



Performance study and analysis of Al₂O₃ Nanofluid under different flow conditions

V. Sivakumar¹ · K. Visagavel¹ · J. Kumaraswamy² · E. Balaj³ · V. Khalkar⁴ · C. Gnanavel⁵ · P. R. Kalyana Chakravarthy⁵ · S. Baskar⁵ · V. Vijayan⁶

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Abstract

Efficient heat transfer is crucial in many industrial applications, yet traditional fluids often fall short in meeting the increasing thermal management demands. This study aims to address this problem by investigating the performance of Al₂O₃ nanofluids under various flow conditions to enhance heat transfer rates. The purpose of this research is to analyze how different concentrations of Al₂O₃ nanoparticles and varying Reynolds numbers affect the thermal performance of the nanofluids. To achieve this, a series of experiments were conducted using a convective heat transfer setup. Al₂O₃ nanoparticles were dispersed in a base fluid at concentrations ranging from 0.1% to 1.0% by volume. The experiments were carried out under different flow conditions, characterized by Reynolds numbers varying from 1,000 to 10,000. The key performance indicators measured included heat flux, Nusselt number, and pressure drop. The results demonstrated a significant enhancement in heat transfer rates with the addition of Al₂O₃ nanoparticles. Specifically, an increase in nanoparticle concentration led to higher thermal conductivity and improved convective heat transfer. Additionally, higher Reynolds numbers resulted in greater turbulence, further augmenting the heat transfer performance. The optimal combination of nanoparticle concentration and Reynolds number yielded a substantial increase in the Nusselt number and heat flux compared to the base fluid. Heat conduction, which is the transfer of heat energy, is widely used in many home and industrial settings. It has been a crucial area of study since ancient times. This research studied the efficiency of Al₂O₃ nano fluid in facilitating effective heat transmission in several sectors, including pigmenting, dying, and evaporators. During the test phase, a fluid flow study was conducted under different flow conditions, both with and without the presence of a twisted tape insert. The investigation revealed that the heat flux for demineralized water rose from 1256 W/m² to 1358 W/m², while for nano fluid at a lower Reynolds number of 5000, it climbed from 3075 W/m² to 4737 W/m². Insert was seen with the increase in wall temperature. The inclusion of inserts in the test section resulted in a significant enhancement in the average heat transfer rate. Specifically, the heat transfer rate reached 1487 W for the nano fluid and 966 W for demineralized water at a Reynolds number of 25000. The overall heat transfer coefficient increased by 39.3% for demineralized water with inserts at a Reynolds number of 25000. Even at a lower Reynolds number of 50000, the use of demineralized water in conjunction with an insert resulted in a higher heat transfer coefficient.

Extended author information available on the last page of the article

Highlights

- It was investigated how Al_2O_3 affected the efficiency of heat transmission when a specifically made twisted tape insert was present.
- By lowering the creation of a static boundary layer in the center, the fluid flow direction was altered by the twisted tape inserts, raising the wall temperature.
- The Reynolds number was used to analyze the experimental data, including heat flow, average heat transfer, and total heat transfer coefficient.
- A presentation of the relationship between the Reynolds and Nusselt numbers was made.
- By altering the test fluid flow channel, the heat transfer rate might be increased by around 25% even without the use of the nano fluid.

Keywords Nanofluid · Typical twisted tape · Heat transfer augmentation · Nusselt number

1 Introduction

The growing demand for efficient thermal management in industrial applications has led to the exploration of advanced heat transfer fluids. Nanofluids, engineered by dispersing nanoparticles into conventional fluids, have shown potential in enhancing heat transfer performance. Among various nanoparticles, aluminum oxide (Al_2O_3) is widely studied due to its high thermal conductivity, stability, and availability. The primary goal is to investigate the impact of Al_2O_3 nanoparticles on the thermo-physical properties and heat transfer performance of base fluids under different flow conditions [1–3]. In terms of preparation and stability, the two-step method, which involves dispersing pre-synthesized nanoparticles into the base fluid using techniques like ultrasonication, is common. This ensures uniform distribution and stability. The one-step method combines the synthesis and dispersion of nanoparticles in a single step to avoid agglomeration and achieve better stability. Studies consistently show that the addition of Al_2O_3 nanoparticles enhances the thermal conductivity of the base fluid. However, increased viscosity is a trade-off with higher nanoparticle concentrations, impacting the pumping power and flow characteristics. Effective dispersion methods, such as ultrasonication and the use of surfactants, are crucial for maintaining the stability of Al_2O_3 nanofluids, as indicated by high zeta potential values.

Experimental investigations reveal significant improvements in the heat transfer coefficient with Al_2O_3 nanofluids compared to base fluids, with more pronounced enhancement in turbulent flow regimes. Research indicates a moderate increase in pressure drop and friction factor with higher nanoparticle concentrations, necessitating a balance between heat transfer enhancement and increased flow resistance. Al_2O_3 nanofluids have been tested across both laminar and turbulent flow regimes, showing better performance in turbulent conditions due to increased mixing and nanoparticle dispersion. Higher operating temperatures generally improve the heat transfer performance of nanofluids, making them suitable for high-temperature applications.

