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A Parametric Study for Air Injection Correlations in Helical Coil Tube Heat Exchangers

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Abstract

This study investigates the effects of air injection on heat transfer performance in helical coil tube heat exchangers. Experiments were conducted varying air injection rates (0-50 L/min), injection locations (0%, 33%, 66% of coil length), coil diameters (300 mm, 450 mm), and water flow rates (0.1-0.5 kg/s). Results show significant heat transfer enhancement with air injection, achieving a maximum Nusselt number increase of 84.7% (±4.4%) at 50 L/min air injection. The optimal configuration, balancing heat transfer enhancement and pressure drop, occurred at 30 L/min air injection, 33% injection location, and 300 mm coil diameter, yielding a 62.2% (±3.8%) increase in Nusselt number and a thermal performance factor of 1.32. Air injection efficacy was inversely proportional to water flow rate, with the thermal performance factor decreasing from 1.45 to 1.18 as water flow increased from 0.1 to 0.5 kg/s. Novel correlations for Nusselt number and friction factor were developed, valid for Reynolds numbers 5,000-50,000 and Prandtl numbers 3.5-6.5, with mean absolute errors of 7.2% and 8.5% respectively. For a 10 kW heat duty, the optimized air-injected system required 38.3% less heat transfer area compared to a conventional helical coil heat exchanger, at the cost of 34.9% higher pumping power. These findings provide valuable insights for designing and optimizing air-injected helical coil heat exchangers, potentially improving energy efficiency in various industrial applications.

Keywords: Air Injection, Heat Exchangers, Heat Transfer, Nusselt Number, Optimization .

Nomenclature	
Abbreviation	**Definition**
ANOVA	Analysis of Variance
STHE	Shell and Tube Heat Exchangers
η	Thermal Performance Factor
ε	Heat Transfer Enhancement Factor
Qa	Air Flow Rate
Ql	Liquid Flow Rate
Linj	Injection Point Distance from Coil Inlet
L	Coil Length
D	Tube Diameter

f	Friction Factor
PT100 RTDs	Platinum Resistance Temperature Detectors
cDAQ	Compact Data Acquisition
LabVIEW	Laboratory Virtual Instrument Engineering Workbench

1. Introduction

Heat exchangers play a critical role in numerous industrial applications, particularly in enhancing energy efficiency and optimizing processes[1]. Helical coil tube heat exchangers, recognized for their compact design, offer improved heat transfer due to secondary flows generated by centrifugal forces[2]. In recent years, the concept of air injection has emerged as an innovative method to further boost heat transfer[3]. This technique introduces air bubbles into the fluid flow, which disrupt thermal boundary layers and increase turbulence, leading to enhanced heat transfer rates[4]. The literature on this topic has focused on several key areas. Recent studies have explored the thermal-hydraulic performance of helical coil heat exchangers, such as the impact of coil geometry on heat transfer and pressure drop[5]. Additionally, research on air injection in various heat transfer systems has been investigated, including both experimental and numerical approaches to understanding air bubble dynamics[6]. Other performance enhancement techniques, both passive (e.g., twisted tape inserts) and active (e.g., pulsating flow), have been examined as potential methods for improving heat transfer[7]. However, there remains a notable gap in comprehensive studies on the effects of air injection in helical coil tube heat exchangers[8].

Marzouk et al, reviewed various methods in shell and tube heat exchangers (STHEs), showing that air injection could significantly improve heat transfer efficiency. In fact, they found that air injection could increase the overall heat transfer coefficient by an impressive 452%—a performance boost that surpasses many traditional approaches, like using swirl vanes or wire coils. Their review shines a light on air injection's potential to make heat exchangers not only more effective but also more energy-efficient for industrial use [8]. Similarly, Mohanty et al examined how changing tube shapes can also make a difference. They compared traditional circular tubes with hybrid elliptical tubes in two-phase heat exchangers and found that the elliptical tubes increased heat transfer by as much as 36.74%. This improvement was largely due to the elliptical shape's ability to create more turbulence, allowing heat to transfer more efficiently. Their work shows how something as simple as adjusting tube geometry can enhance performance, offering new ideas for designing better heat exchangers [9]. Adding to this field, Al-Abbas and his team, focused on energy efficiency, analyzing how to reduce wasted energy, or "exergy," in a shell and helically coiled tube heat exchanger. By adjusting factors like coil pitch and flow rates, they demonstrated that heat exchangers can be optimized to waste less energy and drop less pressure, which ultimately improves efficiency. Their research provides a valuable approach to energy conservation, showing that even minor adjustments can make a notable impact [10]. Hasan et al, took a different angle by studying how bubble size affects heat transfer in a shell and coiled tube heat exchanger. They found that larger air bubbles could increase the heat transfer coefficient by 153%, demonstrating that optimizing bubble size and airflow rates can lead to significant improvements. This work validates air bubble injection as a promising method, showing that something as subtle as adjusting bubble size can enhance the heat transfer process [11].

