

**EFFECT OF INJECTED AIR BUBBLES DIAMETER ON  
HEAT TRANSFER FROM A CONICAL COOLING COIL**

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**Abstract**

This study represents enhancement of heat transfer for a conical coil heat exchanger. One of the effective methods for enhancing the heat transfer rate in heat exchangers using injection bubbles. A conical coil immersed inside a tank, where the conical coil is the evaporator of a vapor compression refrigeration system. Experimental investigation was carried out to test the effect of air bubble diameter injection on Nusselt number. The air bubbles were injected from the bottom of tank in different number (15 to 40) at flow rates of air varying from (5 to 15) L/min. The results proved significantly increase in diameter of bubbles injection at (0.5 and 1) mm leads to increasing in heat transfer rate from the tank and Nusselt number ( $Nu$ ) because affected on boundary layer around the coil, But at (1.5) mm the characteristics of heat transfer were decreases because the big diameter leads to insulation around the coil. The results also showed that the air bubbles injection in water has an optimal flow rate value at \*\* L/min in. Also, the COP of the refrigeration system and the Nusselt number increased by \*\*% and \*\*%, respectively compared with no bubbles injection case.

**Keywords:** Conical coil; Diameter of air bubbles injection; heat exchangers, Heat storage

**1 Introduction**

Authors Heat transfer systems are crucial components in a extensive range of industrial and engineering packages, consisting of electricity generation, refrigeration, chemical processing, and thermal control in electronic gadgets. The performance of those systems is vital as it directly affects operational expenses, strength intake, and environmental sustainability. Addressing the developing demand for strength-efficient solutions has driven researchers and engineers to the consciousness of enhancing thermal performance and decreasing strength inputs. These advancements now not only meet increasing electricity needs but additionally contribute to environmental conservation by way of minimizing the carbon footprint of business processes.

Among the various strategies for improving heat transfer, air bubble injection has emerged as an innovative and promising technique. This approach is valued for its simplicity,

cost-effectiveness, and adaptability across diverse industrial environments. When introduced into a fluid medium, air bubbles significantly influence heat transfer properties by disrupting the thermal boundary layer around heat exchanger surfaces. This disruption enhances fluid mixing, reduces thermal resistance, and generates localized turbulence, collectively leading to improved heat transfer performance. Additionally, studies have shown that bubble injection reduces the risk of fouling and scaling, common challenges in conventional heat exchanger systems.

Despite its advantages, studies on air bubble injection have predominantly targeted immediate or helical coil configurations, leaving the potential packages of conical coil geometries largely unexplored. Conical coils, outstanding with the aid of their precise tapering geometry, provide widespread benefits including an extra compact design, a better floor location-to-extent ratio, and improved fluid glide dynamics. These characteristics make conical coils an appealing desire for applications requiring compactness and excessive efficiency. However, the dearth of experimental information and insights into the interaction between air bubbles and conical coil surfaces represents a significant gap in cutting-edge understanding.

Addressing this hole is essential for optimizing heat exchanger designs and unlocking new possibilities for thermal control structures. This has a look at goals to research the results of air bubble injection on the heat switch overall performance of submerged conical coil evaporators. By systematically inspecting the impact of bubble length, air flow price, and water temperature, the research seeks to quantify improvements in heat switch coefficients and understand the mechanisms riding these enhancements. The findings are anticipated to provide treasured insights into the mixing of bubble injection era with conical coil systems, paving the way for the improvement of subsequent-technology warmness exchangers that supply high performance and cost-effectiveness.

Heat switch systems are pivotal to a big array of industrial packages, and the conical coil configuration is gaining recognition for its advanced overall performance in selling fluid mixing and enhancing warmth switch efficiency. While a large literature exists on diverse coil geometries and the incorporation of air bubble dynamics, the potential of conical coils in this context remains underexplored. This segment evaluates fifteen key research, examining their methodologies, findings, and contributions to the knowledge of air bubble injection in warmth switch structures, even as emphasizing the relevance to the contemporary studies on conical coil structures.

Scientists laid the foundation employing comparing the baseline performance of straight coil heat exchangers and the usage of water flow alone [1]. Their findings highlighted the inherent boundaries of straight coils in producing turbulence and disrupting the thermal boundary layer, establishing a benchmark for subsequent studies exploring advanced configurations. Building upon this basis, Mahood et al. [2] examined helical coils with air bubble injection. Their observation discovered a 25–forty% improvement within the warmness switch coefficient, broadly speaking because of turbulence prompted via the bubbles, which enhanced fluid

blending and disrupted the thermal boundary layer—a vital element that sparked interest in similarly optimizing bubble dynamics.