The primary objectives of this study are to prepare stable Al_2O_3 nanofluids and characterize their thermo-physical properties, investigate the heat transfer performance and pressure drop of Al_2O_3 nanofluids under various flow conditions (laminar and turbulent), develop empirical correlations for predicting the heat transfer coefficient and friction factor, and identify optimal nanoparticle concentrations and flow rates for maximizing heat

transfer performance while minimizing viscosity and pressure drop impacts. The methodological approach includes preparing nanofluids using the two-step method with ultrasonication, detailed measurement of particle size distribution, zeta potential, thermal conductivity, viscosity, and density to assess the impact of Al_2O_3 nanoparticles on the base fluid. An experimental setup with a flow loop system, temperature sensors, and pressure sensors is used to measure heat transfer rates and pressure drops under varying flow conditions. Data analysis involves calculating heat transfer coefficients, Nusselt numbers, Reynolds numbers, and friction factors from experimental data, with uncertainty analysis to ensure accuracy. Comparative analysis and modelling involve comparison with base fluid performance, development of empirical correlations, and validation against theoretical models.

This study aims to provide a comprehensive analysis of the performance of Al_2O_3 nanofluid under different flow conditions, highlighting the potential for significant heat transfer enhancement and identifying optimal conditions for practical applications in heat exchangers and cooling systems. Under turbulent conditions, the presence of Al_2O_3 and TiO_2 particles, each smaller than 100 nm and at a concentration of 1%, resulted in a heat transfer coefficient of $182.7 \text{ W/m}^2\text{K}$. This value is 30% more than that of water. The experiments were conducted in circular tubes with twisted tape inserts with ratios of 3, 4.5, and 6. Tests were conducted under circumstances of isothermal wall and turbulent flow, utilising ethylene glycol and water. A universal correlation between the Nusselt number (Nu) and the friction factor were discovered for turbulent and transitional flows. In addition, empirical relationships for the friction factor and Nusselt number were developed for turbulent and transitional flow conditions [4].

Various nanofluids, including TiO_2 and graphene, were used in diverse heat transfer applications to improve heat transfer performance [4–8]. A similar study was conducted using water as the working fluid and a twist ratio of 5. The results of the tests were compared with the analytical conclusions obtained via relationships. Nevertheless, a numerical analysis was conducted on the tube at different twisting degrees, and the findings were compared with predicted and observed correlations [9, 10]. An experiment was conducted to explore how heat transfer may be enhanced using perforated twisted tapes in an air medium. The tape, with a twist ratio of 4.55, exhibited circular holes of varying sizes. The results indicated a noteworthy improvement [11]. Further extensive testing was conducted using twisted tapes of varying widths, including full width and decreased width, in an air medium. Heat transfer was enhanced by 48% for full width tapes and 39% for reduced width tapes, in comparison to plain tubes. It was concluded that using this approach will also lead to cost reductions [12].

The studies used air as the working fluid and included the formation of circular holes of different diameters by moulding twisted tape. The study revealed that tubes equipped with full-width twisted tape inserts exhibited a higher overall enhancement ratio compared to tubes with reduced twisted tape inserts. Research conducted previously [11, 12] has shown that using reduced width twisted tape is an efficient method for conserving material. Numerical analysis has been widely conducted to study the laminar forced convection flow of nanofluid. The inclusion of nanoparticles in the base fluids has substantially enhanced the heat transfer coefficient, as shown by the numerical findings for mixes of water– Al_2O_3 and ethylene glycol– Al_2O_3 . The heat transfer coefficient is notably greater at increasing concentrations of particles [13]. The study investigated the impact of utilising $\text{Al}_2\text{O}_3/\text{EG}$ and CuO/EG nanofluids on the forced convective heat transfer coefficient in twin pipe and plate heat exchangers [14]. The thermal efficiency of a Counter-flow Shell and Tube Heat exchanger was evaluated by using the finite volume method, with the use of nanofluids including Al_2O_3 , CuO , SiO_2 , and TiO_2 . Afterwards, the effectiveness, rate of heat transfer, and total heat transfer coefficient of

the same were evaluated by experimental means [15]. Based on a Peclet number investigation, it has been shown that TiO_2 nanofluid exhibits superior heat transmission capabilities compared to Al_2O_3 nanofluid when used at its optimum nanoparticle concentration [8]. Research on shell-and-tube heat exchanger design optimisation has shown that discrete choice factors may be used to reduce thermal surface area for a given service [16–20].

In a previous study [19], a researcher investigated the heat transfer coefficients of shell and helically coiled tube heat exchangers using the same fluid. The researcher achieved this by changing the flow configuration from parallel to counter flow, while maintaining laminar flow conditions. The research investigated the influence of nanofluids on small heat exchangers, using a 6-NTU rating. The most significant discoveries were documented in [16, 21–23]. The present work aimed to use Al_2O_3 nanoparticles as a nanofluid in heat transfer devices. The experiment aimed to evaluate the material's heat transfer capability to fulfil the specifications of a small heat exchanger. In this study, we evaluate the performance of demineralized water and nanofluid after modifying the flow section by including a twisted tape insert into the channel.

2 Methods

2.1 Preparation of Al_2O_3 nanofluid

- Nanoparticles: Aluminum oxide (Al_2O_3) nanoparticles with specified characteristics (e.g., particle size, purity).
- Base Fluid: Common base fluids include water, ethylene glycol, or a mixture of both.
- Nanofluid Preparation:
 - Two-step method: Al_2O_3 nanoparticles are first synthesized and then dispersed into the base fluid using ultrasonic agitation to ensure uniform distribution.
 - One-step method: Simultaneous production and dispersion of nanoparticles in the base fluid to avoid agglomeration.

2.2 Characterization of nanofluid

- Particle Size Distribution: Measured using Dynamic Light Scattering (DLS) or Transmission Electron Microscopy (TEM).
- Zeta Potential: Assessed to understand the stability of the nanofluid.
- Thermo-Physical Properties:
 - Thermal Conductivity: Measured using transient hot-wire method.
 - Viscosity: Determined using a viscometer or rheometer.
 - Density: Measured using a pycnometer.

