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Thermal Performance Evaluation of a Helical-Finned Pipe-in-Pipe Heat Exchanger

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Abstract

Efficient heat exchangers are crucial for diverse industrial applications, including chemical processing, petroleum refining, and paper production. Driven by the need for enhanced energy efficiency and environmental sustainability, improving heat transfer performance is a critical objective. This study examines the heat transfer characteristics of a concentric tube heat exchanger, focusing on the synergistic effect of external helical fins and internal tube rotation. A one-meter counter-flow exchanger was constructed, featuring a 21mm fin spacing. Water was utilised as the coolant within the inner tube, while glycerol served as the heating medium in the outer shell. Maintaining a constant cold fluid flow, the hot fluid flow rate was varied. Convective heat transfer coefficients were measured for both static and rotating inner tubes across a range of rotational speeds. The findings revealed a significant enhancement in heat transfer due to the combined application of helical fins and tube rotation. The fins augmented the heat exchange surface area, while rotation promoted fluid mixing, thereby boosting convective heat transfer. Notably, the Nusselt number, a measure of convective heat transfer, exhibited an increase of up to 72% at 110 rpm compared to the stationary finned tube. The experimental results were compared with the established Dittus-Boelter correlation, confirming the efficacy of this approach for improving heat exchanger performance.

Major Findings: *The combination of helical fins and inner tube rotation significantly enhanced heat transfer, increasing the Nusselt number by up to 72% at 110 rpm. Experimental results consistently outperformed predictions from the Dittus-Boelter equation, confirming improved convective performance. This approach enables compact, highly efficient heat exchanger designs for industrial applications.*

Keywords: *Pipe in Pipe Heat Exchanger, Helical Fins, Rotating Inner Tube, Nusselt Number*

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1.0 Introduction

The efficient exchange of heat between fluids is paramount in thermal systems, rendering heat exchangers indispensable across industries such as chemical processing, petroleum refining, power generation, and paper manufacturing. With a growing global emphasis on energy conservation and resource optimisation, the demand for high-performance heat exchangers has reached unprecedented levels. The primary design objective centres on maximising heat transfer while simultaneously achieving compact designs and minimising operational expenditures. A pivotal strategy to realise these objectives involves enhancing heat transfer efficiency. By optimising the rate of heat exchange, these systems can function more effectively, curtail energy consumption, and reduce equipment costs. Established techniques, such as expanding the heat transfer surface area and inducing turbulent flow, are proven methodologies. This can be achieved through the integration of helical fins on the inner tube and the implementation of inner tube rotation. Helical fins increase the available surface area for heat exchange, whereas tube rotation facilitates fluid mixing, thereby disrupting the thermal boundary layer and augmenting convective heat transfer. This investigation examines the heat transfer properties of a concentric tube heat exchanger employing helical fins on a rotating inner tube within a counter-flow configuration. Water and glycerol serve as the cold and hot fluids, respectively, to evaluate the influence of inner tube rotation and finned surfaces on heat transfer. The overarching goal is to elevate heat exchanger efficiency and promote the development of more compact and effective thermal systems for industrial applications. The effectively articulates its objective of enhancing heat transfer performance through the use of helical fins and inner tube rotation, and this aim is consistently pursued throughout the study. The choice of water and glycerol as working fluids is scientifically justified due to their contrasting thermal properties, which help create a representative heat exchange environment. The experimental outcomes are convincingly validated through comparison with the Dittus-Boelter correlation, showing up to a 72% increase in the Nusselt number at 110 rpm, thus confirming the effectiveness of the proposed enhancements. The influence of varying tube rotation speeds is thoroughly examined, with results presented for 0, 60, and 110 rpm. The paper also provides comprehensive details on fin geometry, dimensions, and the fabrication process using a spiral finning machine, ensuring experimental reproducibility. A limitation of the study is the lack of a formal error or uncertainty analysis, which could impact the credibility of the results. While the figures and graphs effectively communicate key findings, the inclusion of error bars or additional performance metrics would further improve clarity. The discussion on thermal performance and convective enhancement is both technically robust and well-supported by experimental data. However, the manuscript does not discuss its limitations or propose future research directions, which would have enhanced its overall scholarly contribution.

