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SIMULATION OF FLUID FLOW AND HEAT TRANSFER IN DOUBLE PIPE HEAT EXCHANGER USING NANOFLUIDS

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ABSTRACT

Using Ansys Fluent, this study provides a thorough examination of the fluid flow and heat transfer properties of a double pipe heat exchanger. For effective heat transfer between two fluids, a twin pipe heat exchanger which consists of concentric inner and outer pipes are frequently utilized in industrial settings. A simulation model was created for this study to assess fluid flow patterns and heat transfer performance across a range of operational situations, such as varying fluid characteristics, flow rates, and temperatures. The simulations shed light on how these parameters impact pressure loss and thermal efficiency in parallel-flow and counter-flow systems. The findings show that heat transfer performance can be enhanced by adjusting flow rates and exchanger dimensions, which could result in increased energy efficiency in real-world applications. Heat transfer and fluid flow in double-pipe heat exchangers are simulated using Ansys Fluent. Double-pipe heat exchangers that concentrate on heat transfer performance under various situations, flow characteristics, and temperature distribution. CFD is used to study both parallel and counter flow configurations to comprehend the impacts of exchanger shape, fluid characteristics, and flow rates at various volume fractions of water-based oxide (Al_2O_3, SiO_2, TiO_2) nanofluids. The findings are validated by comparison with experimental and theoretical data and verified the accuracy of ANSYS FLUENT fluid flow and heat transfer simulations. Provide information for industrial double-pipe heat exchanger design and optimization.

Keywords:
Fluid flow, Heat transfer, Double pipe heat exchanger, ANSYS FLUENT simulation, nanofluid, Energy efficiency

I. Introduction

An apparatus that transfers heat between two or more fluids at different temperature gases, liquids, or both without combining them is called a heat exchanger. Regularly used heat exchanger designs are double pipe heat exchangers, which are utilized in a variety of industries, including food processing, HVAC, chemical processing, and oil & gas. Effective thermal energy transfer between two fluid some running in an inner pipe and the other in an annular space surrounding itis made possible by these devices. The design is an essential part of many thermal systems because it is particularly well-suited for application that requires moderate heat transfer requirements, controllable flow rates, and simple construction. The effective transfer of heat between hot and cold fluids, accomplished by convection within each fluid stream and conduction across the pipe wall, is the fundamental component of double pipe heat exchanger operation. The performance and thermal efficiency of the heat exchanger are directly impacted by important design decisions, including pipe materials, operating circumstances, and fluid flow either counterflow or parallel flow.

1.1 Heat exchanger Types:

1.1.1. Double pipe heat exchanger: One of the most basic kinds of heat exchangers utilized in industry is the double pipe heat exchanger. One fluid flow through the inner pipe of this pair of concentric pipes, while another flows in the annular region between the inner and outer pipes. This configuration enables the two fluids to exchange heat as they pass through the pipes in either a parallel flow or counterflow. They are a well-liked option for processes involving heating or cooling fluids because of their adaptability, dependability, and simplicity.

1.1.2. A shell and tube heat exchanger: One of the most used forms of heat exchangers in industry is the shell and tube heat exchanger, particularly in the oil and gas, power generating, chemical processing, and HVAC systems sectors. For transferring heat between two fluids that may function at different pressures and temperatures, its design is adaptable and efficient. Because of its reputation for durability, effectiveness, and ability to withstand high temperatures and pressures, shell and tube heat exchangers are perfect for demanding applications.

1.1.3. Plate Heat Exchanger: A plate heat exchanger (PHE) is a kind of heat exchanger that effectively transfers heat by separating fluids using thin plates. The plate heat exchanger is widely utilized in a variety of industries, including HVAC, food and beverage processing, pharmaceuticals, chemical processing, and more, because of its small size and great efficiency. High thermal performance is achievable with this kind of heat exchanger, which works especially well when heat transfer between fluids with low to medium viscosities is needed.

1.1.4. Air-to-air or air-to-liquid exchangers: HVAC, industrial, automotive, and energy recovery systems all depend on air-to-air and air-to-liquid heat exchangers. In processes where preserving environmental conditions is essential, these exchangers help to control temperatures, save energy, and increase efficiency by facilitating the passage of heat between air and another medium (air or liquid). The purpose of air-to-air heat exchangers is to move heat from one stream of air to another.

1.2 Common materials used in heat exchangers:

1.2.1 Metals:

1.Copper: Copper is a reddish-brown metal known for its excellent thermal and electrical conductivity. Copper is highly conductive, meaning it can transfer heat effectively. It is resistant to corrosion, particularly in fresh water and air, making it ideal for applications where both thermal efficiency and longevity are required.

2. Aluminium: Aluminium is a lightweight, silvery-white metal that is highly resistant to corrosion due to the natural oxide layer that forms on its surface. It has good thermal conductivity, is lightweight, and is resistant to oxidation. Aluminium is commonly used for applications where weight is a factor, such as in air-cooled heat exchangers.