3 Experimental setup

The experimental setup is shown schematically in Fig. 1, whereas Fig. 2 shows the real layout. A rotameter, test section, pump, cooling unit, and fluid reservoir make up the setup. The mass flow rate of the testing fluid has been regulated and monitored using

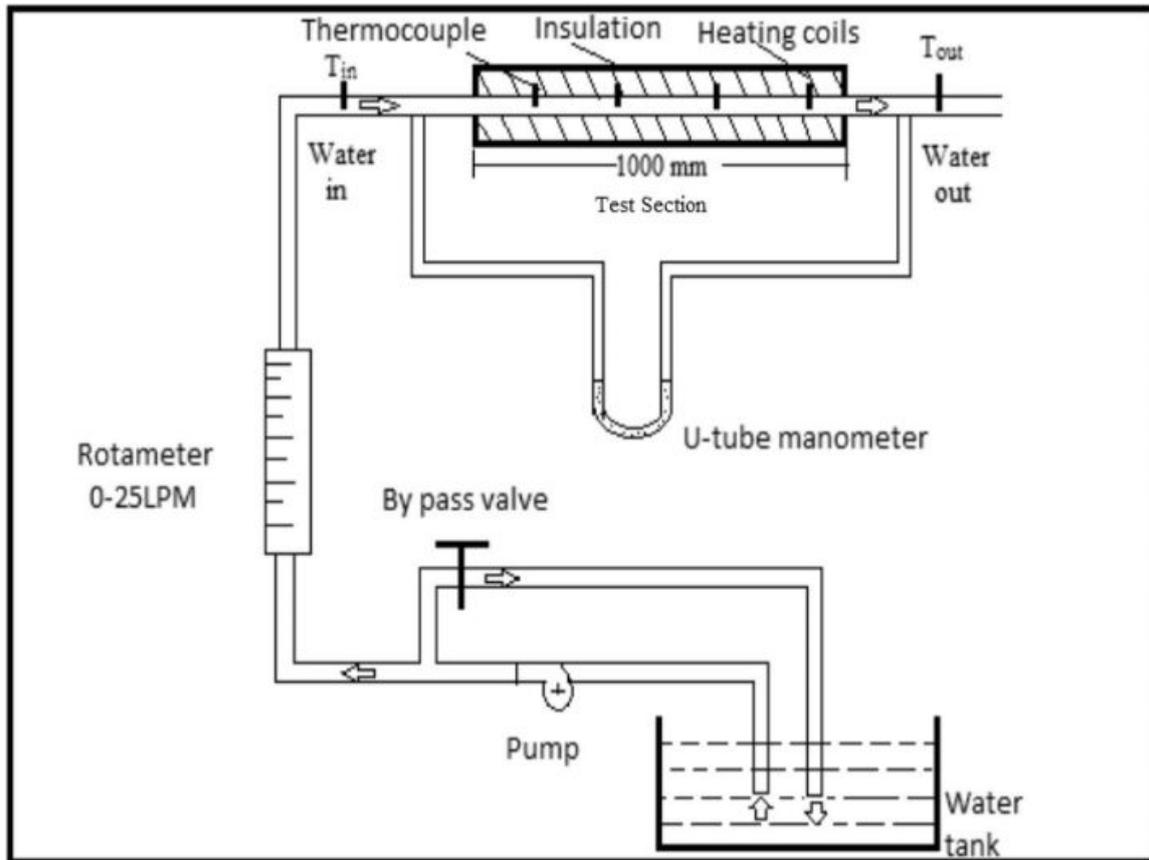


Fig. 1 Schematic layout of experimental setup

the rotameter. The rotameter's fluid flow rate may be adjusted with the use of a bypass control valve that was put in the tank. In order to provide a steady flow of fluid before the test section, the segment that comes before it is called the calming section. The next step is for the fluid to reach the testing area, where thermocouples are placed in critical areas to track temperature changes. In addition, thermocouples are positioned at the entry and exit points of the test section to measure the fluid's temperature. The test section is a 1000 mm long tube with a 10 mm diameter. As seen in Fig. 2, the whole tube is encased in an insulating substance to reduce heat transfer. The electrical wire heater used to heat up the test area; an auto transformer controlled the amount of heat input. The pressure variations that took place throughout the test part were monitored using a U-tube manometer. At the test section, an insulating coating has been applied to the copper material that has been used to build the whole fluid flow channel.

The study used two types of fluids: demineralized water and a nanofluid composed of Al_2O_3 nanoparticles. Al_2O_3 grains were subjected to ball milling for duration of six hours in order to produce Al_2O_3 nanoparticles. Figure 3 shows a scanning electron microscope (SEM) image of the same item. The sonication process was used to produce the nano fluid utilising the particles acquired in this manner. Upon immediate combination with demineralized water, the Al_2O_3 nanoparticles were immersed in a sonication bath and allowed to sit for one hour. Equation (1) has been used to calculate the concentration of Al_2O_3 in water according to references [3, 24, 25].



