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Experimental and Computational Investigation of Heat Transfer and Fluid Dynamics in Shell-and-Tube Heat Exchangers with Helically Dimpled Tubes

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ABSTRACT

This study investigates the enhancement of heat transfer rates and fluid flow properties in a shell-and-tube heat exchanger using helically dimpled tubes, aiming to improve thermal performance over traditional designs. Computational fluid dynamics (CFD) simulations were performed with hot water mass flow rates of 0.03-0.15 kg/s, a hot water inlet temperature of 50℃, and a cold water inlet temperature of 22℃. The helically dimpled tube design demonstrated superior performance, reducing the hot water exit temperature by up to 6.4% at higher flow rates and achieving a 3℃ lower exit temperature at 0.15 kg/s compared to smooth tubes. Experimental validation, using a custom-built test rig, showed temperature and pressure measurements closely matching simulation results, with deviations within 10%. While the dimpled tubes achieved improved heat transfer, they also exhibited a 26.2% higher pressure drop, highlighting a trade-off between efficiency and hydraulic resistance. This study underscores the potential of helically dimpled tubes in optimizing heat exchanger performance for industrial applications, contributing to energy efficiency and sustainability.

1. INTRODUCTION

1.1 Background overview

Heat exchangers are extremely important components that are heavily used across various industrial sectors [1-4]. These sectors include, but not limited to, the following: power generation, chemical processing, HVAC (heating, ventilating, and air conditioning), and refrigeration. Essentially, heat exchangers facilitate the transfer of heat between two or more fluids which makes them crucial for the general optimization of energy use and the enhancement of a selected system performance [5-7]. Figure 1 elaborates on the design and construction classification of heat exchangers.

The functionality of heat exchangers hinges on the principles of thermodynamics and fluid mechanics [8]. By allowing heat to pass from a hotter to a cooler fluid, heat exchanges efficiently manage energy within systems through the minimizing of energy losses and overall improved efficiency procedures. The design and operational effectiveness of heat exchangers directly impact their performance that in turn influences some factors such as energy consumption, operational costs, and environmental impact. There are several types of heat exchangers, namely shell-and-tube, plate, and finned tube, each serve a distinct application and chosen based on factors like temperature ranges, pressure levels, and fluid properties [9]. The choice of a particular type of heat exchanger and its design considerations are critical for achieving desired heat transfer rates while maintaining pressure drop and material compatibility within acceptable limits. The importance of heat exchangers is being recognized more and more as industries press for improvement in energy efficiency and process optimization. Heat exchanger design innovations cater to demands for enhanced energy efficiency to meet the sustainability goal of reducing carbon emissions and enhancing the green credentials of industrial operations.

1.2 Fundamentals in heat exchanger design and heat transfer enhancement

Heat exchangers are classified by their flow arrangements—counterflow, parallel flow, and crossflow—each affecting thermal efficiency and industrial applicability. Counterflow maximizes the temperature gradient for higher efficiency, while parallel flow leads to quicker equilibrium and lower efficiency, and crossflow offers a middle ground, ideal for space-constrained applications. Common types include shell-and-tube, plate, and double-piped exchangers, with shell-and-tube being the most widely used due to its adaptability and potential for enhancements like dimples. Improving heat transfer efficiency involves surface modifications such as ribbing, corrugation, and dimpling to create turbulence, along with material advancements using high-conductivity composites like graphene or copper and phase change materials (PCMs) for thermal stabilization. Optimized flow arrangements, particularly counterflow, enhance efficiency by maintaining strong temperature gradients, while nanofluids improve thermal conductivity with minimal impact on fluid dynamics. This thesis focuses on helically dimpled tubes in shell-and-tube exchangers, examining their potential to enhance thermal performance through increased surface area and turbulence. Figure 2 summarizes these techniques in enhancement to bring out the diversity in usage and benefits.