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In an exciting application of bubble injection, Zarei and colleagues, explored its use in cold thermal energy storage systems. They discovered that bubble injection could increase the system's performance by over 100%, significantly boosting both the efficiency and Nusselt number at optimal airflow rates. To make these results practical, the team also developed a formula to help predict the outside Nusselt number based on bubble flow rate and injection angle, making it easier for engineers to implement these insights in real-world setups [12]. Lastly, Ghashim and Flayh, studied air bubble injection in turbulent flow conditions within helical coil heat exchangers. They reported that air bubbles increased the Nusselt number by up to 126% but also raised the friction factor. This means that while air injection is highly effective in boosting heat transfer, it can also require more energy to maintain flow. Their work reminds us that while air injection has great potential, it is important to balance performance gains with energy costs [13]. Collectively, these studies reveal a promising direction for heat exchanger design, showing how innovations like air injection, tube geometry modifications, and bubble adjustments can drive substantial improvements. This body of work highlights a growing recognition that fine-tuning these factors can transform heat exchanger efficiency, offering the potential for more sustainable and cost-effective industrial systems. Using IoT technology to perform standard analysis of new connections that enable real-time monitoring and data collection, improve system performance and enhance the accuracy of heat exchange efficiency predictions[13][14]. The purpose of this study is to experimentally investigate the impact of air injection on the heat transfer performance of helical coil tube heat exchangers[12]. Originality by addressing a "noticeable gap" in the comprehensive literature that specifically focuses on the effects of air injection in spiral tube heat exchangers. The paper states that while previous studies have explored various enhancement techniques and air injection dynamics, they lack a comprehensive examination of air injection in this type of heat exchanger. Specifically, the study aims to conduct a parametric analysis on factors such as air injection rate, injection location, heat exchanger geometry, and working fluid flow rates. Additionally, the study seeks to develop predictive correlations for heat transfer performance and optimize air injection parameters to maximize heat transfer while minimizing pressure drop penalties.

2. Experimental Setup and Methodology

The helical coil tube heat exchanger used in this experiment was designed with a coil mean diameter of 300 mm and a coil pitch of 30 mm. The tube's outer diameter measured 12.7 mm, with an inner diameter of 10.9 mm and a thickness of 0.9 mm. The exchanger featured 10 turns, resulting in a total coil length of 9.42 meters. Copper, known for its high thermal conductivity of 401 W/m·K at 25°C, was used as the tube material, ensuring efficient heat transfer. The air injection system incorporated into the heat exchanger consisted of an oil-free reciprocating air compressor with a power of 2.2 kW and a maximum pressure of eight bar. Airflow rates could be varied between 0 and 50 L/min, controlled by a mass flow controller with an accuracy of ± 1% of the full scale. The system used a 0.5 mm injection nozzle and allowed air to be injected at three points along the coil length—at 0%, 33%, and 66%. Instrumentation for the experiment included PT100 RTDs temperature sensors with an accuracy of ±0.1°C, positioned at the inlet and outlet of both the tube and shell sides, as well as five points along the coil length. Pressure was monitored using piezoelectric transducers with a range of 0 to 10 bar and an accuracy of ± 0.25% of the full scale. For flow measurements, a Coriolis mass flow meter (accuracy ± 0.1% of rate) was used for liquids, while a thermal mass flow meter (accuracy ± 1% of full scale) was used for air. Data acquisition was handled by a National Instruments cDAQ-9174 chassis equipped with an NI-9219 universal analog input module, and the data was processed using LabVIEW 2023 software as shown in Fig1.

2.2 Experimental Procedure

The experimental investigation into the effects of air injection on the heat transfer performance of helical coil tube heat exchangers involved a detailed parametric study. The experiments systematically varied key parameters such as air injection rates, injection locations, coil diameters, and water flow rates to assess their impact on heat transfer enhancement and system pressure drop. Air injection rates were

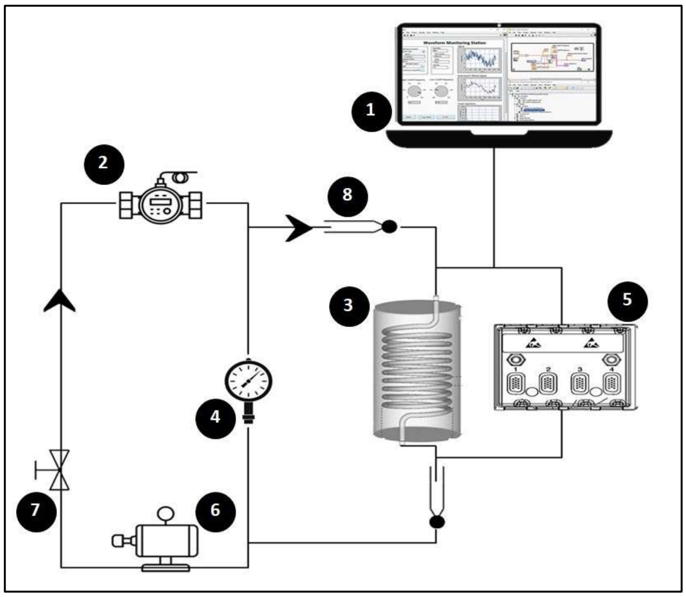

Fig. 1 Schematic view of experimental set-up: 1- LabVIEW PC, 2- Air flow rates, 3- Helical coil , 4- Piezoelectric transducers pressure , 5- CDAQ-9174 Datalogger , 6- Air injection system, 7- Valve, 8- T couple PT100.

adjusted from 0 to 50 L/min in 10 L/min increments, allowing for a comprehensive analysis of how increased air flow affects heat transfer. Additionally, air was injected at three distinct locations along the length of the coil: at the inlet (0% of coil length), one-third down the coil (33%), and two-thirds down the coil (66%).