3. Stainless Steel: Stainless steel is a corrosion-resistant alloy primarily made of iron, with chromium, nickel, and other elements added to enhance its properties. Stainless steel is durable, resistant to corrosion, and can withstand high pressures and temperatures.

4. Titanium: Titanium is a strong, corrosion-resistant metal known for its ability to withstand extreme conditions without degrading. Titanium is highly resistant to corrosion, particularly in seawater and chlorine environments, making it ideal for marine and chemical processing applications. It also has a high strength-to-weight ratio but is costly.

5. Nickel Alloys Definition: Nickel alloys are metals made by combining nickel with other elements such as chromium, molybdenum, and iron to enhance specific properties like strength and corrosion resistance.

1.2.2 Non-Metals:

1. Graphite: Graphite is a naturally occurring form of carbon with a layered, hexagonal lattice structure, which gives it high thermal conductivity and resistance to heat. Graphite is an excellent heat conductor and is highly resistant to oxidation and chemical attack, making it ideal for extreme temperature and

aggressive chemical environments. However, it is brittle and can be difficult to handle in certain conditions. It is also a good electrical conductor.

2. Ceramics: These are more brittle yet can withstand extremely high temperatures and are resistant to corrosion. utilized in high-heat industrial processes and gas turbines, among other high-temperature applications. Polymers and plastics: Water treatment systems and other low-temperature applications with low to moderate heat transfer needs and corrosion concerns frequently use polymers and plastics (PTFE, PVC, etc.).

1.2.3 Composite materials:

1. Fiber-Reinforced Plastics: FRP are beneficial in chemical and wastewater treatment applications because they combine the structural strength of fibres with the corrosion resistance plastics.
2. Carbon Fiber Composites: Used in specific industries where weight is an issue, like aerospace, these lightweight materials have exceptional strength and thermal conductivity.

II. Literature

Jalali, A et,al.,[1] reported that is Experimental Investigation on Active Heat Transfer Improvement in Double-Pipe Heat Exchangers. Input parameters are Hot Water Flow Rate, Cold Water Flow Rate, Ultrasonic Power, Inlet Temperatures& Output parameters are Heat Transfer Rate, Overall Heat Transfer Coefficient, Temperature Measurements. The research showed that using ultrasonic waves can significantly improve how well heat is transferred in a double-pipe heat exchanger. Specifically, the heat transfer rate can increase by as much as 104% when the ultrasonic power is set to a high level, especially at certain temperatures of the hot water.

Salim et,al.,[2] reported thatThermal performance investigation of N-shape double-pipe heat exchanger using Al_2O_3, TiO_2, and Fe_3O_4-based nanofluids. Input parameters are Nanofluid concentrations, Reynolds number, Temperature, Geometric Configurations and Output parameters are Heat Transfer Coefficient, Effectiveness, Nusselt Number. The study found that the N-shaped double-pipe heat exchanger using Al_2O_3 nanofluid significantly enhances heat transfer efficiency, with a 2.09% increase in heat transfer coefficient at a 1% volume fraction, outperforming other materials like Inconel 625.

M. A., & Shehab et,al.,[3] reported thatNumerical analysis of heat convection through a double-pipe heat exchanger. Dimpled influence. Input parameters are Inner Tube material, Dimensions, Dimple Arrangements, Reynolds Number (Re), heat flux and Output parameters are Nusselt Number (Nu), Pressure Drop, Thermal Performance Factor. The study reveals that staggered dimpled tubes significantly enhance heat transfer performance, achieving up to a 50% higher Nusselt number compared to inline arrangements, particularly at lower pitch ratios. Additionally, the pressure Drop increases with the arrangement of dimples, indicating a trade-off between heat transfer efficiency and pressure loss.

Bhattacharjee et, al.,[4] reported the performance of Parallel Flow and Heat Transfer in Concentric Tube Heat Exchanger using Computational Fluid Dynamics. Input parameters are Fluid Temperatures, Fluid Properties, Geometric Parameters, Boundary Conditions and Output parameters are Temperature Profiles, Average Fluid Temperatures, Nusselt Number. The research demonstrates that the heat transfer efficiency in a concentric tube heat exchanger is significantly enhanced by using a counterflow arrangement compared to parallel flow, with a notable increase in the Nusselt number indicating improved convective heat transfer.

Almendros-Ibáñez et, al.,[5] reported the numerical investigations of double pipe heat exchanger with different heat transfer fluids. Input parameters are Fluid Temperatures, Reynold's Number, Fluid Properties, Geometric Configuration and Output parameters are Heat Transfer coefficient, pressure Drop, Thermal Performance, Temperature Distribution. The numerical investigation revealed that the heat transfer performance of the double pipe heat exchanger is significantly influenced by the choice of heat transfer fluids and their respective temperatures, with optimal configurations leading to enhanced thermal efficiency.