1.3 Significance and introduced novelties

In enhancing heat transfer in such industrial systems, the energy consumption will be reduced, operational costs will be minimized, and environmental degradation will be reduced. The emerging potentials of heat exchange technologies address global concerns in terms of sustainability and increased call towards stringent environmental regulations. A practical solution to the problem of effective heat transfer mechanisms reduces energy consumption since it ensures there is effective thermal energy exchange with minimal loss; this particular factor is valuable in systems where heat recovery reduces energy requirements, such as in power plants. Whereas innovations like dimpled tubes in shell-and-tube exchangers-this paper's focus-disturb laminar flow to introduce turbulence, therefore enhancing heat transfer by breaking up thermal boundary layers [10]. Computational modeling and experimental methods have rapidly gained pace for engineers to iteratively refine these designs, setting new benchmarks in thermal efficiency. This study aims at contributing to solutions for the current energy and environmental challenges by exploring potential solutions that could result from the use of helically dimpled tubes when optimizing heat exchanger performance. The primary aim of this study is to enhance heat transfer and fluid flow properties in a shell-and-tube heat exchanger using a helically dimpled tube. The study's novelty lies in the following objectives:

1. Investigating the effects of mass flow rate variations on heat transfer efficiency and pressure drop by comparing dimpled and non-dimpled tubes.
2. Conducting computational simulations in ANSYS Fluent to model heat transfer and fluid flow for smooth vs. dimpled tubes under varied boundary conditions.
3. Validating simulation results through experimental tests on a fabricated setup, ensuring alignment with real-world conditions.

This paper is organized into six sections: The introduction provides an overview, aim, and objectives. The literature review examines recent advancements in heat exchangers with a focus on dimpled tubes for heat transfer enhancement. The Theoretical Approach outlines ANSYS simulations of heat transfer and flow dynamics. Section 4 describes the experimental work of the setup and procedures for validating simulations. The results and discussion are in section 5 where it presents and analyzes findings, while conclusions and recommendations summarize key insights and suggest future research directions in section 6.