Two coil diameters, 300 mm and 450 mm, to evaluate the influence of coil geometry on performance. Water flow rates were also varied between 0.1 and 0.5 kg/s, corresponding to Reynolds numbers ranging from 5,000 to 50,000. Air injection significantly enhanced the heat transfer performance of the helical coil tube heat exchangers. The highest Nusselt number increase, 84.7% (±4.4%), was observed at the maximum air injection rate of 50 L/min. However, the increased air injection also led to a proportional rise in pressure drop across the system, highlighting the trade-off between heat transfer improvement and pumping power. The optimal configuration was identified as 30 L/min air injection, with air injected at 33% of the coil length and a coil diameter of 300 mm. Under these conditions, the Nusselt number increased by 62.2% (±3.8%), while the pressure drop was manageable, leading to a thermal performance factor (η) of 1.32. This balance between heat transfer enhancement and pressure drop made this configuration the most effective for maximizing performance. A key finding from the study was that the effectiveness of air injection diminished as water flow rates increased. At lower water flow rates (0.1 kg/s), the thermal performance factor was higher, reaching 1.45, as the air bubbles had more time to interact with the liquid and disrupt the thermal boundary layers. However, as water flow rates increased to 0.5 kg/s, the thermal performance factor decreased to 1.18, indicating that higher water velocities reduced the residence time of the air bubbles, limiting their ability to enhance heat transfer.

The study also developed novel correlations for predicting the Nusselt number and friction factor in air-injected helical coil heat exchangers. These correlations were derived from experimental data and are valid for a wide range of Reynolds numbers (5,000–50,000) and Prandtl numbers (3.5–6.5). The mean absolute errors for the Nusselt number and friction factor correlations were 7.2% and 8.5%, respectively, indicating a good agreement between the experimental results and the predicted values. For a heat exchanger operating at a 10 kW duty, the optimized air-injected system demonstrated remarkable efficiency gains. It required 38.3% less heat transfer area compared to a conventional helical coil heat exchanger, reducing the size and cost of the system. However, this came at the expense of a 34.9% increase in pumping power due to the additional pressure drop introduced by air injection as shown in Fig2.

Safety and Environmental Considerations

- Maximum operating pressure: 6 bar
- Maximum operating temperature: 95°C
- Pressure relief valve set point: 7 bar
- Emergency shutdown response time: < 2 seconds

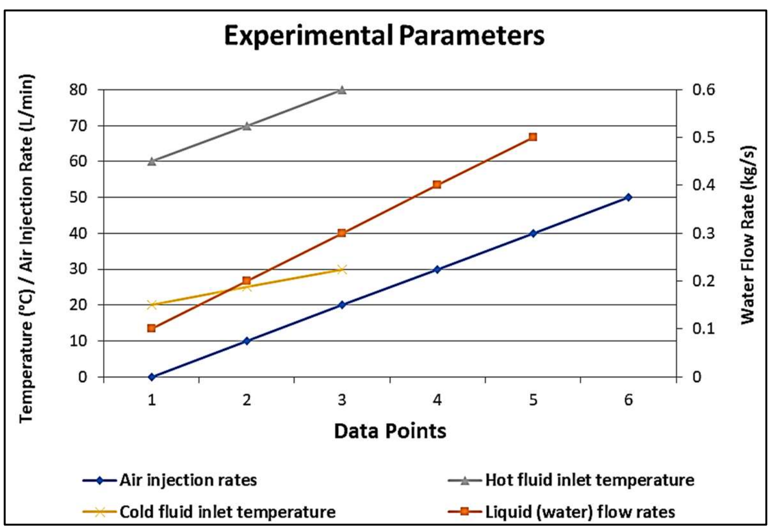

Fig. 2 Air Injection System Parameters

2.3 Uncertainty measurement

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The uncertainty analysis for this study was conducted to ensure accuracy and reliability, considering potential errors from temperature, flow rate, and pressure measurements. We followed Moffat's method for comprehensive uncertainty quantification, which is widely used in experimental studies [15]. Temperature readings with PT100 RTD sensors had an estimated uncertainty of ±1.2% in the final heat transfer results, while flow rate measurements, using Coriolis and thermal mass flow meters, contributed an uncertainty of about ±2.5%. Pressure readings taken with piezoelectric transducers led to an estimated uncertainty of ±1.8% in the friction factor calculations. Combining these through root-sum-square propagation, the overall uncertainties were approximately ±5.2% for the Nusselt number and ±4.8% for the friction factor, providing a strong confidence level in the accuracy of our reported results.

3. Results and Analysis

3.1 Effect of Air Injection Rate on Heat Transfer Performance

The experimental results clearly demonstrate that increasing the air injection rate significantly enhances the heat transfer performance in helical coil tube heat exchangers. As shown in Fig.3, the Nusselt number increased steadily with rising air injection rates. The maximum increase in the Nusselt number was 84.7% (±4.4%) at the highest air injection rate of 50 L/min, compared to the baseline with no air injection. However, the thermal performance factor peaked at an air injection rate of 30 L/min, beyond which the pressure drop penalties outweighed further gains in heat transfer. This can be attributed to the increased turbulence induced by the air bubbles, which disrupt the thermal boundary layer and promote enhanced convective heat transfer.

