective heat transfer, their benefits must be evaluated alongside the additional pumping requirements. This trade-off is particularly important for practical thermal systems in which energy efficiency depends on both heat transfer enhancement and hydraulic power consumption.

The combined evaluation of thermal enhancement and pressure drop, presented in Figure 10, provides a more comprehensive interpretation of system performance. The dimensionless performance indicator compares the relative improvement in the Nusselt number with the corresponding change in pressure drop between nanofluid and water operation. Values greater than unity indicate that the relative heat transfer enhancement exceeds the relative pressure drop increase according to the adopted performance criterion. The experimental results identify the tube with a curvature ratio of 0.042 at a Dean number of approximately 450.87 as the most favorable operating condition among the investigated cases. This finding suggests that the optimum thermal-hydraulic performance does not necessarily occur at the highest Dean number or the greatest absolute heat transfer rate. Instead, the optimum condition depends on achieving a suitable balance between improved heat transfer and increased flow resistance. However, further evaluation using actual pumping power and system-level energy consumption would be necessary before concluding that this configuration provides the highest overall energy efficiency.

The experimental friction factor analysis provides an additional basis for assessing the reliability of the hydraulic measurements. Figures 11 and 12 compare the

experimentally determined friction coefficients of water and Al_2O_3–water nanofluid with theoretical predictions based on the Ito correlation [33]. The results generally follow the theoretical trend, indicating that the experimental measurements capture the principal relationship between flow conditions and frictional resistance in curved tubes. Nevertheless, deviations between the experimental and theoretical values are evident, with reported errors ranging from approximately 9% to 28%. These differences may arise from measurement uncertainty, flow development effects, geometric characteristics, and the limitations of applying a theoretical correlation to the investigated conditions. The uncertainty evaluation follows the general principles described by Bell [30] and Moffat [31], emphasizing the importance of accounting for measurement errors in experimental heat transfer analysis. Accordingly, the comparison supports the qualitative consistency of the experimental results but does not establish complete agreement between measured and predicted friction factors.

The findings have practical implications for the design and optimization of compact heat exchangers, curved piping systems, and thermal management equipment. The results indicate that combining a low-concentration Al_2O_3–water nanofluid with an appropriate curved-tube configuration can enhance heat transfer performance without requiring a substantial increase in nanoparticle concentration. However, the observed pressure drop penalty demonstrates that thermal enhancement alone is insufficient for determining the suitability of a working fluid or tube geometry. The investigation is limited to a single nanoparticle concentration of 0.1%, three curvature ratios, and the tested Dean number range under approximately constant wall temperature conditions. Furthermore, the effects of long-term nanoparticle stability, particle deposition, erosion, and changes in thermophysical properties during extended operation were not evaluated. Future research should investigate a wider range of nanoparticle concentrations, flow conditions, and tube geometries while incorporating direct measurements of pumping power and long-term operational stability. Such investigations would help establish more comprehensive thermal-hydraulic performance criteria and determine the applicability of Al_2O_3–water nanofluids in industrial heat transfer systems.

5. Conclusion

Improving heat transfer systems has attracted the attention of researchers and industrial sectors in recent years. The use of nanofluids with suitable thermal properties and changes in physical structure are methods that are being studied in particular. In this study, an attempt was made to investigate the heat transfer of a 0.1% volume water-alumina nanofluid in curved tubes with curvature ratios of 0.116, 0.074, and 0.042 with the same external surface area and material at a constant wall temperature using a laboratory method. In Fig. 11. Comparison of experimental friction coefficient and Ito's for-mula in different Dean numbers, for curved tubes with curvatures of:

a) 0.116, b) 0.074 and c) 0.042

Figure 11 Comparison of the experimental friction coefficient with the Ito equation in terms of Dean for (a) a curved pipe with a curvature ratio of 0.116 (b) a curved pipe with a curvature ratio of Curvature 0.074 (c) Curved pipe with curvature ratio 0.042

This research has studied the effect of curvature ratio and the presence of nanoparticles on heat transfer and pressure drop, and the results show that adding nanopowder to Theoretical friction coefficient

The base fluid and the reduction of the curvature ratio significantly increase the heat transfer in the curved tube. The random displacement and collision movements of nano particles in the tube with a lower curvature ratio and a longer length lead to a change in the temperature profile.

Also, the penetration and dispersion of nano particles along the wall leads to a rapid increase in heat transfer from the wall to the fluid mass. In addition, the simultaneous effects of heat transfer and pressure drop at three different curvature ratios are presented and compared. The present study is one of the first papers on the experimental investigation of nanofluids and the comparison of heat transfer between three curved tubes with different curvature ratios, and this research work is considered innovative.

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