Ali et, al.,[6] reported thatAnalysis study of nano fluids and longitudinal fins on the heat transfer in the counter flow double pipe heat exchanger. Input parameters are Hot Water Flow Rate, Cold Water Flow Rate, Nanofluid Concentration, Fin Dimensions and Output parameters are Heat Transfer Rate, Pressure Drop, Nusselt Number, Thermal Performance Factor. The use of longitudinal rectangular fins significantly improves heat transfer rates in the heat exchanger. The study found that the heat transfer coefficient increases with higher mass flow rates and nanofluid concentrations.

Khalil et,al.,[7] reported thatNumerical Investigations of Heat Transfer enhancement in double pipe heat exchanger using twisted tape. Input parameters are Twisted Tape Ratio (H), Reynolds Number (Re), Fluid Properties, Boundary Conditions and Output parameters are Performance Evaluation Criteria (PEC). Twisted tape helps to mix the hot and cold fluids better, which leads to a significant increase in heat transfer. In fact, at a specific setting (twisted ratio of H=1.7), the heat transfer rate can be 1.8 times higher than that of a plain tube at a certain flow speed (Re=18,000).

Akisin et,al.,[8] reported that, CFD Analysis of Parallel Flow in Double Pipe Heat Exchangers Evaluating Thermal Performance and effectiveness. Input parameters are Inlet Temperatures, Flow Rates, Mesh Characteristics and Output parameters are Outlet Temperature of Hot Fluid, Effectiveness of the Heat Exchanger, Thermal Performance Metrics. The study presents a comprehensive CFD analysis of parallel flow double pipe heat exchanger, revealing significant insights into their thermal performance and effectiveness.

Somanchi et,al.,[9]reported that, Experimental investigations on heat transfer enhancement in a double pipe heat exchanger using hybrid nanofluids. Input parameters are volume concentration, Mass Flow Rate, Nanoparticle Ratio and Output parameters are Heat Transfer Coefficient (HTC), Friction Factor, Nusselt Number. The study observed that the overall HTC increased with higher Reynolds numbers and greater volume concentrations of Sic-water nanofluids, indicating a positive correlation between flow conditions and heat transfer performance.

Vijayaragavan et,al.,[10] reported that Heat transfer characteristics of double pipe heat exchanger having externally enhanced inner pipe. Input parameters are Heat transfer coefficient, temperature changes, heat transfer rate, numerical and experimental results and Output parameters are Fluid flow rates, fluid temperature, heat exchanger length, geometric configuration. The analysis shows that increasing the length of the heat exchanger enhances heat transfer performance. Specifically, the temperature drop of the hot fluid remains higher than the temperature rise of the cold fluid, even when the flow rates are reversed.

III. METHODOLOGY

Ansys fluent simulations provide a powerful and cost-effective approach to designing and analyzing double-pipe heat exchangers. By following a structured workflow spanning geometry definition, meshing, boundary conditions setup, simulation execution, post-processing, and performance analysis engineers can gain detailed insights into fluid and thermal behaviour, enabling informed decision-making for design and optimization. The iterative process also ensures that the final product is both efficient and reliable as shown in fig 3.1.

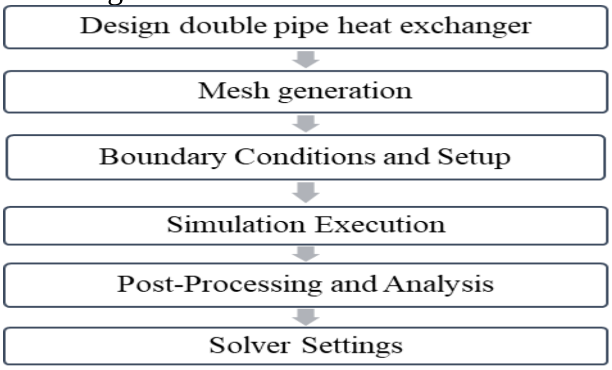

Fig.3.1. Methodology flowchart outlining steps

3.1 Design Double pipe heat exchanger:

Find out the specific heat, density, and viscosity of the hot and cold fluids that were used. Determine the fluids' flow rates within the heat exchanger. For both fluids, provide the ideal input and exit temperatures. Initialize the double-pipe geometry creation as shown in fig 3.2.