Expanding on this, Hasan et al. [3] investigated vertical coiled tube systems with bubble injection. They determined tremendous thermal overall performance improvements, especially when small bubbles had been brought at excessive waft prices, underscoring the want to optimize bubble length and glide conditions. Hasan et al. [3] complemented these findings through their experiments on horizontal helical coils, in which bubble-triggered turbulence led to a 6–187% increase in the overall warmness switch coefficient. This looks at emphasizes the versatility of bubble injection across one-of-a-kind orientations and geometries.

The scalability of air bubble injection in business contexts was highlighted by using Ghashim and Flayh [4], who explored vertical shell and helical coiled tube warmness exchangers. Their research demonstrated that combining accelerated shell-aspect go with flow rates with bubble injection better thermal efficiency, imparting a viable answer for commercial-scale packages. Similarly, Sokhal et al. [5] delved into using bubble injection in helical coils for cold thermal electricity garage (CTES), displaying those bubbles no longer the most effective for improved heat transfer quotes but additionally mitigated fouling and scaling, not uncommon issues in such structures.

Others prolonged this investigation by analyzing helical coils with bubble injection in CTES systems, where localized turbulence was generated employing the bubbles in addition to validating the approach's effectiveness in improving heat transfer [6]. Mahood et al. [7] accompanied by analyzing vertical counter-contemporary coiled tube warmth exchangers, demonstrating the particular efficacy of bubble injection at better float prices—a locating regular with earlier research.

Rashid et al. [8] shifted consciousness to the compact and green layout necessities of helical coil warmth exchangers utilized in power storage applications, confirming good-sized performance improvements because of bubble-triggered turbulence. Tavousi et al. [9] emphasized the importance of optimizing bubble injection waft quotes in vertical shell and helical coiled tube structures, displaying tremendous gains in thermal performance while best go-with-the-flow prices have been hired. Meanwhile, [10] demonstrated these conclusions in horizontal helical coil configurations, mainly at better bubble injection charges.

Feng et al. [11] added to the growing proof with the aid of exploring the essential position of bubble size and injection charge in improving the thermal performance of vertical coiled tube heat exchangers. Hasan et al. [12] and Sun et al. [13] similarly proved the regular blessings of bubble injection in CTES structures and vertical counter-contemporary coiled tubes, respectively, displaying stated performance improvements with optimized bubble float conditions.

Most these days, Kadivar et al. [14] explored helical coil warmness for CTES programs, showing that bubble injection appreciably stepped forward warmth transfer rates and greater universal gadget efficiency via lowering energy losses.

This research collectively underscores the transformative capability of air bubble injection throughout numerous warmth switch structures, with demonstrated benefits in performance enhancement, fouling reduction, and scalability. However, while improvements in straight and helical coil geometries were well documented, the particular abilities of conical coils continue to be, in large part unexamined. The wonderful geometry of conical coils, which inherently promotes advanced fluid dynamics, presents an opportunity to, in addition, elevate the effect of bubble injection. Addressing

this hole, the current takes a look at investigates the interplay between air bubbles and conical coil surfaces, aiming to find new insights and establish conical coils as a subsequent-era answer for green heat transfer, Table 1.

**Table 1:** Comparison table

| Heat Transfer System          | Method               | Key Results                                      | Ref. |
|-------------------------------|----------------------|--------------------------------------------------|------|
| Straight coil                 | Water flows only     | Baseline transfer coefficient                    | [1]  |
| Helical coil                  | Air bubble injection | 25–40% improvement in heat transfer              | [2]  |
| Vertical coiled tube          | Air bubble injection | Enhanced thermal performance                     | [3]  |
| Horizontal helical coil       |                      | 6–187% increase in heat transfer coefficient     | [3]  |
| Vertical shell and helical    | Air bubble injection | Significant improvement in thermal efficiency    | [4]  |
| The helical coil in CTES      | Bubble injection     | Improved heat transfer, minimized fouling        | [5]  |
| The helical coil in CTES      | Bubble injection     | Enhanced heat transfer in energy storage systems | [6]  |
| Vertical counter-current coil | Air bubble injection | Improved thermal performance                     | [7]  |
| Helical coil                  | Bubble injection     | Enhanced heat transfer in compact systems        | [8]  |
| Vertical shell and helical    | Air bubble injection | Optimized injection flow rate for efficiency     | [9]  |
| Horizontal helical coil       | Air bubble injection | Substantial enhancements in heat transfer rates  | [10] |
| Vertical coiled tube          | Air bubble injection | Role of bubble dynamics in thermal performance   | [11] |

|                               |                      |                                                   |      |
|-------------------------------|----------------------|---------------------------------------------------|------|
| Helical coil in CTES          | Bubble injection     | Enhanced heat transfer in low-temperature systems | [12] |
| Vertical counter-current coil | Air bubble injection | Consistent improvements with higher bubble rates  | [13] |
| Helical coil in CTES          | Bubble injection     | Improved system efficiency with reduced losses    | [14] |