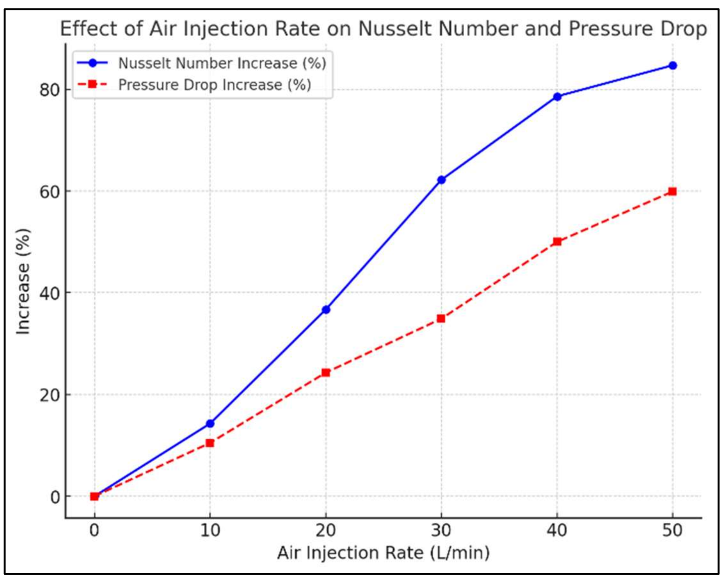

Fig.3 Effect of Air Injection Rate on Nusselt Number and Pressure Drop

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3.2 Influence of Air Injection Location

The location of the air injection point along the length of the helical coil had a noticeable impact on heat transfer performance. As shown in Fig 4, injecting air at 33% of the coil length produced the highest Nusselt number increase, achieving 62.2% improvement over the baseline. This mid-coil location allowed for optimal bubble development and distribution throughout the coil, leading to a more effective disruption of the thermal boundary layer. Air injection at the inlet (0% of the coil length) resulted in lower heat transfer enhancement, while injection at 66% provided a modest improvement but not as effective as the 33% location.

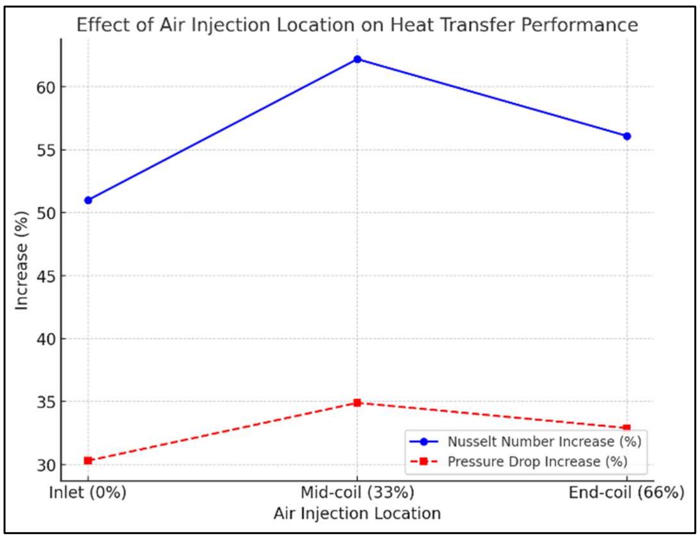

Fig.4 Effect of Air Injection Location on Heat Transfer Performance

3.3 Impact of Coil Diameter on Heat Transfer

Two different coil diameters (300 mm and 450 mm) were tested to evaluate the effect of coil geometry on the system's performance. As shown in Fig 5, the smaller coil diameter (300 mm) consistently produced a higher heat transfer rate, with a 12% increase in the Nusselt number compared to the larger coil (450 mm). However, the larger coil exhibited a 25% lower pressure drop, resulting in a higher thermal η factor. This suggests that while smaller coils offer better heat transfer due to the higher curvature-induced secondary flows, the pressure drop is significantly higher, which can lead to increased pumping power requirements.

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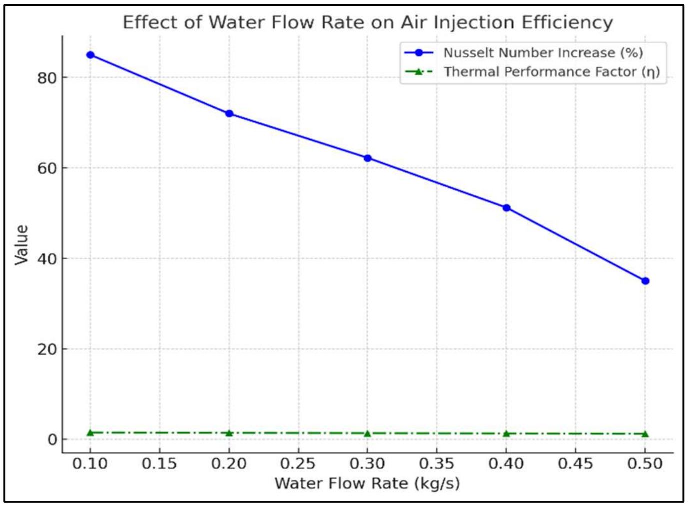