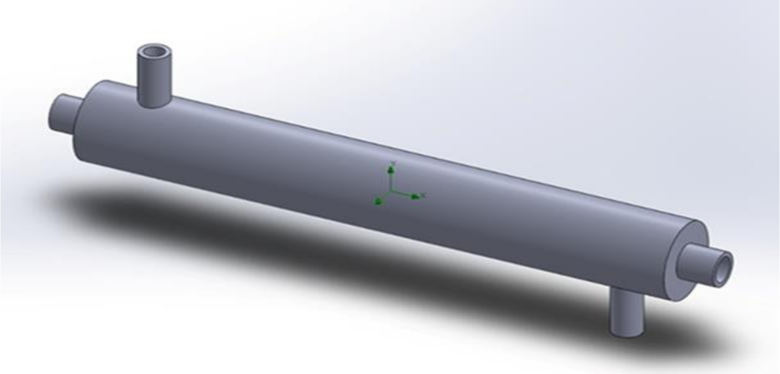

Fig. 3.2 Double pipe heat exchanger using ANSYS

3.2 Mesh generation:

Use ANSYS Meshing to create an unstructured or structured mesh as shown in fig 3.3. To capture boundary layer effects, make sure the fluid-wall interface has sufficient resolution. To guarantee precision and computational effectiveness, conduct a mesh sensitivity analysis. Adjust the mesh until the flow and temperature parameters are in the agreement.

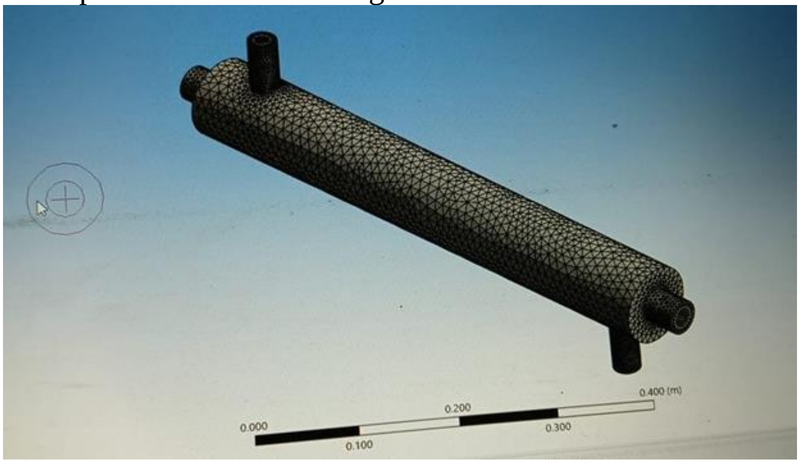

Fig.3.3. Mesh Analysis of Double Pipe Heat Exchanger

An initial Reynolds number estimation is carried out to determine the flow displays turbulent characteristics. The definition of this parameter is as follows:

$$Re = \frac{\rho V D}{\mu} \tag{3.1}$$

Table 3.1. Characteristics of Boundary Conditions

Boundary conditions	Types of fluids	Nano particle volume concentration	Reynolds Number (Re)	Temperature (k)	Velocity (m/s)
Inner pipe (NF)	Al_2O_3, TiO_2 & SiO_2	0.1	297.91	300	0.094
Inner pipe	Water	-	294.84	333	0.080
Outer pipe	Al_2O_3, TiO_2& SiO_2 Water	-	-	Turbulent	-

The physical characteristics and volume concentrations of nanofluids determine their effectiveness in this situation.

Table 3.2. Typical Reynolds number scales

Quantity	Symbol	Inner pipe (Water)	Outer pipe (Nanofluids)
Density	ρ	983.13 kg/m^3	996.86 kg/m^3
Length	D	130 cm	120 cm
Viscosity	μ	0.001 kg/m.s	0.00047 kg/m.s

3.3 Mathematical Modelling:

The following is an expression for the nanofluid's effective density:

$$\rho_{nf} = (1-\Phi)\rho_{bf} + \Phi\rho_{np} \tag{3.2}$$

The following computation is used to determine the nanofluid's specific heat:

$$C_{pNf} = (1-\Phi)C_{pbf} + \Phi C_{pNp} \tag{3.3}$$

The Maxwell model is used to calculate a nanofluid's thermal conductivity:

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np}+k_{bf}+2\Phi(k_{np}-k_{bf})}{k_{np}+2k_{bf}-\Phi(k_{np}-k_{bf})} \tag{3.4}$$

The viscosity of the nanofluid is estimated using the Einstein model:

$$\mu_{nf} = \mu_{bf}(1+2.5\Phi) \tag{3.5}$$

To measure the heat flow rate, an efficiency study must be performed as the first step.

For the hot fluid(water):

$$q_{th} = m_w C_{pw}\left(T_{i,w} - T_{o,w}\right) \tag{3.6}$$

For the cold fluid (Nanofluid):

$$q_{tc} = m_{nf} C_{pnf}\left(T_{o,nf} - T_{i,nf}\right) \tag{3.7}$$

The Reynolds and nondimensionalized Nusselt numbers are computed by, respectively

$$Nu = \frac{hD}{k} \text{and } Re = \frac{4m}{\pi D\mu} \tag{3.8}$$

Hence, the following formula yields the convective heat exchange coefficient

$$h = \frac{Nuk}{D} \tag{3.9}$$

For Parallel flow, the log mean temperature difference (LMTD) is defined as

$$LMTD = \frac{\left(T_{o,w}-T_{i,nf}\right) - \left(T_{i,w}-T_{o,nf}\right)}{\ln\frac{\left(T_{o,w}-T_{i,nf}\right)}{\left(T_{i,w}-T_{o,nf}\right)}} \tag{3.10}$$