The motivation for combining helical fins with tube rotation is clearly articulated within the context of contemporary heat transfer enhancement techniques, highlighting the synergistic advantages of increased surface area and induced turbulence. The experimental setup and instrumentation, including detailed descriptions of fin geometry, fluid properties, rotational control, and temperature measurement methods, are sufficiently detailed to ensure reproducibility. The manuscript effectively distinguishes between the contributions of finning and tube rotation to the overall thermal performance improvements. The governing equations and data reduction methodologies employed are appropriate for the type of heat exchanger studied and are well-justified. The comparison with the Dittus-Boelter correlation is thoughtfully utilised to validate the experimental results, demonstrating significant improvements over traditional expectations. Variations in the Nusselt number with Reynolds number and rotational speed are thoroughly analysed and supported by sound physical interpretations related to boundary layer disruption and enhanced fluid mixing. Although the effects of fin geometry, such as height, pitch, and thickness, are mentioned, a more in-depth discussion on their specific influence on heat transfer performance would further enrich the study. The literature review is comprehensive and effectively connects the current findings with previous research, providing a strong contextual foundation. Figures, graphs, and schematic diagrams are clear, well-labelled, and directly relevant to the text. However, while the technical analysis is

robust, the manuscript would benefit from a more explicit discussion of the practical implications and real-world industrial applications of the proposed design improvements.

Previous studies have explored various methods to enhance heat transfer. For example, Zhang *et al.*[1] found that helical fins combined with vortex generators significantly improved heat transfer in a double-pipe exchanger. El-Maghlany *et al.*[2] demonstrated that rotating the inner tube of a double-pipe exchanger increased the Reynolds number, Nephelometric Turbidity Unit (NTU), and effectiveness. Zhang *et al.*[3] examined helically baffled heat exchangers with finned tubes, achieving good agreement between experimental and numerical results. El-Sadi *et al.*[4] explored micro screw heat exchangers for compact applications. Nobari and Gharali[5] numerically investigated internal fins in rotating pipes, finding that optimised fin heights significantly enhanced heat transfer. Salimpour[6] studied temperature-dependent engine oil in coiled tube exchangers, noting that smaller coil pitches improved heat transfer.

Further research by Kurhade *et al.*[7-12], Waware *et al.*[13-15], and Khot *et al.*[16-20] has explored techniques such as material selection, twisted tape inserts, and Computational Fluid Dynamics (CFD) analysis for heat transfer enhancement. Kurhade *et al.*[21-23] also investigated solar collector performance and engine efficiency with biodiesel blends, while Waware *et al.*[24] reviewed nanofluids in heat exchangers. Kurhade *et al.*[25-30] studied Minimum Quantity Lubrication (MQL) grinding and electronic component heat transfer, emphasising the influence of substrate thermal conductivity and phase change materials. Additional studies have analysed Integrated Circuit (IC) chip heat transfer, electronic cooling in harsh environments, aerofoil design optimisation, and mechanical behaviour of curved plates[31,32], electronic component thermal performance[33] and twisted tape heat transfer[34,35], advanced electronics cooling[36], and CFD

Table 1. Literature review: Advances in heat transfer and heat exchanger technologies

S. No.	Authors	Title and Details	Key Points
1	Li Zhang *et al.*[1]	Increased heat transfer rate by 87-115 % in a double-pipe heat exchanger with helical fins and delta-wing vortex generators.	Significant enhancement in heat transfer compared to smooth inner tubes.
2	W. El-Maghlany *et al.*[2]	Study on a double-pipe heat exchanger with a rotating inner tube, showing increased Reynolds number, NTU, and effectiveness with rotational speed.	Rotational speed enhances both parallel and counter-flow configurations.
3	Zhengguo Zhang *et al.*[3]	Examination of a helically baffled heat exchanger with three-dimensional finned tubes, using the Wilson-plot method for heat transfer coefficient determination.	Good agreement between experimental and numerical results for Nusselt number and pressure drop.
4	Haifa El-Sadi *et al.*[4]	Combined experimental and numerical study of a micro screw heat exchanger for compact and efficient heat transfer applications.	Highlights potential for high efficiency in compact designs.
5	M.R.H. Nobari and K. Gharali[5].	Numerical investigation on internal fins in rotating straight and stationary curved pipes, maximising heat transfer rate and coefficient.	Achieved a sixfold increase in heat transfer coefficient compared to plain tubes under optimal conditions.