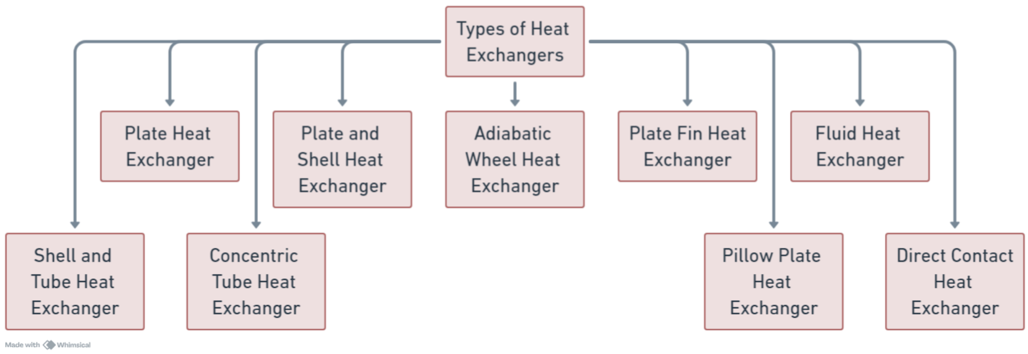


Figure 1. Typical heat exchangers design/construction classification

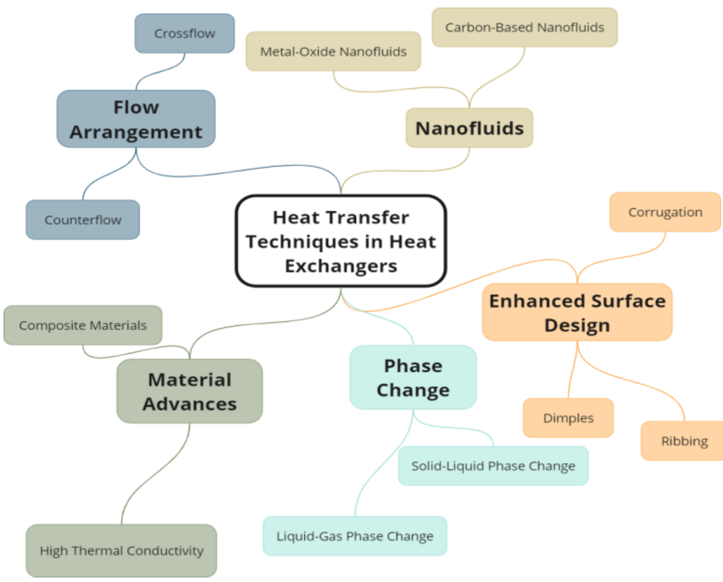


Figure 2. Heat transfer enhancement methodologies in heat exchangers

2. LITERATURE REVIEW

2.1 Recent state-of-the-art reviews

The dynamic evolution of heat exchanger technologies continues to attract great academic and industrial interest, mainly due to the serious implications for energy efficiency and environmental sustainability. A critical review of recent literature highlights innovative designs and applications and also reveals a variety of enhancements that appear poised to redefine the operational standards of these systems. This section provides a detailed review of state-of-the-art surveys in the diverse advancements of heat exchanger technology. In 2021, Rashidi et al. [11] provided an in-depth review of helix-shaped geothermal heat exchangers with respect to land-use efficiency against traditional straight configurations. Their results further emphasized the advantages that the helical design brings by including simpler assembly and higher coil density, which could help improve heat extraction from the ground. Their review showed that much work has currently been done on the optimization of these systems' thermal performance, while not much attention is being paid to the economic side—specifically, regarding their installation costs. Much more focus has been placed in the calculation of pressure drop through HEs in various helical tubes configurations, as shown in Figure 3.

Table 1 presents key survey articles discussed in this section with a brief overview, providing a succinct summary that facilitates comparisons and highlights advances and challenges in heat exchanger technologies. By consolidating these insights, the comparison and summary establish a valuable reference for understanding the current landscape. The table identifies potential areas for further research, or addresses existing gaps.

2.2 Recent state-of-the-art research works

This subsection provides details on the very most recent theoretical and experimental works that have considerably moved heat exchanger technology. The examples reported outline the diversity of work related to the design of heat exchangers, from new geometries and surface treatments like dimples and helical coils to the use of state-of-the-art simulation techniques. The next sections present a brief overview of major findings reported in some research articles. It focuses on the results and demonstrates various methods of performance improvement in a heat exchanger.

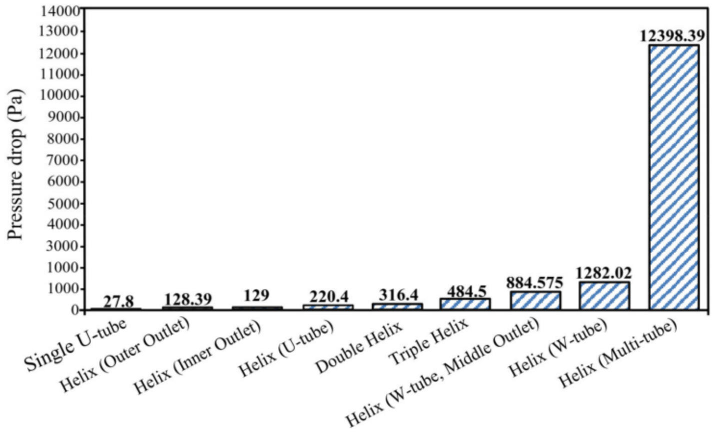


Figure 3. Pressure drop estimations of different helical tubes HEs [11]

Table 1. Summary of the previously discussed review articles

Ref.	Study Focus	Key Findings
[11]	Helical-shaped geothermal heat exchangers	Highlighted the compact design and efficient heat extraction; noted a lack of focus on installation costs.
[12]	Ground heat exchanger parameters	Identified critical parameters affecting geothermal pump performance such as inlet temperature and fluid velocity.
[13]	Use of nanofluids in heat exchangers	Found that nanofluids enhance thermal conductivity but increase viscosity, affecting pumping power.
[14]	Performance of ground heat exchangers	Emphasized the importance of geometric configurations and materials in improving performance.
[15]	Computational methods in compact heat exchangers	Discussed the capabilities and limitations of various computational approaches.
[16]	Impact of structural parameters on heat exchangers	Demonstrated that fins and vortex generators significantly enhance heat transfer efficiency.
[17]	Enhancements in plate heat exchangers	Showed optimal geometrical parameters that maximize heat transfer while conserving energy.
[18]	PCM-based heat exchangers for energy storage	Reviewed the impact of design and operational parameters on PCM heat exchangers' efficiency.
[19]	Backfill materials in ground heat exchangers	Analyzed conventional and modern backfill materials, highlighting their effects on performance.
[20]	Advancements in helical baffles	Noted superior performance of helical baffles over segmental types in reducing dead zones and enhancing heat transfer
[21]	Heat transfer enhancements in shell and tube HEs	Scored the best methodologies in terms of better heat transfer approaches, specifically on the shell and tube Heat Exchangers