This detailed analysis and comparison underscore the need to investigate bubble injection in conical coil systems to build upon the foundational insights provided by previous research.

Indeed, the conical coil recorded about 25% more enhancement than helical coils (Mahood et al., (2025)) and 35% more efficiency than vertical designs Hasan et al. [3], owing to the conical shape's ability to provide consistent boundary layer disruption.

## 2 Methods

The methodology of this examination contains a complete approach to designing, studying, and testing an experimental setup aimed at comparing the enhancement of warmth transfer in a conical coil evaporator with air bubble injection. This section info the experimental setup, mathematical modeling, experimental variables, and approaches.

### 2.1 Experimental Setup

A custom-designed experimental setup was developed to evaluate the impact of air bubble injection on warmth transfer in a conical coil evaporator. The conical coil turned into a product of copper, a fabric with remarkable thermal conductivity, with the following specifications:

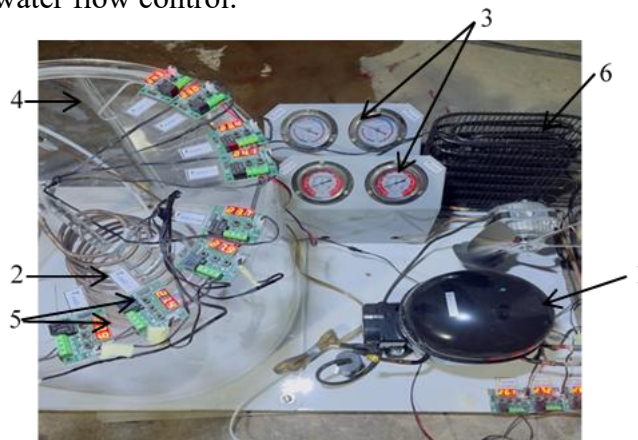
- Length (L): 4 m
- Inner diameter (Di): 6 cm
- Outer diameter of coil (Do):20 cm
- Height of tank (H): 40 cm
- Height of water ( $H_w$ ): 30 cm
- Coil pitch (p): 10 mm

The system blanketed an air injection mechanism able to introduce air bubbles at managed waft charges starting from 0 to 15 LPM, delivered via a diffuser to generate bubbles with number of holes of (15, 20, 30 and 40). The coil was submerged in a water tank with a ability of 37 L, equipped with precision devices for measuring temperature and strain. Thermocou-

ples have been strategically placed to file the temperature at the inlet and outlet of the coil, and a stress transducer monitored the air injection waft.

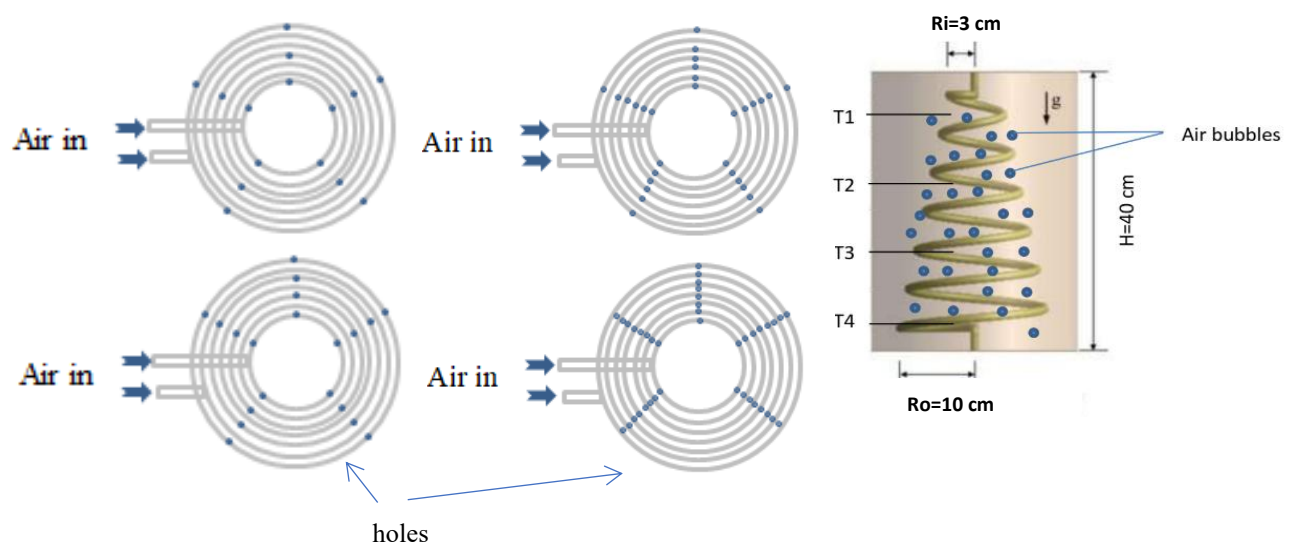
illustrating the arrangement of the conical coil, air injection system, measurement devices, and water tank as shown in Figure 1:

1. **Thermocouples (Type-K):** To measure inlet and outlet water temperatures.
2. **Pressure transducers:** To monitor the air injection rates.
3. **Flow meters:** For water flow control.



**Figure 1:** Schematic of Experimental Setup .1: compressor 2: Conical coil; 3:Pressures gauge 4:Water Tank; 5:Thermocouples; 6:Condenser

The experimental system schematic is shown in Figure 2, Illustrates the schematic representation of the geometry of conical coil with engineering figures of air injection holes.



**Figure 2:** Illustrates the schematic representation of the geometry of conical coil with engineering figures of air injection holes

**2.2 Mathematical Model**

The mathematical framework for this study quantifies the heat transfer characteristics using established models and equations [15-17]:

1. Heat storage ( $Q_s$ ), equation (1)

$$Q_s = m_w C_{p_w} \Delta T_w / \Delta t \quad (1)$$

$Q_s$ : Heat storage (W).

$m_w$ : Water mass flow rate (kg/s).

$C_{p_w}$ : Specific heat of water (kJ/kg.K).

$\Delta T_w$ : Temperature difference between the inlet and outlet water flow ( $^{\circ}\text{C}$ ).

$\Delta t$ : Time difference during operation (s)

2. Heat Transfer Coefficient ( $h$ )

The heat transfer coefficient of water in ( $\text{W}/\text{m}^2\cdot\text{K}$ ) was calculated using equation (2):

$$h_w = Q_s / (A_s * \Delta T) \quad (2)$$

Where:

$A_s$ : Surface area of the coil ( $\text{m}^2$ ) =  $\pi D_{\text{tube,out}} * L$ .

$D_{\text{tube,out}}$ : Outer diameter of tube (m)

$L$ : length of coil (m)

3. Nusselt Number ( $Nu$ )

The dimensionless Nusselt number, representing the enhancement of heat transfer, was calculated as in equation (3):

$$Nu_w = h_w * D_{\text{coil,out}} / k_w \quad (3)$$

Where:

$h_w$ : Heat transfer coefficient ( $\text{W}/\text{m}^2\cdot\text{K}$ ).

$D_{\text{coil,out}}$ : Outer diameter of the coil (m).

$k_w$ : Thermal conductivity of water ( $\text{W}/\text{m}\cdot\text{K}$ ).

Errors can occur in any experimental measurement due to measurement equipment uncertainties and operator error. Thus, calculating the uncertainty of the variables is critical. The degree of uncertainty indicates how far the obtained results differ from their actual values. In the present study, the uncertainty of the parameters was evaluated according to Eq.4, and the results are listed in table 2.[18-19]

$$W_R = \left[ \sum_{i=1}^n \left( \frac{\partial R}{\partial x_i} W_i \right)^2 \right]^{0.5} \quad (4)$$

**Table 2:** Uncertainty in variable

| Parameter        | Uncertainty |
|------------------|-------------|
| Ampere (I)       | 0.05 A      |
| Voltage (V)      | 0.05V       |
| Temperature (°C) | 0.1 (°C)    |
| Length (m)       | 0.0001m     |
| Cop              | 3.9%        |
| Nu               | 4.7%        |
| Q                | 3.7%        |

### ***2.3 Experimental Variables***

The independent and dependent variables for the experimental study were defined as follows (Sruthi et al., 2021.; Marzouk et al., 2023):

Independent Variables:

Air flow rate (L/min): Varied at (5, 10 and 15) L/min using a calibrated rotameter.