Table 3.3. Thermophysical characteristics of fluids and nanofluids comprising Al$_2$O$_3$, TiO$_2$, and SiO$_2$

Thermophysical properties	Base fluid (Water)	Al$_2$O$_3$ Nano particles	Tio$_2$Nano particles	SiO$_2$Nano particles
Density, ρ (kg/m^3)	997	3960.14	4250	2220
Specific heat, C_p (J/kg.K)	4180	761.55	686.2	703
Thermal conductivity, k (W/m.K)	0.67	37.17	8.9	1.2
Viscosity, μ× 10^{-3} (kg/m.s)	0.00089	-	-	-

3.4 Calculation:

Temperature=60°c
Density = 985kg/m^3
Diameter =0.028mm
Viscosity=0.000467 kg/m.s
Cp=4173 J/kg.k, K=0.6513w/mk

$$Re = \frac{\rho VD}{\mu}$$

$$5000 = \frac{985 \times V \times 0.028}{0.000467}$$

$$V = \frac{5000 \times 0.000467}{985 \times 0.028} = 0.15277 \text{ m/s}$$

$$Re = \frac{4 \times m}{\pi \times D \times \mu}$$

$$5000 = \frac{4 \times m}{\pi \times 0.028 \times 0.000467}$$

m = 0.0513 kg/s

Table 3.4. Velocity& Mass flow rate

S.No	Reynolds number	Velocity(m/s)	Mass flow rate(kg/s)
1	5000	0.0846	0.0513
2	10000	0.1694	0.1026
3	15000	0.2539	0.1540
4	20000	0.3386	0.2053
5	25000	0.4233	0.2567

IV RESULTS AND DISCUSSIONS

4.1 Hot fluid Graph plotting in Theoretical & Simulation:

The graph presents the results of a theoretical analysis on the heat transfer characteristics of a hot fluid flow. The x-axis represents Reynolds number from 5000 to 25000, a dimensionless parameter that characterizes the flow variability in turbulent, while the y-axis indicates Nusselt number, which quantifies the convective heat transfer rate. The plot demonstrates a positive correlation between Reynolds number and Nusselt number, suggesting that higher Reynolds numbers lead to enhanced heat transfer as shown in fig 4.1.

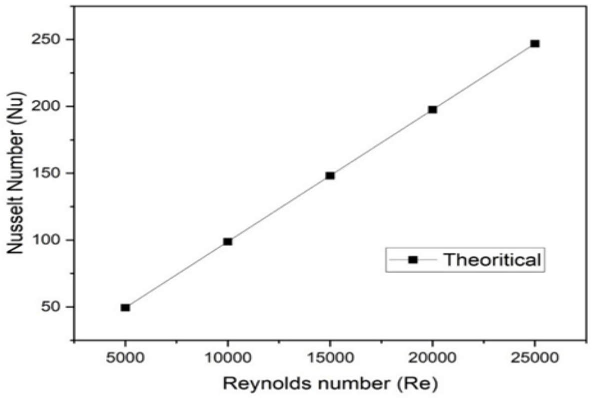

Fig.4.1 Variation of Nusselt number with Reynolds Number for water

This graph illustrates the relationship between the Nusselt number (Nu) and the Reynolds number (Re) for a particular experimental setup. The Nusselt number is a dimensionless number that represents the ratio of convective to conductive heat transfer. characterizes the flow variability of a fluid in fig 4.2. X-axis (Horizontal): Reynolds number (Re) are taken from 5000 to 25000. Y-axis (Vertical): Nusselt number (Nu). Higher values indicate a greater contribution of convective heat transfer to the overall heat transfer process.

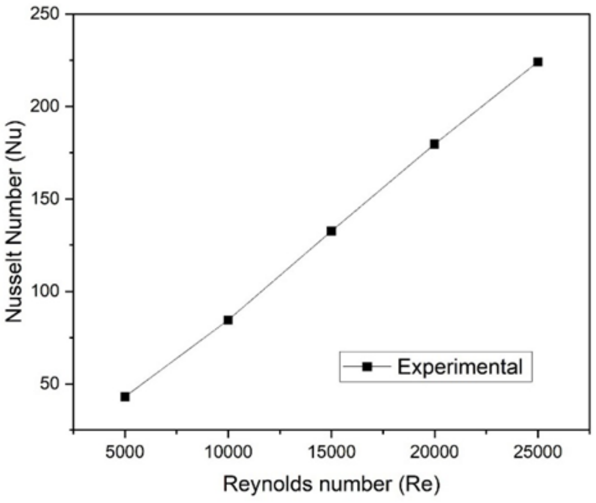

Fig.4.2 Variation between Reynolds Number Vs Nusselt Number in simulation

4.2 Validation Graph plotting between Theoretical and Simulation:

The graph plots the Nusselt number (Nu) against the Reynolds number (Re). It presents two sets of data in fig 4.3. In Theoretical represents the values predicted by a theoretical model or equation. They are based on assumptions and idealizations, often neglecting certain complexities of the real-world system. In simulation these values are obtained through simulation. They are subject to various uncertainties and errors.