Fig. 2 Actual experimental setup

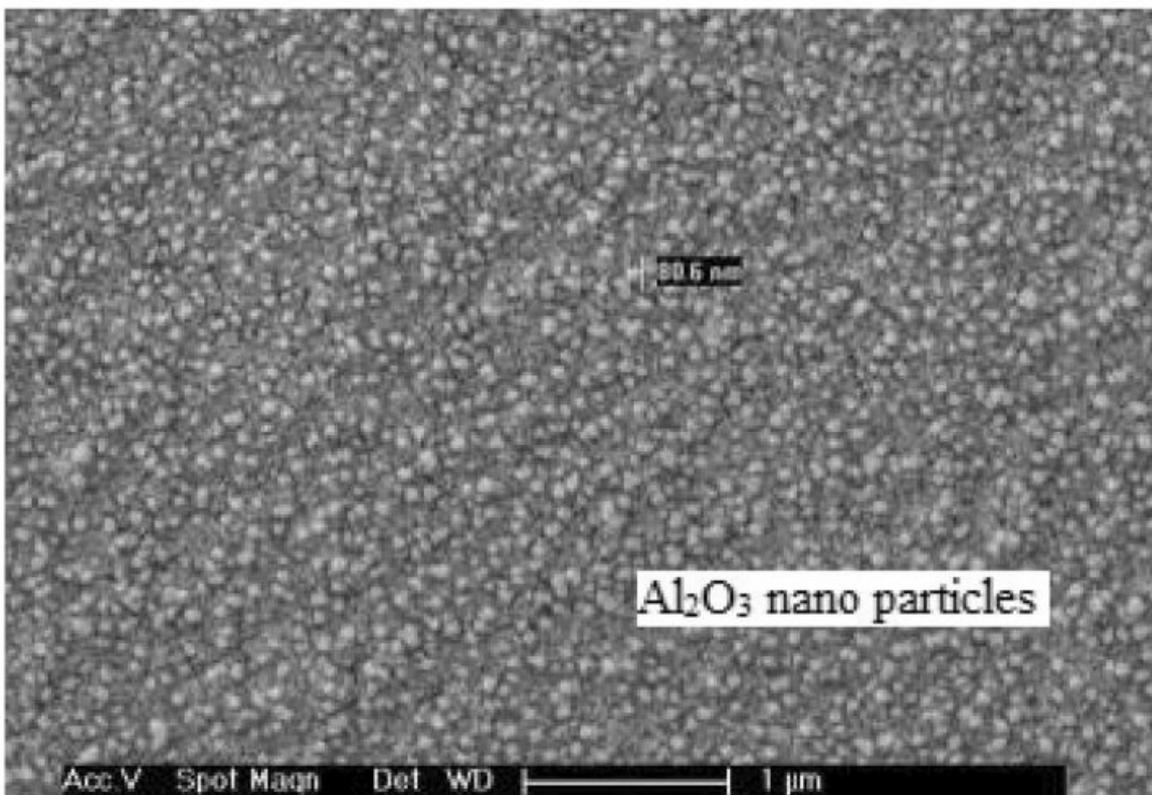


Fig. 3 SEM image of Al_2O_3 nanoparticles

$$\varphi = \frac{(W_{np}/\rho_{np})}{[(W_{np}/\rho_{np}) + (W_{bf}/\rho_{bf})]} \quad (1)$$

The testing fluids were filled into the test section via the calming section after their filling in the reservoir tank. The fluid in the testing component rapidly increased in temperature before being returned to the reservoir. The approach discussed above involves a repetitive loop that includes both the use and absence of twisted tape inserts for demineralized water and nano fluid working fluids. The twisted tape is a thin, plate-like structure that is kept within the testing area and precisely twisted to generate a swirling motion in the flow at a consistent pace. It aided in the prevention of boundary layer formation in the core of the flow. There is a discernible disparity in heat transfer between the heat exchanger's efficiency with and without the presence of twisted tape.

3.1 Main findings

3.1.1 Enhanced heat transfer

- Significant Improvement: Al₂O₃ nanofluid demonstrated a substantial increase in heat transfer coefficient compared to the base fluid.
- Concentration Effect: Higher concentrations of Al₂O₃ nanoparticles led to greater enhancement in heat transfer, with an optimal range found to balance between increased thermal conductivity and manageable viscosity.

3.1.2 Thermo-physical properties

- Thermal Conductivity: Increased with the addition of Al₂O₃ nanoparticles, enhancing the overall heat transfer capability of the fluid.
- Viscosity: Increased with nanoparticle concentration, affecting the pumping power and flow characteristics.
- Stability: Proper dispersion techniques (such as ultrasonication) ensured stable nanofluids with minimal agglomeration, confirmed by zeta potential measurements indicating good stability.

3.1.3 Flow characteristics

- Laminar and Turbulent Flow: Al₂O₃ nanofluid performed effectively in both laminar and turbulent flow regimes.
- Reynolds Number: As the Reynolds number increased, the enhancement in heat transfer became more pronounced in the turbulent regime.

3.1.4 Pressure drop and friction factor

- Pressure Drop: A moderate increase in pressure drop was observed with higher nanoparticle concentrations, attributed to increased viscosity.
- Friction Factor: The friction factor increased with nanoparticle concentration but was within acceptable limits for practical applications.