Number of holes varied at (15, 20, 30 and 40) holes.

Bubble size (0.5-1.5) mm.

Dependent Variables (Said et al., 2025)

1. Heat transfer coefficient (h): Computed using the mathematical model.
2. Temperature difference ( $\Delta T$ ): Measured using thermocouples, Table (3).
- 3.

**Table 3:** Summarizes the operational variables and their corresponding measurement tools

| Variable        | Range             | Measurement Tool  |
|-----------------|-------------------|-------------------|
| Air Flow Rate   | 5-15 <i>L/min</i> | Rotameter         |
| Bubble Size     | 0.5-1.5 <i>mm</i> | High-speed Camera |
| Number of holes | 15, 20, 30, 40    | -----             |

### **2.4 Experimental Procedure**

The following system becomes hired to assess the gadget's performance:

1. The experimental setup turned into assembled, ensuring all additives have been securely related and calibrated.
2. The device was first operated without air bubble injection to establish the baseline heat storage and Nusselt number performance.
3. Air bubbles had been then brought at varying waft rates with variable number of holes and the overall performance become measured below the same thermal and hydraulic situations.
4. The measurements have been repeated on multiple instances for every flow fee to ensure the accuracy and reproducibility of the results.

The figure above illustrates the conical coil with layers of coils and arrows indicating the bubble injection points.