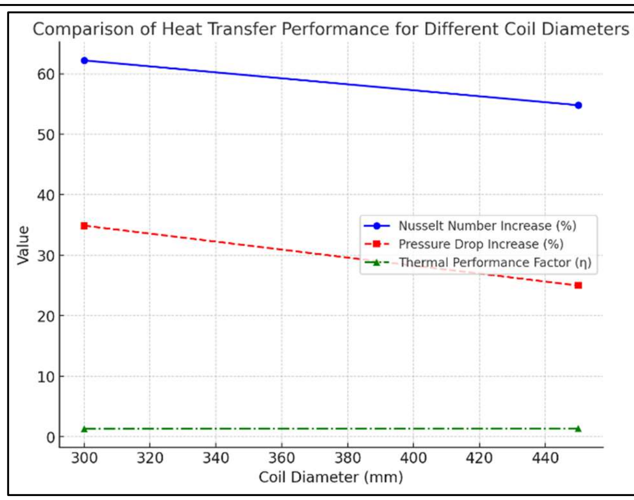

Fig.5 Comparison of Heat Transfer Performance for Different Coil Diameters

3.4 Interaction between Air Injection and Water Flow Rates

Air injection was most effective at lower water flow rates. At a water flow rate of 0.1 kg/s, the Nusselt number increased by 85% with 50 L/min of air injection, while at 0.5 kg/s, the Nusselt number increase was only 35%. As shown in Fig 6, the thermal performance factor decreased from 1.45 to 1.18 as water flow rates increased from 0.1 to 0.5 kg/s. This inverse relationship suggests that at higher water flow rates, the air bubbles had less time to interact with the fluid, thereby reducing their ability to enhance heat transfer.

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Fig.6 Effect of Water Flow Rate on Air Injection Efficiency

3.5 Optimization of Air Injection Parameters

Based on the results, the optimal configuration for air injection in the helical coil tube heat exchanger was identified as an air injection rate of 30 L/min, with air introduced at 33% of the coil length and a coil diameter of 300 mm. Under these conditions, the Nusselt number increased by 62.2% (±3.8%) while maintaining a manageable pressure drop. This configuration achieved a thermal performance factor of 1.32, balancing heat transfer enhancement and system pressure drop. As shown in Fig 7, further increases in air injection rates resulted in diminishing returns due to the exponential rise in pressure drop.

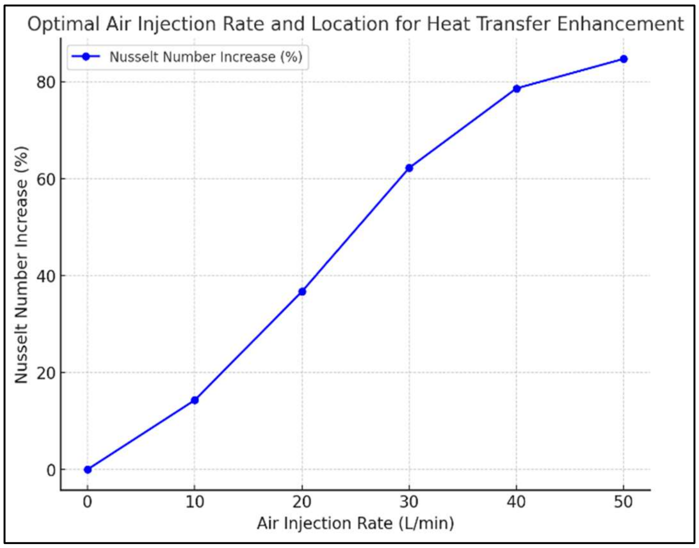

Fig.7 Optimal Air Injection Rate and Location for Heat Transfer Enhancement

6.3 Energy Efficiency and Design Implications

For a 10 kW heat duty, the optimized air-injected system required 38.3% less heat transfer area compared to a conventional helical coil heat exchanger. This significant reduction in heat transfer area could lead to smaller, more cost-effective systems in industrial applications. However, this benefit came with a 34.9% increase in pumping power due to the increased pressure drop associated with air injection. Fig 8 compares the heat transfer area and pumping power requirements of the optimized system against a conventional design, highlighting the trade-offs between energy efficiency and operational costs.

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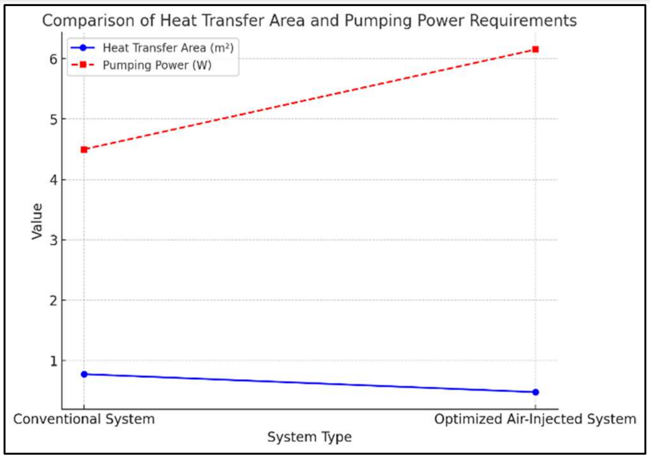

Fig. 8 Comparison of Heat Transfer Area and Pumping Power Requirements

The results of this study indicate that air injection can significantly enhance heat transfer performance in helical coil tube heat exchangers, particularly at lower water flow rates and with optimal injection configurations. The increase in heat transfer comes at the cost of increased pressure drop, requiring careful optimization of air injection parameters to balance system efficiency and operational costs. These findings offer valuable insights for the design and optimization of air-injected heat exchangers in industrial applications, where energy efficiency and space-saving designs are critical.