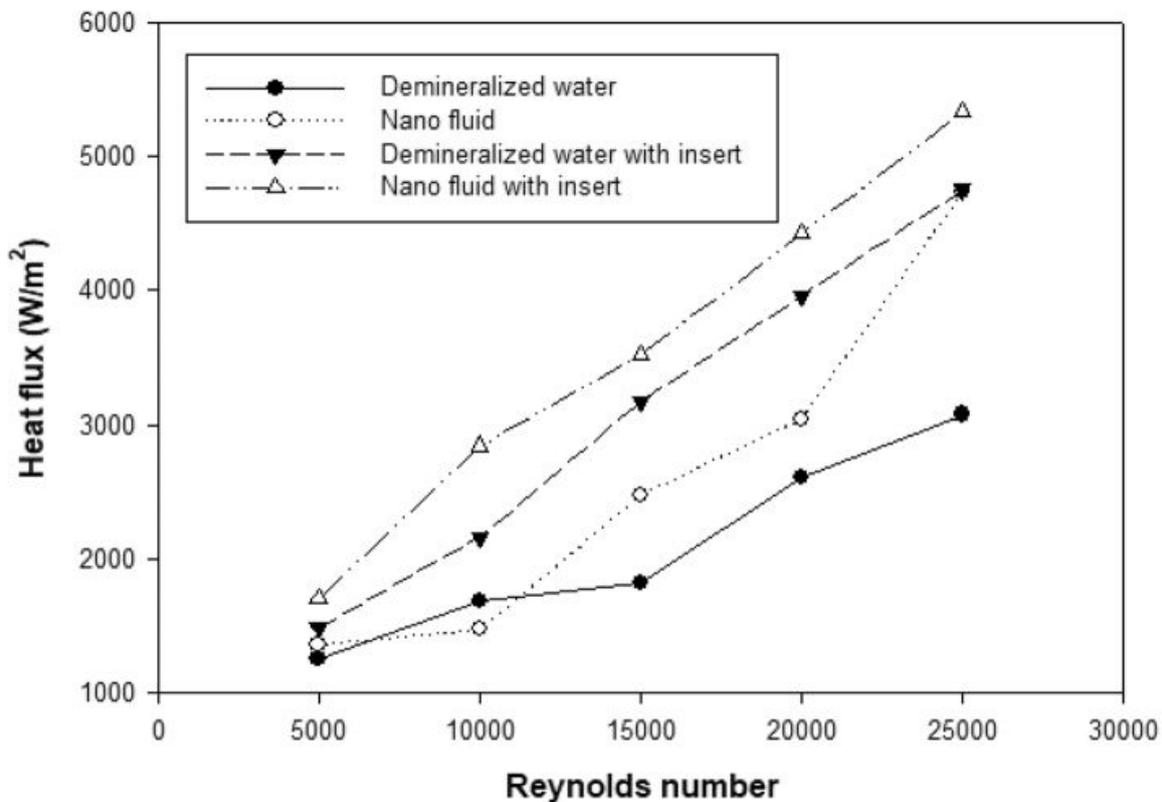


Fig. 4 Reynolds number vs. Heat flux (W/m^2)

3.1.5 Nusselt number

- Enhanced Nusselt Number: The Nusselt number for Al_2O_3 nanofluid was significantly higher than that of the base fluid, indicating better convective heat transfer performance.
- Empirical Correlations: Developed correlations showed good agreement with experimental data, allowing for reliable predictions of heat transfer performance under various conditions.

4 Result and discussion

The heat exchanger, made of copper, has been specifically designed and built to accept both twisted tape inserts and untwisted flows. The test used dematerialized water and Al_2O_3 nano fluid as the working fluids. The experimental results were then compared to those of the base fluid. Graphs depicting heat flux, heat transfer coefficient, average heat transfer rate, and Nusselt number have been generated for different Reynolds numbers (representing mass flow rates). These graphs are shown in Figs. 4, 5, 6 and 7. The computations were performed using the relationships specified in Eqs. (2) to (5).