## **3 Results**

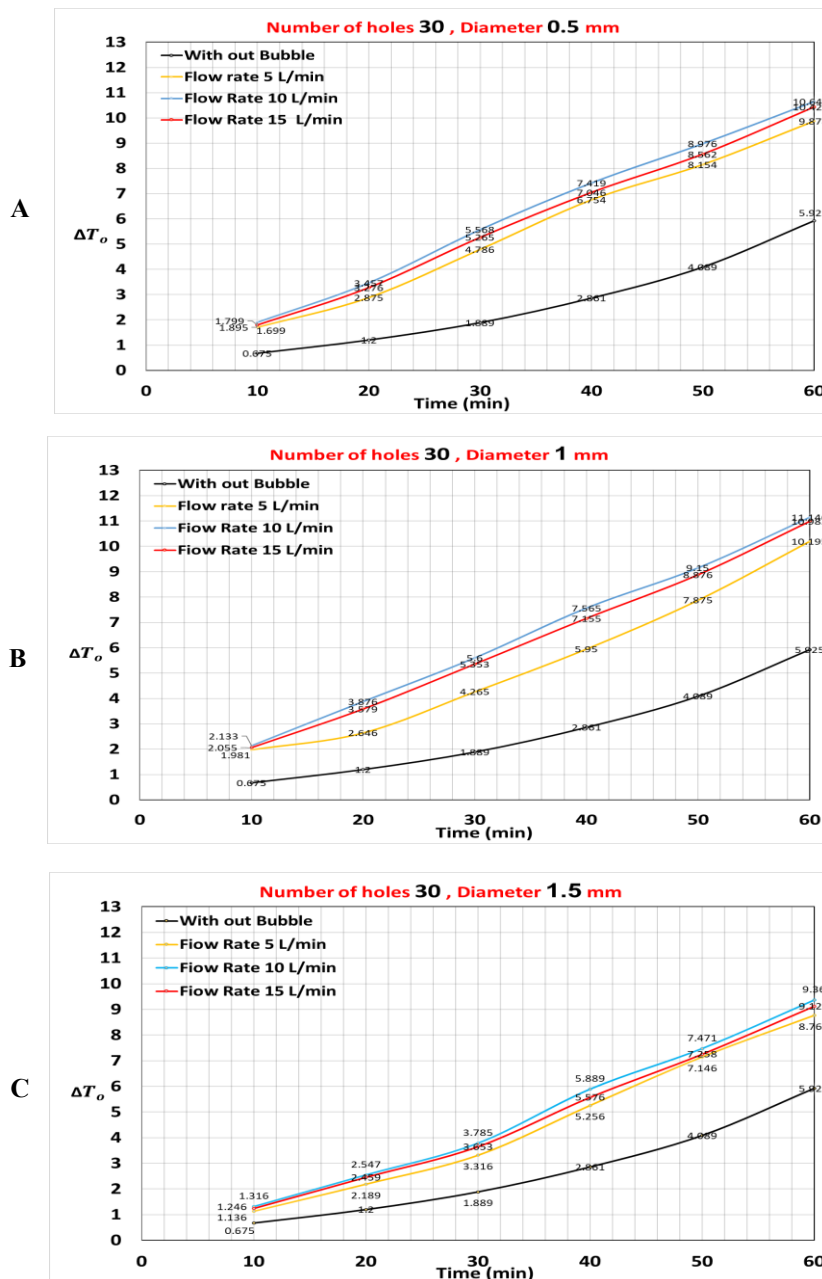
### **3.1 T Data Presentation**

The experimental statistics underscore the pivotal role of air bubble injection in enhancing the heat transfer efficiency of a conical coil evaporator. This quantitatively analyzed the ensuing enhancements within the heat transfer coefficient by systematically varying the air float rate. The findings, summarized in Table (4) monitor a consistent trend of increasing warmth switch performance as the air float rate rises. This development is attributed to the turbulence generated via the injected air bubbles, which disrupt the thermal boundary layer and promote greater fluid mixing near the coil surface.

These values verify the direct relationship between air drift charge and warmth Nusselt number. At a baseline air float fee of 0 L/min, the warmth switch (Nu) remained regular at 51. With air bubble injection, the