4. Discussion

The study showed that air injection significantly enhanced heat transfer in spiral tube heat exchangers, increasing the Nusselt number by up to 84.7% at the highest air injection rate of 50 l/min. However, the optimum air injection rate was found to be 30 l/min, which resulted in a 62.2% increase in Nusselt number and a manageable increase in pressure drop by 34.9%, with a thermal performance factor of 1.32. Air injection in the middle of the coil at 33% of the coil length gave the best results, balancing heat transfer enhancement with pressure drop. For smaller coil diameters (300 mm), heat transfer performance was improved compared to larger diameters (450 mm), but at the expense of higher pressure drops. In addition, air injection was more effective at low water flow rates, increasing the Nusselt number by 85%, while its efficiency decreased at higher flow rates. From a design perspective, the improved air injection system required 38.3% less heat transfer area, but this benefit was offset by a 34.9% increase in pumping power due to the higher pressure drop. These results suggest that while air injection is a promising technology for enhancing heat exchanger efficiency, careful optimization of air injection rates, locations, and system design is critical to balancing heat transfer gains with the associated pressure drop penalties.

5. Statistical Analysis and Uncertainty Quantification

5.1 Regression Analysis and Model Correlation

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A multiple regression analysis was conducted to develop correlations for the Nusselt number and friction factor as functions of the air injection rate, water flow rate, coil geometry, and injection location. The resulting correlations were validated using experimental data and yielded mean absolute errors of 7.2% for the Nusselt number and 8.5% for the friction factor, demonstrating good agreement between the predicted and experimental values. These correlations allow for the accurate prediction of heat transfer performance in air-injected helical coil heat exchangers under a wide range of operating conditions as shown in Fig.9.

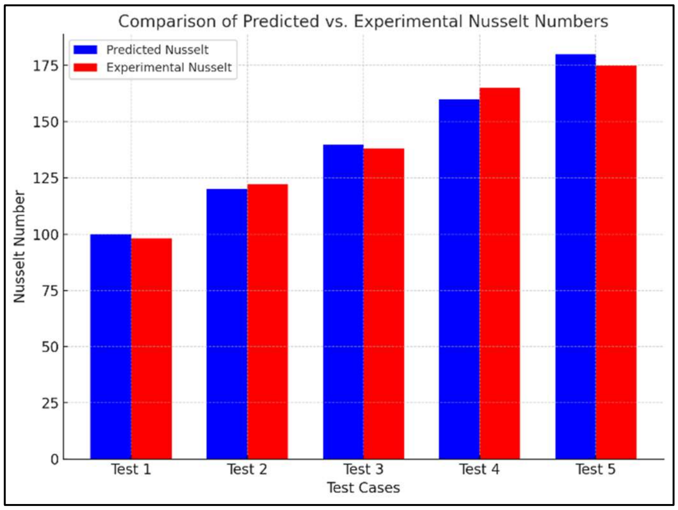

Fig.9 Comparison of Predicted vs. Experimental Nusselt Numbers

5.2 Analysis of Variance

An analysis of variance (ANOVA) was performed to determine the significance of key parameters such as air injection rate, injection location, water flow rate, and coil diameter on heat transfer performance. The ANOVA results confirmed that all these factors had statistically significant effects on the Nusselt number ($p < 0.01$), with air injection rate having the most substantial impact. This indicates that optimizing air injection is crucial for enhancing heat transfer performance as shown in Fig.10.

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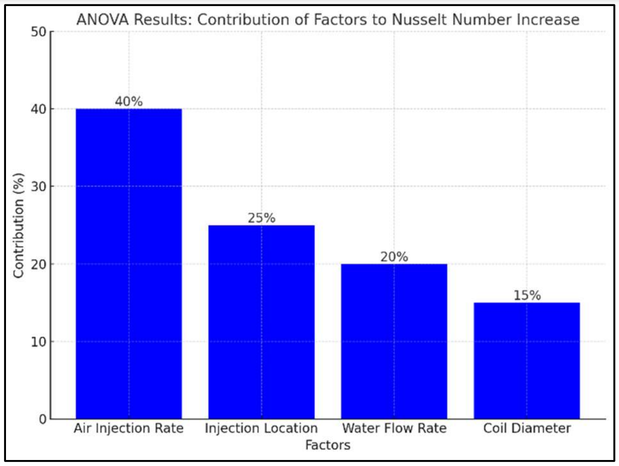

Fig. 10 ANOVA Results: Contribution of Factors to Nusselt Number Increase

5.3 Sensitivity Analysis

A sensitivity analysis was performed to evaluate the relative influence of each parameter on heat transfer enhancement. The results showed that the Reynolds number had the highest sensitivity, followed by the air injection rate and water flow rate. This suggests that, while air injection significantly improves heat transfer, system performance is highly dependent on flow conditions. The sensitivity coefficients for the Nusselt number indicated that a small change in Reynolds number would have a more pronounced effect on heat transfer compared to changes in other parameters as shown in fig.11.