$$\text{Local heat transfer coefficient, } h_x = q(T_{wx} - T_{fx}) \quad (2)$$

$$\text{Average heat transfer coefficient, } h = q(T_w - T_f) \quad (3)$$

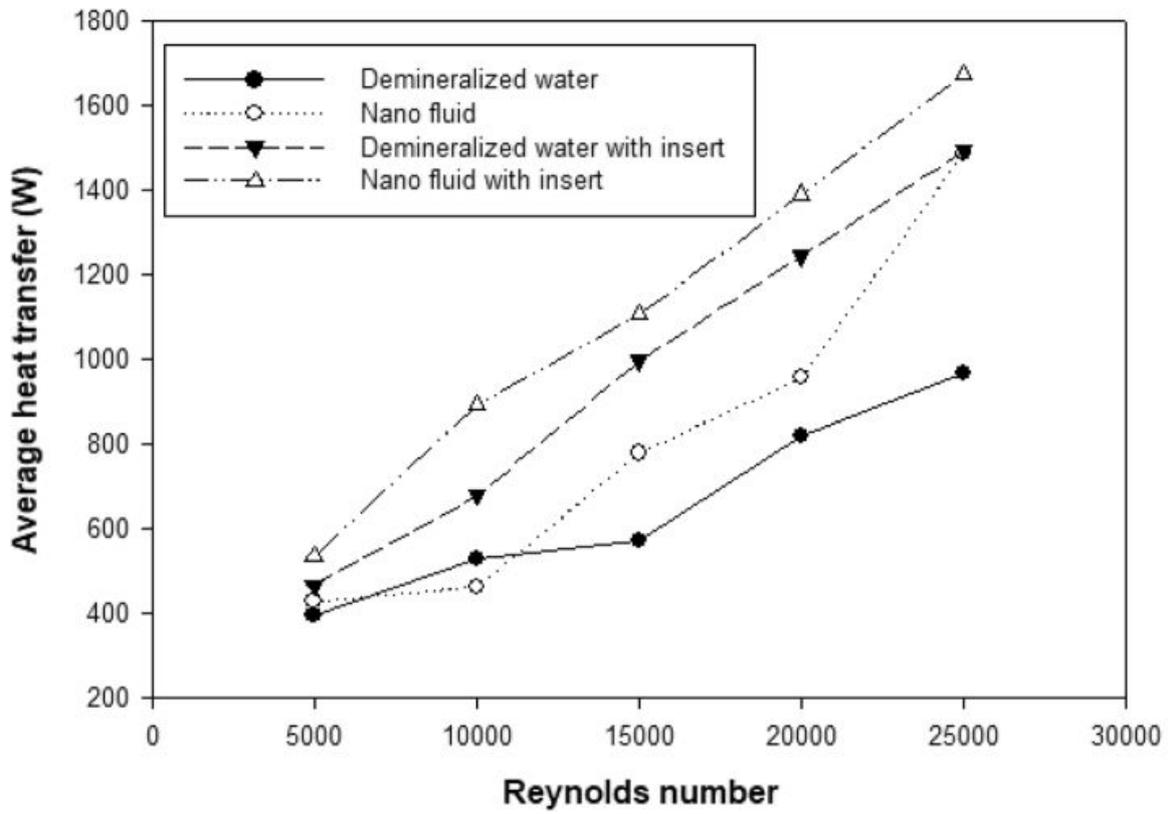


Fig. 5 Reynolds number vs. Average heat transfer (W)

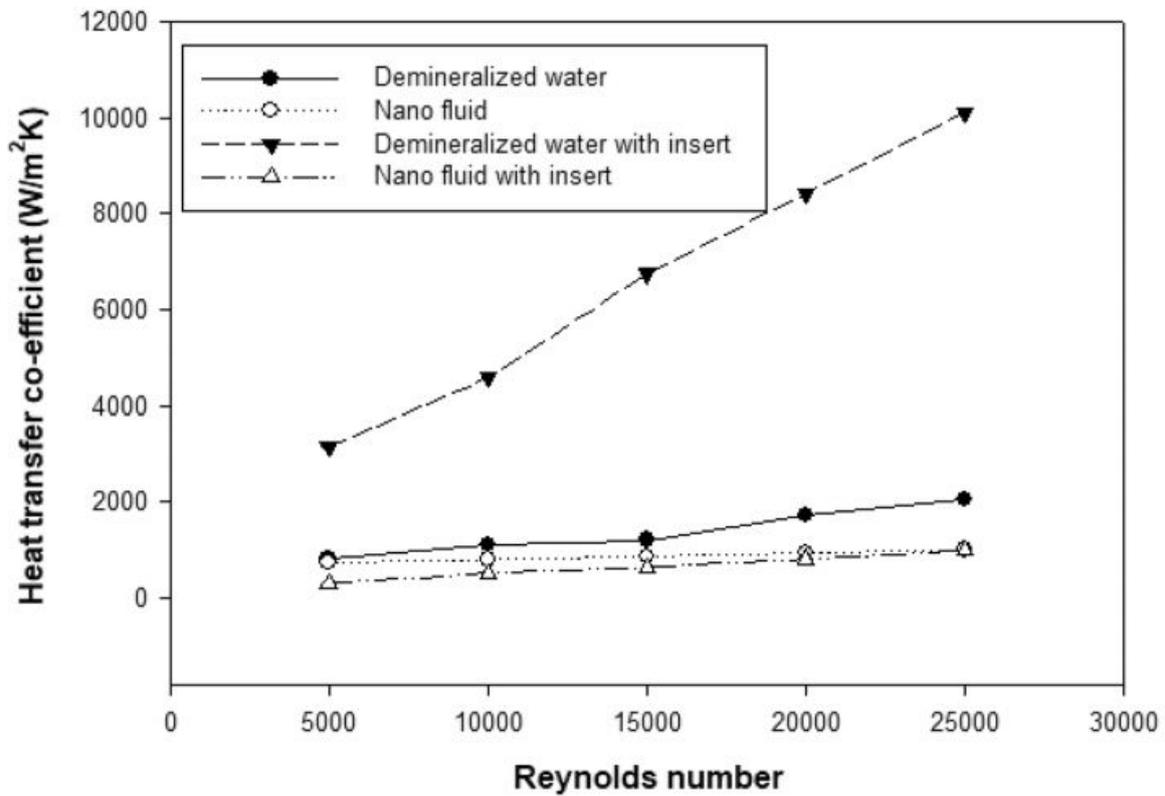


Fig. 6 Reynolds number vs. Heat transfer co-efficient (W/m²K)