6	Salimpour[6]	Investigation on temperature-dependent engine oil in shell-and-coiled tube heat exchangers, emphasising higher heat transfer coefficients with smaller coil pitches.	Smaller coil pitches are crucial for elevated temperature applications.
7	Kurhade *et al.*[7-12]	Various studies on heat transfer enhancement techniques, including material selection, twisted tape inserts, and CFD analysis.	A comprehensive approach to improving heat transfer efficiency across different methods.
8	Waware *et al.*[13-15]	Exploration of nanofluids in heat exchangers and their impact on thermal performance.	Nanofluids show promise in enhancing heat transfer capabilities in exchangers.
9	Khot *et al.*[16-20]	Research on heat transfer enhancement strategies, such as material properties and CFD applications.	Focus on optimising material properties and computational methods for heat exchangers.
10	Kurhade *et al.*[21-23]	Analysis of solar collector performance and the influence of biodiesel and dimethyl carbonate blends on engine efficiency.	Explored alternative fuels and their impact on thermal performance in solar applications.
11	Waware *et al.*[24]	Review of studies on nanofluids in heat exchangers.	Summarised advancements and challenges in nanofluid applications for heat transfer.
12	Kurhade *et al.*[25-30]	Study on MQL grinding and heat transfer in electronic components, focusing on substrate thermal conductivity and phase change materials.	Investigated advanced cooling techniques and their effectiveness in electronic applications.
13	Various (Fuzzy logic, CFD)	Aerofoil design optimisation using CFD simulations and fuzzy logic for heat transfer enhancement with twisted tape inserts.	Combined computational and heuristic methods for optimising heat exchanger designs.

optimisation of heat exchangers[37-40]. Table 1 presents a literature review summarising key advancements in heat transfer and heat exchanger technologies, focusing on helical fins, rotational effects, and compact designs.

2.0 Experimental Procedure

The experimental arrangement, as depicted in Figure 1, was created to examine heat transfer and pressure drop within a concentric tube heat exchanger equipped with helical fins. The inner tube, one meter long, featured fins along 1100mm of its length. These fins, with a height of 18mm, a thickness of 2mm, and a pitch of 21mm, were applied using a spiral finning machine (Figure 2). The system comprised two distinct fluid circuits: one for heated glycerol circulated through the outer shell, and another for chilled water maintained at a stable temperature, flowing through the inner tube. By employing a counter-flow configuration, the setup aimed to optimise heat transfer

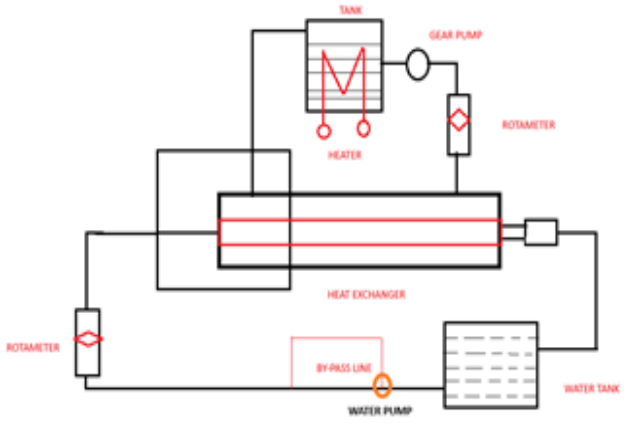


Figure 1. Schematic of experimental set-up.

by ensuring a maximised temperature difference across the heat exchanger. The schematic in Figure 1 illustrates the experimental setup comprising a heat exchanger system integrated with a heater, rotameters, pumps, and a water circulation loop.

To accurately determine the inlet and outlet temperatures of both the glycerol and water, K-type thermocouples were carefully positioned within small, 0.3 mm diameter holes. A pressure gauge was utilised to monitor the pressure difference across the shell side. The water flow rate was held constant at 810 litres per hour, while the glycerol flow rate was varied between 210 and 430 litres per hour. A direct current motor was employed to regulate the rotation of the inner tube, with speeds ranging from 0 to 110 revolutions per minute. Temperature measurements were specifically taken at 0, 60, and 110 RPM. To minimise thermal losses, the experimental apparatus was insulated with rubber. This setup allowed for a thorough evaluation of thermal performance by calculating Reynolds and Prandtl numbers, heat transfer coefficients, and Nusselt numbers. Figure 2 depicts an inner tube equipped with helical fins on its outer surface to enhance heat transfer performance.