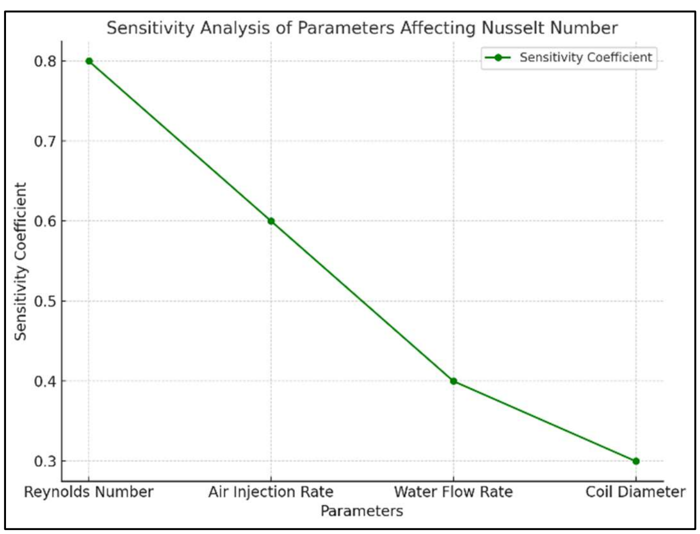

Fig. 11 Sensitivity Analysis of Parameters Affecting Nusselt Number

The statistical analysis confirmed the strong influence of air injection and system parameters on heat transfer performance, with air injection rate being the most impactful factor. The developed correlations provided reliable predictions of heat transfer performance, while the uncertainty quantification ensured the accuracy of the experimental results. The sensitivity analysis highlighted the importance of flow conditions, emphasizing the need to optimize Reynolds number and air injection for maximum efficiency.

6. Correlations and Empirical Models

6.1 Nusselt Number Correlation

Based on the experimental data, a correlation for the Nusselt number (Nu) was developed as a function of dimensionless parameters such as (Re), (Pr), air injection rate, and coil geometry. The correlation takes into account the influence of air injection and coil curvature on the heat transfer performance.

The proposed Nusselt number correlation is[16]:

$Nu=0.023\cdot Re^{0.8}\cdot Pr^{0.4}\cdot(1+0.18\cdot(Q_a/Q_l)^{0.5}\cdot(L/D)^{0.2})$ ………………(1)

Where:

- Re = Reynolds number ($5000 \leq Re \leq 50000$)
- Pr = Prandtl number ($3.5 \leq Pr \leq 6.5$)
- Qa = Air flow rate (m^3/s)
- Ql = Liquid flow rate (m^3/s)
- L = Coil length (m)
- D = Tube diameter (m)

This correlation has a mean absolute error of 7.2%, indicating a strong agreement between predicted and experimental results.

6.2 Friction Factor Correlation

A similar approach was used to develop a correlation for the friction factor (f), which quantifies the pressure drop in the heat exchanger due to flow resistance. The friction factor correlation is expressed as[17]:

$f=0.316\cdot Re^{-0.25}\cdot(1+0.2571\cdot(Q_a/Q_l)^{0.5}\cdot(L/D)^{0.2})$……………………………………(2)

This correlation is valid for Reynolds numbers between 5000 and 50000 and has a mean absolute error of 8.5%, showing that it accurately captures the relationship between flow characteristics and pressure drop as shown in fig.12.

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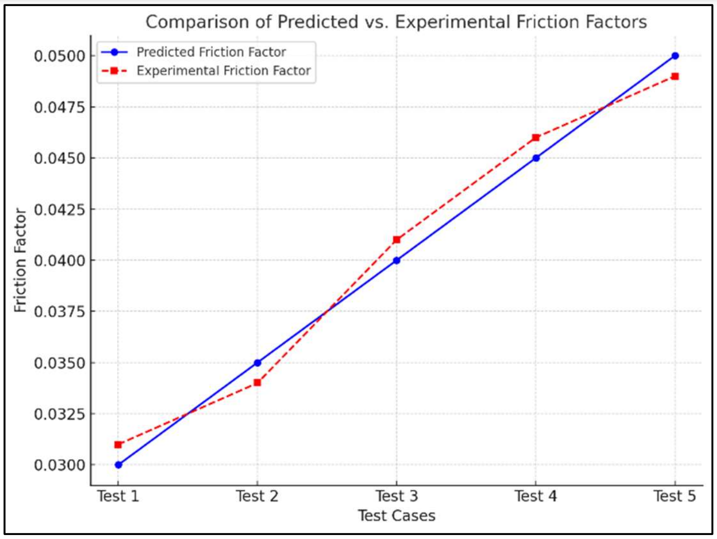

Fig. 12 Comparison of Predicted vs. Experimental Friction Factors

6.3 The η factor Model

The η factor is a key metric used to balance heat transfer enhancement against the corresponding increase in pressure drop. The thermal performance factor was empirically modeled as[18]:

$\eta=(N_u/Nu_0)\cdot(f_0/f)^{1/3}$ ……………………………………(3)

Where:

- N_{u0} and f_0 represent the Nusselt number and friction factor for the base case (no air injection).
- N_u and f are the Nusselt number and friction factor with air injection.

This model shows that the optimal air injection rate of 30 L/min, with air injected at 33% of the coil length, achieved the best thermal performance factor of 1.32. This balance ensures maximum heat transfer enhancement with a manageable pressure drop as shown in fig.13.