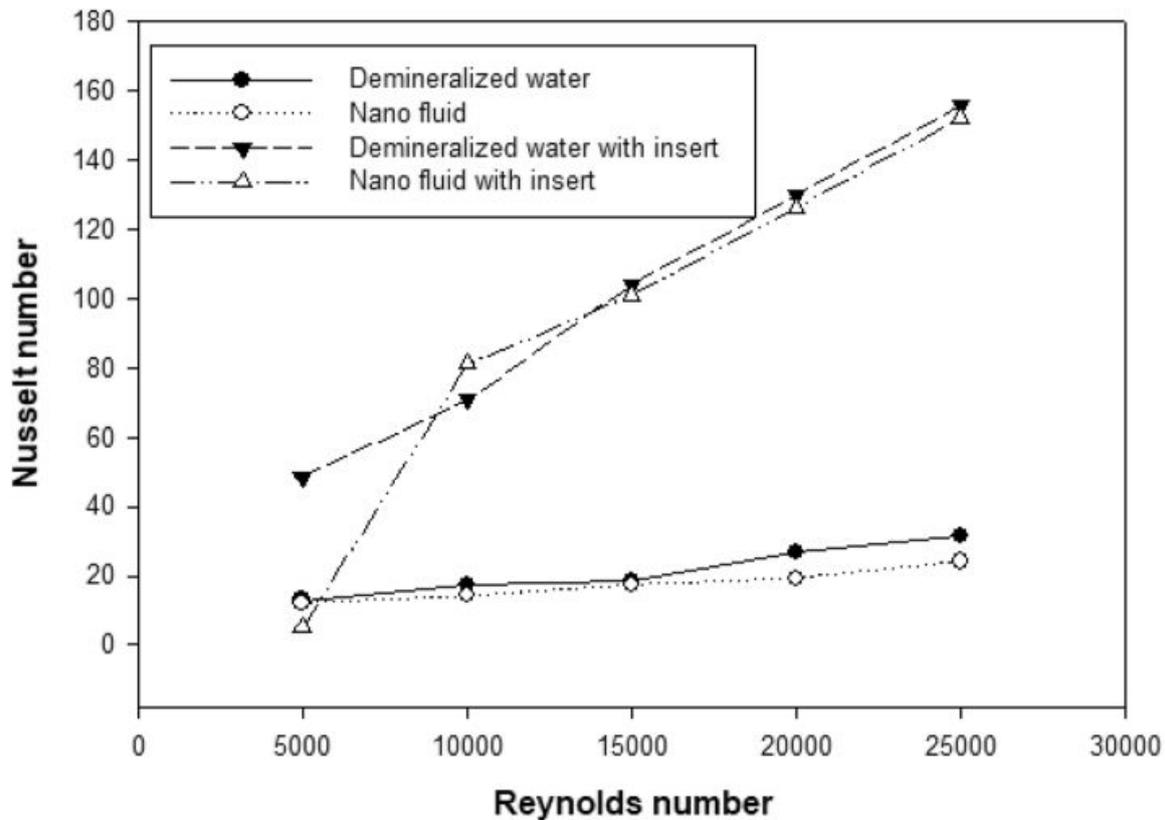


Fig. 7 Reynolds number vs. Nusselt number

$$\text{Heat flux, } q = \frac{Q}{\pi DL} \quad (4)$$

$$\text{Nusselt number, } Nu = \frac{hD}{k} \quad (5)$$

$$\text{Heat generated } Q_1 = V \times I \quad (6)$$

$$\text{Heat absorbed by the fluid } Q_2 = m \times C_p \times (T_{out} - T_{in}) \quad (7)$$

The heat flux of any heat exchanger may be modified by modifying the mass flow rate, Reynolds number (Re), and heat input. In heat transfer, the Nusselt number (Nu) and heat flux are critical parameters used to describe the efficiency of heat exchange processes. An increase in the Reynolds number (Re) and the inclusion of nanoparticles in a base fluid can significantly enhance these parameters. When twisted tape inserts are included into the flow path, the heat flux is enhanced compared to the traditional bare tube configuration [12]. An analogous event was seen in Fig. 4. At a Reynolds number of 5000, the heat flux value rose from 1256 W/m² to 1358 W/m². Similarly, with a higher Reynolds number of 25000, the heat flow rose from 3075 W/m² to 4737 W/m². The surface area of the nano fluid increased in comparison to demineralized water, leading to the observed outcome. In comparison to alternate designs, such as twisted tubes, dimples inside the testing section, wicks, and others, a standard tube filled with testing fluid in heat exchangers has a lower heat transfer rate [5, 9]. When the

twisted tape inserts were introduced, the amount of improved energy increased to 1482 W/m^2 for demineralized water and 1705 W/m^2 for nano fluid [26, 27].

Thermal energy has been transferred from the test fluid to the inside surface of the tube due to the design modification. As a result, there was a substantial enhancement in heat transfer and enhanced interaction between the wall and the fluid. When comparing the heat flux of demineralized water with different combinations of flows including twisted tape inserts and nanofluid, it is evident that the heat flux is reduced. Even without the insertion of twisted tape, the wall temperature decreases during the flow of nanofluid. The heat flux is larger in the flow that includes the insert containing nanofluid, relative to the other flows.

The amount of heat transferred to the test fluids was evaluated by measuring the temperature at the entrance and exit points of the experimental apparatus. Equation (7) was used to quantify the amount of heat absorbed by the fluid, whereas Eq. (6) was used to estimate the amount of heat generated by the heater. The average heat transfer that happened was determined by taking the average of the preceding statistics. According to Fig. 5, the nano fluid exhibited a higher heat transfer rate of 1487 W compared to the demineralized water, which had a heat transfer rate of 966 W at a Reynolds number (Re) of 25000 . The increase in surface area, as mentioned before [28], is the cause of this outcome. Similarly, the inclusion of twisted tape in the test section resulted in a considerable enhancement in the heat transfer rate for demineralized water and nano fluid, reaching 1492 W and 1675 W , respectively [26, 27]. Whenever the twisted tapes are introduced into a stream of demineralized water or nano fluid, the temperature of the wall increases correspondingly. When an insert is present and the flow medium consists of nanofluid, the average heat transfer is enhanced.

The heat transfer coefficient plays a crucial role in convective heat transfers. The feature in question is subject to changes when the fluid's composition, velocity, and dynamic properties are modified [3, 20, 29]. Figure 6 displays the heat transfer coefficient values of the test fluids, comparing the cases with and without twisted tape inserts in the tube. According to the results, the nano fluid is adversely affected when compared to demineralized water. The reason for this is because in nanofluids, conductive heat transmission has a greater impact than convective heat transfer. According to the comparison in Fig. 6, the demineralized water with inserts has the highest heat transfer value, ranging from $3153.2 \text{ W/m}^2\text{K}$ to $10114.3 \text{ W/m}^2\text{K}$ for Reynolds numbers (Re) of 5000 to 25000 , respectively.