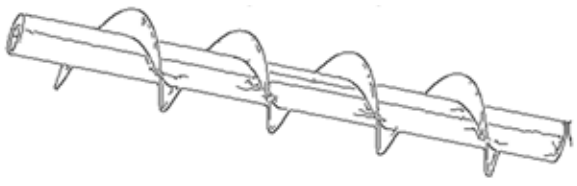


Figure 2. Inner tube with helical fins on outer surface[1].

3.0 Data Reduction

To study the heat transfer characteristics of pipe in pipe heat exchanger with helical fins on the outer surface of rotating inner tube, the shell side heat transfer coefficient ho must be determined.

Heat released by the hot fluid (glycerol):

$$Q_{glycerol} = m_{glycerol} * Cp_{glycerol} * (T_{glycerol_in} - T_{glycerol_out})$$

Heat absorbed by the cold fluid (water):

$$Q_{water} = m_{water} * Cp_{water} * (T_{water_out} - T_{water_in})$$

Average heat transfer rate:

$$Q_{avg} = (Q_{glycerol} + Q_{water}) / 2$$

The thermodynamic and transport properties of both fluids are evaluated at their respective bulk mean temperatures.

$$T_{mean_bulk} = (T_{bulk_inlet} + T_{bulk_outlet}) / 2$$

Alternative average heat transfer rate:

$$Q_{avg} = U * A_o * LMTD$$

Overall heat transfer coefficient:

$$U = \frac{Qavg}{Ao\ LMTD}$$

Ao is the heat transfer area, considering the outer surface area of the inner tube and total surface area of fins, and LMTD is Log Mean Temperature Difference.

Log mean temperature difference:

$$LMTD = (\theta_1 - \theta_2) / \ln(\theta_1 / \theta_2)$$

$$\theta_1 = T_{glycerol_in} - T_{water_out}$$

$$\theta_2 = T_{glycerol_out} - T_{water_in}$$

Outer surface area:

$$A_o = \pi * d_{o1} + A_f$$

Where A_f = surface area of helical fins.

Total fin surface area:

$$A_f = n * A_{fin}$$

$$n = l / p$$

$$A_{fin} = A_{c/sfin} - A_{c/s_o}$$

$$A_{c/sfin} = [(2 * h_{fin}) + d_o]^2$$

$$A_{c/so} = d_o^{\ 2}$$

The overall heat transfer coefficient based on the outer surface area of the inner tube is

$$\frac{1}{U} = \frac{1}{ho} + \frac{Ao}{Ai} Rwall + \frac{Ao}{Aihi}$$

Inner surface area:

$A_i = \pi * d_i * l$

$R_{wall} = \ln(d_o / d_i) / (2 * \pi * k_t * l)$

K_t = thermal conductivity of inner tube material.

By substituting the value of hi, the shell side heat transfer coefficient ho is obtained.

Nusselt number (shell side):

$Nu = h_o * d_h / k$

Where, d_h = hydraulic diameter for the shell side The shell side can be considered as the helical channel with rectangular cross section[1].

Hydraulic diameter (shell side):

$d_h = 4 * h_c * p / (2 * h_c + p)$

$h_c = h_{fin} + c$

Reynolds and Prandtl numbers:

$R_e = (\rho * v * d_h) / \mu$

$P_r = (C_p * \mu) / k$

4.0 Results and Discussions

The study involved testing the system by altering the glycerol flow rate, ranging from 210 to 430 litres per hour, while keeping the water flow rate fixed at 810 litres per hour. Simultaneously, the inner tube's rotation speed was adjusted between 0 and 110 revolutions per minute. The experimental outcomes were then compared to theoretical values obtained using the Dittus-Boelter equation, which is standard for simple, non-finned concentric tube heat exchangers. Figure 3 demonstrates the relationship between the Nusselt number and the Reynolds number for a non-rotating inner tube. Notably, the helical-finned inner tube exhibited a Nusselt number roughly four times greater than that of a smooth tube. The influence of inner tube rotation on heat transfer is depicted in Figure 4, which reveals a direct correlation between rotational speed and Nusselt number. Specifically, at 60 RPM, the Nusselt number was 38% higher than that of