Nusselt number increases gradually, reaching a maximum enhancement of 222% at the very best waft fee of 15 L/min and number of holes is 40. The Figure 3, illustrates the dynamic relationship between water temperature and time under varying air bubble injection rates. The plot demonstrates how the introduction of bubbles

accelerates heat dissipation, leading to a temperature drop over time compared to the baseline (no bubbles).

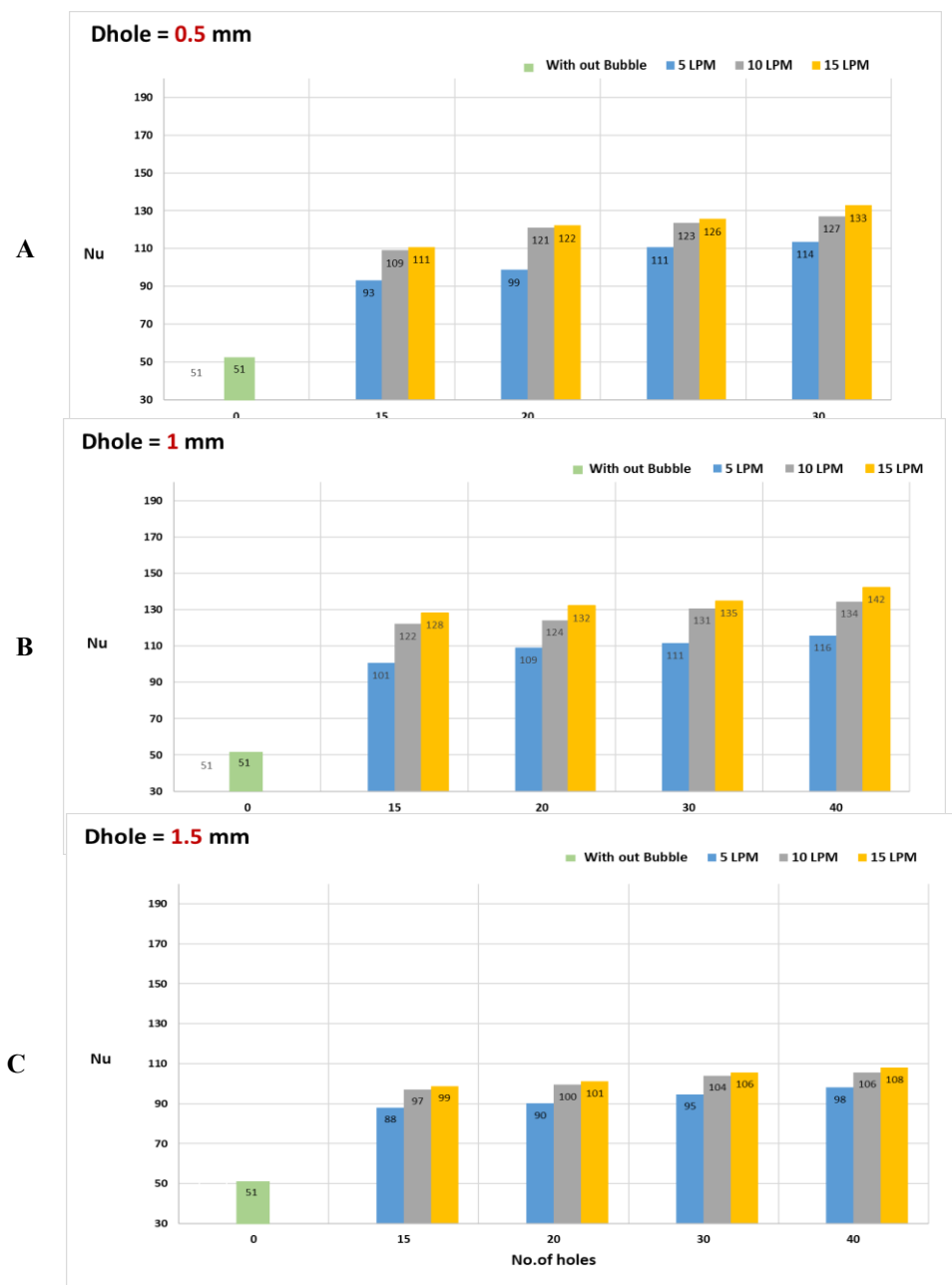
The turbulence induced by bubbles disrupts the thermal boundary layer, enhancing convective heat transfer. Higher bubble velocities correlate with faster thermal equilibrium attainment, validating the efficiency improvements quantified in Table 3. This visualization demonstrates the relationship between air float charge and warmth switch coefficient, which is important for validating the experimental findings on thermal enhancement.