Whenever alterations are made to the flow of the heat exchanger, the heat transfer coefficient experiences an increase. The use of inserts leads to an augmentation in the heat transfer coefficient values due to the enhanced thermal conductivity of the working fluids and increased wall temperature. Nevertheless, the absence of inserts resulted in a reduced Nusselt number for the flow of test fluids, as seen in Fig. 7. The addition of inserts [4, 11, 12] enhances the heat transfer properties of the system. At a Reynolds number of 25000 , it was observed that the Nusselt number for demineralized water increased from 31.58 to 155.84 . At a Reynolds number (Re) of 25000 , the nanofluid shown a significant improvement, increasing from 24.12 to 152.2 . The steady state value stays constant for flows with twisted inserts, irrespective of the heat-carrying capacity of the test fluid. The objective was to manipulate the mass flow rate while keeping the heat flux constant in the flow.

5 Conclusion

An investigation was conducted to assess the thermal conductivity of Al_2O_3 in a heat exchanger. Custom-designed and produced twisted tapes were used in this experiment to modify the flow patterns. The performance of demineralized water was evaluated and compared to that of Al_2O_3 nano fluid as a working fluid. Varying flow conditions were used throughout the experiment, and the results were recorded. The following conclusions were derived from the data:

- The addition of twisted tape inserts to the flow channel enhances heat flux compared to the typical bare tube design.
- When demineralized water was employed, the heat flux value rose from 1256 W/m^2 to 1358 W/m^2 at a lower Reynolds number of 5000.
- When nano fluid was used, the heat flux value exhibited an increase from 3075 W/m^2 to 4737 W/m^2 at a higher Reynolds number (Re) of 25000.
- The user's text consists of a single bullet point. When comparing the heat transfer rates of demineralized water and the nano fluid at a Reynolds number of 25000, it was found that the nano fluid had a higher heat transfer rate of 1487 W, whereas demineralized water had a heat transfer rate of 966 W.
- The heat transfer rate for demineralized water and nano fluid saw a substantial rise to 1492 W and 1675 W, respectively, upon the insertion of a twisted tape into the test region.
- The user's text consists of a bullet point. The highest heat transfer coefficients are seen in demineralized water with inserts, ranging from $3153.2 \text{ W/m}^2\text{K}$ to $10114.3 \text{ W/m}^2\text{K}$ for Reynolds numbers (Re) of 5000 to 25000, respectively.
- At a Reynolds number (Re) of 25000, the Nusselt number for demineralized water increased from 31.58 to 155.84. At a Reynolds number (Re) of 25000, the nanofluid exhibited a significant improvement, increasing from 24.12 to 152.2.

Subsequent investigations will analyze the same study with additional modifications implemented on other elements, such as twist ratio and alternative nanoparticles. In order to improve the effectiveness of heat transfer, it was necessary to examine their effects on the heat flow of shell and tube heat exchangers. Given the significant impact of Reynolds number and nanoparticles on heat transfer, future studies should focus on further optimization and exploration of these factors to maximize heat transfer rates. Here are some specific areas to consider as Twisted Tape Inserts.

Author contributions V. Sivakumar: Conceptualization, methodology, investigation, data curation, writing—original draft, visualization.

K. Visagavel: Supervision, project administration, funding acquisition, writing—review and editing.

Kumaraswamy J: Formal analysis, validation, resources, software, writing—review and editing.

Balaj E: Experimental setup, data collection, writing—review and editing.

V. Khalkar: Computational modeling, software development, writing—review and editing.

C. Gnanavel: Data analysis, experimental design, writing—review and editing.

P.R. Kalyana Chakravarthy: Literature review, data interpretation, writing—review and editing.

S. Baskar: Technical support, data visualization, writing—review and editing.

V. Vijayan: Statistical analysis, result interpretation, writing—review and editing.

Data availability The data available with me and ready to share if needed.

Declarations

Competing interests The authors declare no competing interests.

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Authors and Affiliations

V. Sivakumar¹ · K. Visagavel¹ · J. Kumaraswamy² · E. Balaj³ · V. Khalkar⁴ · C. Gnanavel⁵ · P. R. Kalyana Chakravarthy⁵ · S. Baskar⁵ · V. Vijayan⁶

✉ V. Sivakumar
sivakumarpalapati@gmail.com

K. Visagavel
visaagavelu@yahoo.com

J. Kumaraswamy
kumaraswamyj1985@gmail.com

E. Balaj
balaji.dew@gmail.com

V. Khalkar
vikas_khalkar@rediffmail.com

C. Gnanavel
gnanavelmech1986@gmail.com

P. R. Kalyana Chakravarthy
kalyanstructure12@gmail.com

S. Baskar
baskar133.se@velsuniv.ac.in

V. Vijayan
vijayan.me@gmail.com

- ¹ Department of Mechanical Engineering, Knowledge Institute of Technology, Salem, Tamil Nadu 637504, India
- ² Department of Mechanical Engineering, R. L. Jalappa Institute of Technology (Visvesvararaya Technological University, Belagavi), Doddaballapur 561203, Karnataka, India
- ³ Department of Mechanical Engineering, Vel Tech Multi Tech Dr Rangarajan Dr Sakunthala Engineering College, Avadi, Chennai 600062, Tamil Nadu, India
- ⁴ Department of Mechanical Engineering, Gharda Institute of Technology, Lavel, Khed, Ratnagiri, Maharashtra 415708, India
- ⁵ School of Engineering, Vels Institute of Science, Technology and Advanced Studies, Chennai 600117, Tamil Nadu, India
- ⁶ Department of Mechanical Engineering, K.Ramakrishnan College of Technology, Tiruchirappalli, Tamil Nadu, India