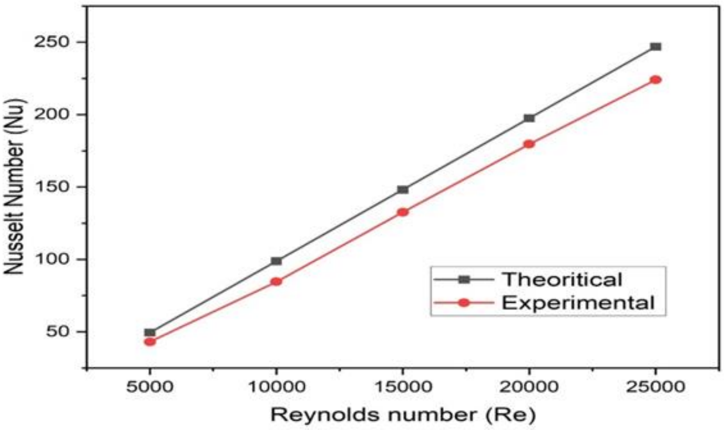

Fig.4.3 Validation between Reynolds Number Vs Nusselt Number

4.3 Variation of Nusselt Number & Heat transfer coefficient with Reynolds Number for water-Al_2O_3 Nano fluid

The line graph "Graph Plotting between Reynolds Number & Nusselt Number" with "Water + Al2O3" illustrates the various between Reynolds Number (x-axis) and Nusselt Number (y-axis) in fig 4.4. Number of lines are drawn, each of which represents a distinct Al2O3 nanoparticle concentration in water. In a heat exchanger using a water-Al_2O_3 nanofluid, the Reynolds number versus Nusselt number graph for different volume fractions (up to 5%) shows how flow velocity and nanoparticle concentration impact heat transfer.

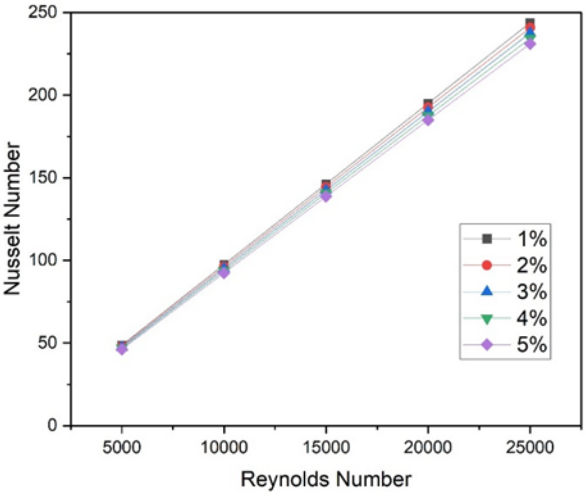

Fig. 4.4 Variation of Nusselt Number with Reynolds Number for water-Al2O3 nano fluid

The "Graph Plotting Between "Reynolds Number & Heat Transfer Coefficient" for "Water + Al2O3." The relation between Re & h for water combined with different quantities of Al2O3 nano particles is shown graphically in fig 4.5. In a heat exchanger using water-Al_2O_3 nanofluid, the graph of Reynolds number versus heat transfer coefficient shows that the heat transfer coefficient increases with Reynolds number, particularly in turbulent flow, where mixing improves heat transfer.

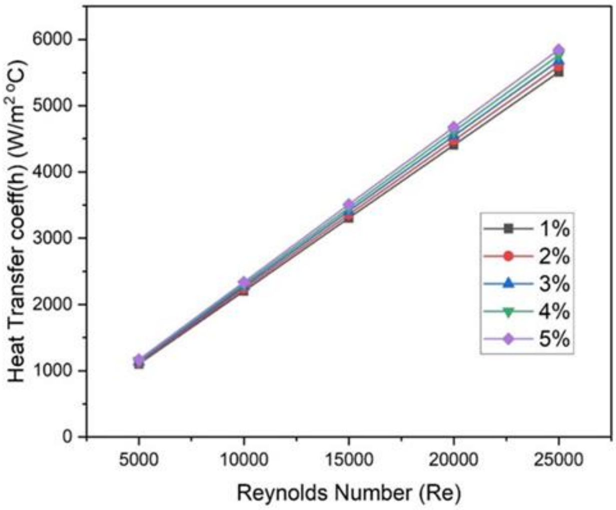

Fig.4.5 Variation of heat transfer coefficient with Reynolds Number for water-Al2O3

4.4 Variation of Nusselt Number & Heat transfer coefficient with Reynolds Number for water-TiO_2 Nano fluid

The "Graph Plotting between Reynolds Number & Nusselt Number TiO2.The relationship between Reynolds Number (Re) and Nusselt Number (Nu) for water combined with different quantities of TiO2 nanoparticles is shown in this line graph fig 4.6. In a heat exchanger using water-TiO_2 nanofluid, the graph of Reynolds number versus Nusselt number for different TiO_2 volume fractions (1 to 5%) shows how flow rate and nanoparticle concentration affect heat transfer.