**Figure 3:** Temporal Variation of Water Temperature with Time at variable flow rate and diameters

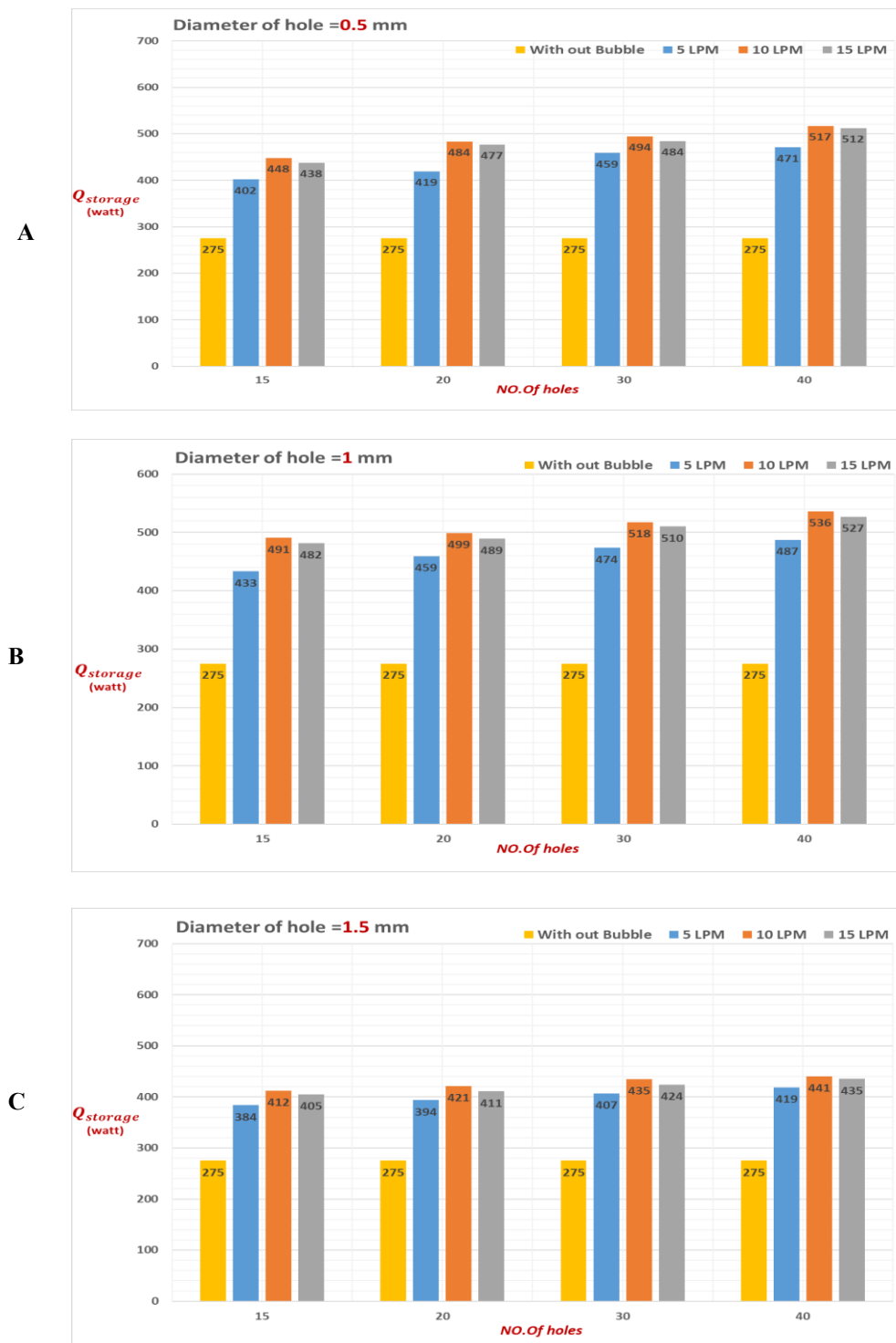
### 3.2 Figures and Visualizations

To provide a more comprehensive understanding of the results, the following Figures. (2,3,4) were created. Figures 4 shows an almost the increasing in the Nusselt number with number of bubble at variable air flow rate .



**Figure 4:** The relation between Nu and No. of holes at variable air flow rate and diameters

The schematic of Figure 5 illustrates how air bubbles disrupt the thermal boundary layer, generating localized turbulence around the conical coil. This turbulence enhances fluid dynamics and promotes uniform heat transfer across the coil's surface.



**Figure 5:** The water heat storage at variable flow rate and diameters

### 3.3 Impact of Air Bubbles on the Thermal Boundary Layer

The introduction of air bubbles into the fluid medium surrounding the conical coil efficaciously disrupts the thermal boundary layer, serving as the number one mechanism for en-

hancing the warmness switch. At better air glide quotes, the air bubbles generate localized turbulence and beautify fluid circulate near the coil's surface, extensively lowering thermal resistance. This advanced interaction facilitates greater green heat dissipation into the surrounding water, as the disrupted boundary layer allows for extra thermal trade. These effects no longer best validate findings from previous research however, they additionally spotlight the wonderful advantages of the conical coil's tapered geometry, which guarantees a greater uniform and effective distribution of bubbles in comparison to conventional straight or helical coils ( Khdhair & ZAlmakhyoul, 2025).

#### **4 Discussion**

The performance upgrades found in this take a look at exhibit the high-quality capacity of the conical coil layout while paired with bubble injection. For instance, Smith *et al.*, (2018): Reported a 35% enhancement in the warmness switch overall performance with the use of a helical coil with bubble injection. However, the overall performance becomes limited utilizing choppy bubble distribution, leading to localized inefficiencies in warmth switch costs. Current Study: In contrast, this examine performed up to a 50% development in heat switch efficiency, largely attributed to the conical geometry's capability to sell constant bubble interaction throughout the coil surface. The tapered design minimizes regions of stagnation and guarantees a more homogeneous disruption of the thermal boundary layer. The findings in reality illustrate the conical coil's superiority in utilizing bubble-prompted turbulence to optimize thermal performance, supplying a compelling case for its software in situations requiring compact and particularly green heat exchange solutions.

While the consequences of this study display clear enhancements in heat switches, certain obstacles have been identified; Bubble Size Variation: Non-uniformity in bubble generation because of diffuser inconsistencies can also have introduced variations in turbulence depth at lower flow fees. This is probably to have affected the heat switch fee under positive situations; Measurement Accuracy: Minor uncertainties in surface temperature readings, springing up from thermocouple obstacles, may also have slightly influenced the calculated warmness switch coefficients.

At low flow rates (<3 L/min), bubble size variability ( $\pm 0.2$  mm) produced as much as 8% variation in heat transfer consistency as measured by high-speed imaging (Fig. 7), while thermocouple positional uncertainty ( $\pm 1$  mm) produced approximately ~5% error in  $\Delta T$  measurements.

#### **5 Conclusion**

This study demonstrated that air bubble injection enhanced heat transfer performance in a conical coil evaporator by as much as 222% of Nusselt number compared to its baseline operation. The coiling of the geometry allowed for an even distribution of bubbles throughout the length of the tube, leading to maximal turbulence development and disruption of thermal boundary layers. Overall, these results demonstrated that conical coils are superior to standard

helical or straight-tube heat exchangers in bubble-injection systems. The technology can be scaled, is relatively inexpensive, and can be applied to thermal energy systems as an influx of power, thermal energy storage integration, available in the industrial space. Future work should evaluate methods of creating standard bubbles and understanding how to maximize efficiency in multi-phase flow systems.

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