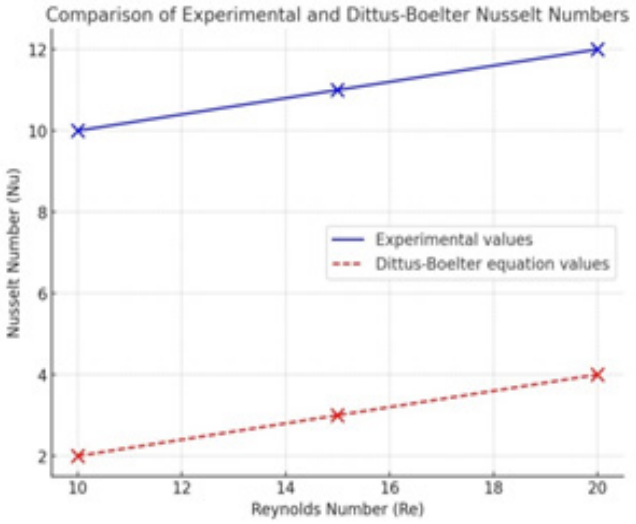


Figure 3. Comparison of experimental results with Dittus-Boelter equation results for a stationary inner tube.

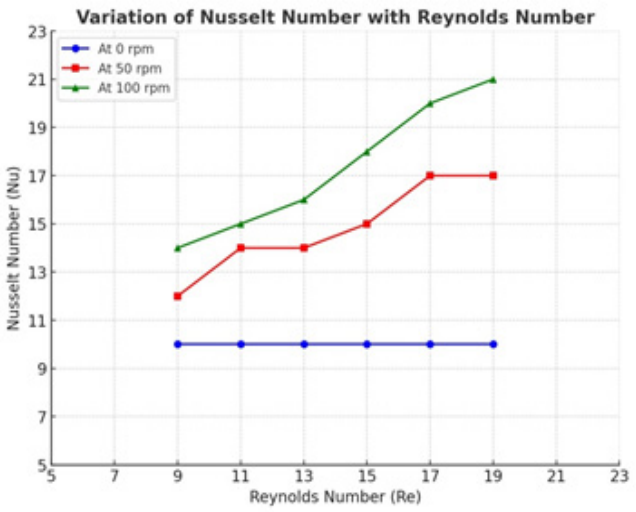


Figure 4. Comparison of experimental results for different speeds.

the stationary tube. Furthermore, at 110 RPM, it was 72% higher, with a 21% increase observed between 60 and 110 RPM. These results indicate that rotating the inner tube significantly enhances heat transfer effectiveness. Figure 3 presents a comparison between experimental Nusselt numbers and those predicted by the Dittus-Boelter equation for a stationary inner tube. Figure 4 shows the variation of Nusselt number with Reynolds number at different rotational speeds (0, 50, and 100 rpm).

5.0 Conclusions

The experiments conclusively show that combining helical fins with inner tube rotation significantly boosts heat transfer effectiveness, as evidenced by increased Nusselt numbers and improved convective performance. Key findings include:

- The measured Nusselt numbers exceeded those predicted by the standard Dittus-Boelter equation.
- Adding helical fins to the inner tube expanded the heat exchange surface area and simultaneously decreased the flow channel's hydraulic diameter, resulting in enhanced thermal efficiency.
- Rotating the inner tube generated turbulence and improved fluid mixing, which effectively amplified convective heat transfer.
- With a stationary inner tube, the helical-finned design yielded a Nusselt number approximately four times greater than that of a smooth tube.
- Rotating the inner tube at 60 RPM resulted in a 38% increase in the Nusselt number compared to the stationary setup.
- At 110 RPM, the Nusselt number showed a 72% increase relative to the non-rotating tube.
- The Nusselt number at 110 RPM was 21% higher than at 60 RPM, demonstrating a clear relationship between rotational speed and heat transfer improvement.
- The combination of helical fins and tube rotation produced a marked increase in the heat transfer rate.
- Increased turbulence due to rotation further enhanced the efficiency of convective heat transfer.
- These experimental outcomes confirm the efficacy of utilizing helical fins and rotational motion to substantially improve the overall heat transfer performance of the system.

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