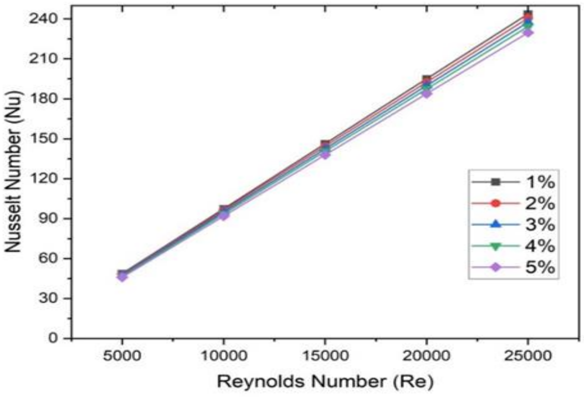

Fig. 4.6 Variation of Nusselt Number with Reynolds Number for water-TiO2 nano fluid

The "Graph Plotting between Reynolds Number & Heat Transfer Coefficient" graph in the image you sent has the caption, "Water + TiO2." The relationship between Reynolds Number (Re) and Heat Transfer Coefficient (h) for water combined with different quantities of TiO2 nanoparticles is shown fig 4.7 graphically in this line graph. As Reynolds number increases (x-axis), flow shifts from laminar to turbulent, enhancing heat transfer by disrupting thermal boundary layers.

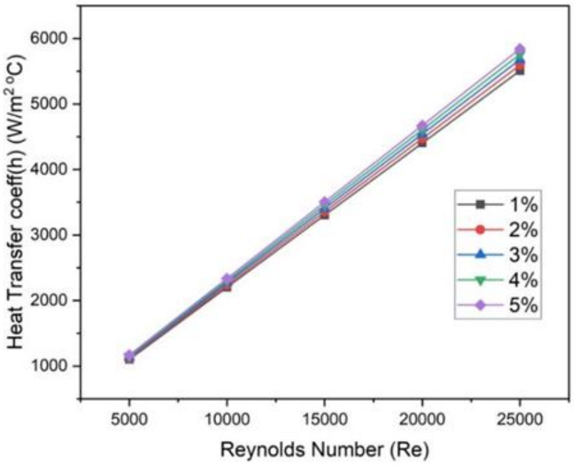

Fig.4.7 Variation of heat transfer coefficient with Reynolds Number for water-TiO2 nano fluid

4.5 Variation of Nusselt Number & Heat transfer coefficient with Reynolds Number for water-SiO_2 Nano fluid

The "Graph Plotting Between Reynolds Number & Nusselt Number" graph in the image you sent has the caption "Water + SiO2." The relationship between Reynolds Number (Re) and Nusselt Number (Nu) for water combined with different quantities of SiO2nanoparticles is shown graphically in this line graph fig 4.8. In a heat exchanger with water-SiO_2 nanofluid, the graph of Reynolds number versus Nusselt number for different SiO_2 volume fractions (1 to 5%) shows the effects of flow rate and nanoparticle concentration on heat transfer.

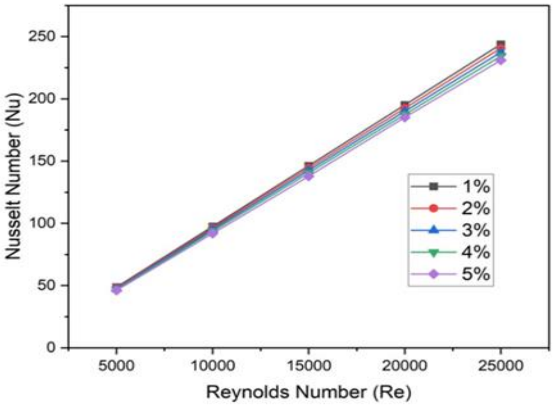

Fig. 4.8 Variation of Nusselt Number with Reynolds Number for water-SiO2 nano fluid

The "Graph Plotting Between Reynolds Number & Heat Transfer Coefficient" graph in the image you sent has the caption, "Water + SiO2." The relationship between Reynolds

Number (Re) and Heat Transfer Coefficient (h) for water combined with different quantities of SiO2 nanoparticles is shown graphically in this line graph fig 4.9. In a heat exchanger using water-SiO_2 nanofluid, the graph of Reynolds number versus heat transfer coefficient for different SiO_2 concentrations (up to 5%) shows how flow rate and nanoparticle concentration affect heat transfer.