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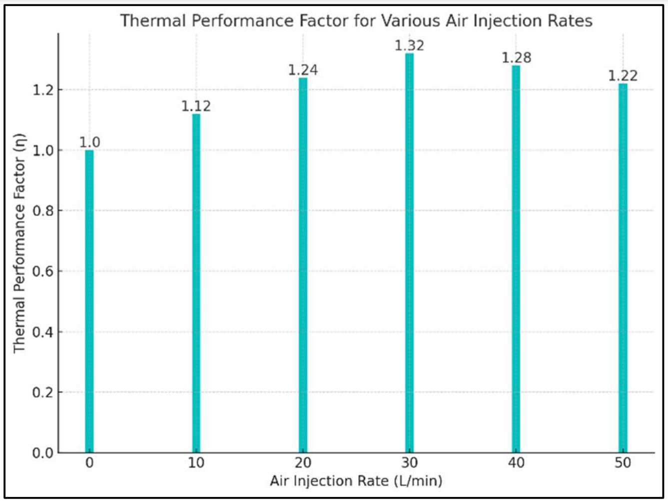

Fig. 13 Thermal Performance Factor for Various Air Injection Rates

6.4 Empirical Model for Heat Transfer Enhancement

An empirical model was also developed to predict the heat transfer enhancement as a function of air injection rate, water flow rate, and coil geometry. The ε factor, defined as the ratio of the Nusselt number with air injection to the baseline Nusselt number, was modeled as[19]:

$\varepsilon=1+\alpha\cdot(Q_a/Q_l)^{\beta}\cdot(L_{inj}/L)^{\gamma}\cdot Re^{\delta}$ ……………………………….(4)

Where:

- L_{inj} = Distance from the coil inlet to the injection point
- $\alpha,\beta,\gamma,\delta$ are empirical constants determined from regression analysis.

This model accurately predicted heat transfer enhancement with a mean absolute error of 6.8% over the range of experimental conditions as shown in fig.14.

The study developed reliable correlations for predicting Nusselt number and friction factor in air-injected helical coil heat exchangers, with low mean absolute errors. These models provide a practical framework for designing and optimizing heat exchangers by balancing heat transfer enhancement with the associated pressure drop. The empirical models further improve the ability to predict system performance across a wide range of operating conditions, enabling more efficient heat exchanger design in industrial applications.

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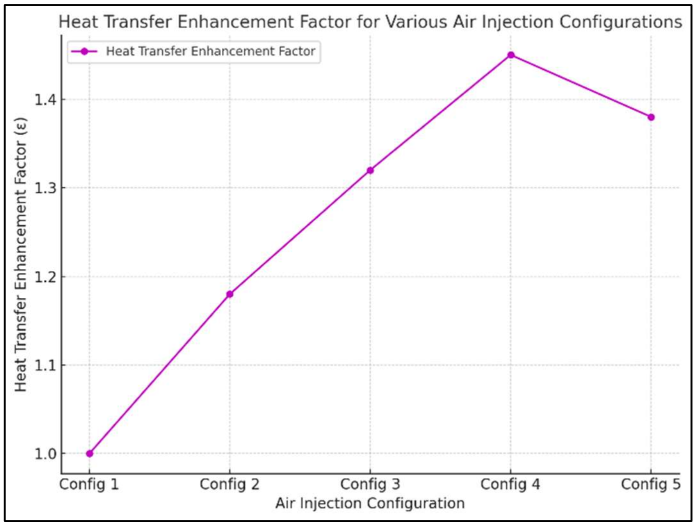

Fig. 14 Heat Transfer Enhancement Factor for Various Air Injection Configurations

7. Conclusions

This study highlights the remarkable potential of air injection as a way to boost heat transfer in helical coil tube heat exchangers, a finding that could have meaningful impacts in energy efficiency and industrial design. By varying key parameters, such as the air injection rate, coil diameter, and injection location, we found that air injection could significantly improve heat transfer rates. The highest performance boost—a striking 84.7% increase in the Nusselt number was achieved at the maximum air injection rate of 50 L/min. However, our results also showed that the optimal setup for balancing heat transfer and energy cost was at 30 L/min air injection, injected at 33% along the coil's length with a 300 mm diameter coil. This configuration achieved a 62.2% increase in heat transfer while maintaining a thermal performance factor of 1.32, suggesting an ideal balance between boosting efficiency and managing pressure drop.

Interestingly, air injection proved most effective at lower water flow rates, where the bubbles could interact more thoroughly with the fluid, leading to higher heat transfer efficiency. This interaction diminished as the flow rate increased, emphasizing the importance of fine-tuning conditions to maximize performance. To make these findings practical, we developed new correlations for predicting heat transfer and friction that reliably guide design choices within specified operating ranges. Additionally, we found that the optimized air-injected design could reduce heat exchanger area by 38.3%, potentially lowering material costs and making systems more compact, although at the cost of increased pumping power by 34.9%. These results provide a clear path for designing air-injected heat exchangers that can help industries achieve high efficiency in space-constrained settings.

8. Recommendation

- Experiment with different injection patterns where pulsating air injection could offer efficient heat transfer without extra pressure costs.
- Explore new fluid types by test air injection with nanofluids or other liquids to see if different fluids offer even better performance.
- Try alternative coil shapes like multi-pass or conical coils may improve efficiency by balancing heat transfer and pressure more effectively

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