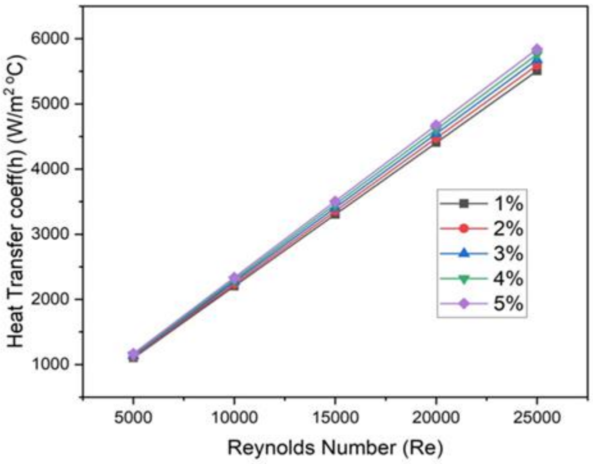

Fig.4.9 Variation of heat transfer coefficient with Reynolds Number for water-SiO2 nano fluid

4.6 Validation Graph plotting between Nu & h with Re with different nanofluids:

The graph plots the Nusselt number (Nu) in y - axis against the Reynolds number (Re) from 5000 to 25000 in x - axis. It presents three sets of data in fig 4.10. Among the three nanoparticles, Al2O3 seems to provide the highest heat transfer enhancement, followed by TiO2 and SiO2. This could be due to various factors such as particle size, concentration, and thermal conductivity of the nanoparticles in fig 4.10. All three curves show an increasing trend with the Reynolds number. This is expected, as higher Reynolds numbers correspond to higher flow velocities, which generally lead to better convective heat transfer**.**

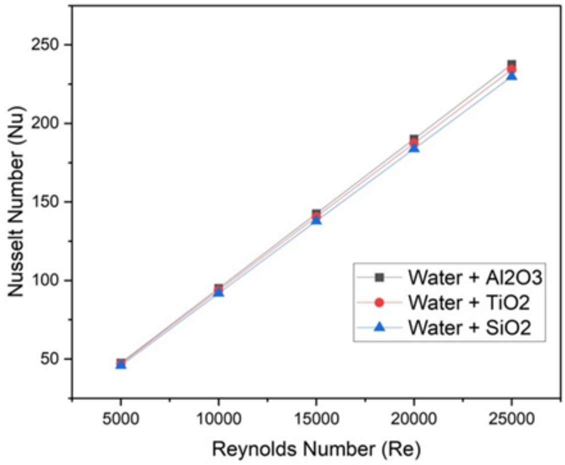

Fig.4.10. validation between Re vs Nu with different nanofluids at 5% volume fraction

The graph plots the heat transfer coefficient (h) against the Reynolds number (Re) from 5000 to 25000. It presents three sets of data in fig 4.11 The graph illustrates the heat transfer enhancement due to the addition of nanoparticles to water. The heat transfer coefficient (h) represents the rate of heat transfer per unit area per unit temperature difference. A higher heat transfer coefficient indicates better heat transfer in fig 4.11. All three curves show an increasing trend with the Reynolds number. This is expected, as higher Reynolds numbers correspond to higher flow velocities, which generally lead to better convective heat transfer.

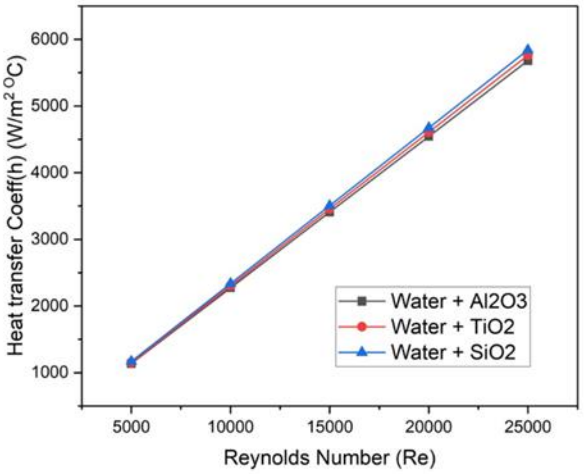

Fig.4.11. validation between Re vs h with different nanofluids at 5% volume fraction

V. Conclusion

At a Reynolds number of 5000, the Nusselt number was observed to be 48.775. As the Reynolds number increased to 10000, 15000, 20000, and 25000, the corresponding Nusselt numbers were found to be 97.55, 146.32, 195.101, and 243.877, respectively. This shows a steady and near-linear growth in the heat transfer rate with increasing Reynolds number, particularly within the turbulent flow variability. The current findings focus on a 1% volume fraction. Extending this analysis to higher volume fractions, up to 5%, would provide further insights into how particle concentration influences the heat transfer characteristics. Higher volume fractions are expected to further enhance thermal conductivity and convective heat transfer, contributing to improved system performance.

Maximize agricultural output. This may be accomplished by using environmentally friendly sensors and communication systems that are powered by artificial intelligence and the internet of things.

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