2.2.1 Numerical simulation works

Zheng et al. [22] conducted numerical simulations on enhanced tubes with crossed helical dimples and observed a significant increase in heat transfer performance. The study explored various geometrical parameters, noting that deeper dimples and shorter spiral pitches led to higher heat transfer enhancements and friction factors. At the highest Reynolds number tested, the performance evaluation criteria peaked at 2.25, indicating substantial gains over smooth tubes. In another piece of research, Mehrjardi et al. [23] conducted a numerical simulation-based investigation on elliptical dimples over a shell-and-tube heat exchanger, as shown in Figure 2. It is discovered that an increase of 40.6% in heat capacity with elliptical dimples opens huge possible avenues for downsizing and lightweighting of the heat exchanger in industrial applications. Kaood et al. [24] examined the thermal-hydraulic characteristics of turbulent flow in conical tubes with dimples using numerical methods. Their analysis highlighted that conical tubes with dimples enhanced heat transfer performance considerably, with a performance evaluation criteria increase of 29.54% compared to smooth tubes. This design was especially effective at lower Reynolds numbers, enhancing energy efficiency and reducing potential CO_2 emissions. The mesh generation for the conical dimpled tube with a diameter ratio of 3 is illustrated in Figure 4.

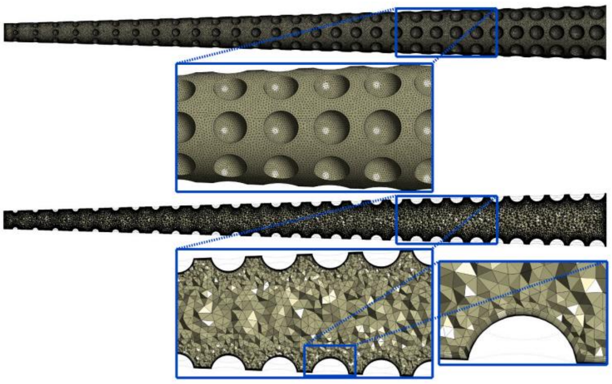


Figure 4. Comprehensive and cross-sectional mesh diagrams of a conical dimpled tube with a diameter ratio of 3 [24]

A study by Xie et al. [25] presented the performance of a tube with helical dimples. It is shown in this numerical analysis that helical dimples can significantly enhance the Nusselt number and raise thermal performance up to 270% higher compared to that of a plain tube. Accordingly, as shown by the results, the helical dimples are able to create very strong vortex flow, which finally enhances the heat transfer efficiency. Zheng et al. [26] conducted numerical simulations to assess the impact of dimples in helically coiled mini-tubes. The study demonstrated that dimples increased the Nusselt number significantly, with the highest increase reaching over double that of smooth tubes. This enhancement was attributed to the dimples' ability to disrupt flow and increase turbulence, thereby improving heat transfer. The numerical study by Miansari et al. [27] on the effect of grooves in helically grooved shell and coil tube heat exchangers confirmed that adding grooves to both the inner and outer walls of the annulus shell improved thermal performance by up to 20%, particularly at lower flow rates and with higher groove depths. This enhancement was attributed to improved fluid mixing and an increased thermal boundary layer facilitated by the grooves. Zhang et al. [28] performed numerical analyses on heat transfer and flow characteristics inside helically coiled mini-tubes equipped with cross-combined ellipsoidal dimples. Their study found that these dimples increased the heat transfer index by 24.8% on average compared to traditional single dimple tubes. The enhanced performance was attributed to significant changes in temperature distribution and flow dynamics induced by the dimples, leading to improved thermal and hydraulic performances. Zhang et al. [28] carried out some numerical analyses for heat transfer and flow characteristics inside helically coiled mini-tubes with cross-combined ellipsoidal dimples. Overall, their results showed that the heat transfer index is largely increased by 24.8% on average when in comparison with traditional single dimple tubes, which is attributed to the fact that the great change in temperature distribution and flow dynamics by the dimple is favorable for enhancing both thermal and hydraulic performance.

2.2.2 Experimental works

Solanki and Kumar [29] presented experimental findings on the condensation heat transfer characteristics of R-600a in smooth and dimpled helical coiled tubes. Their findings indicated that the dimpled tubes significantly outperformed the smooth ones, with the developed correlations accurately predicting the condensation heat transfer coefficients within a 20% margin. Heeraman et al. [30] have conducted an experimental study on the thermal performance of a double pipe heat exchanger with inserted twisted tapes in a dimple configuration. In this regard, it was found that the use of such inserts significantly enhances the Nusselt number at higher Reynolds numbers. Therefore, compared with a plain tube, considering dimple inserts would increase the heat transfer drastically with a change of friction factor. The same proved the efficiency of using twisted tapes with a dimple configuration in heat exchangers. The configuration is shown in Figure 5 which is adapted from their experimental study.

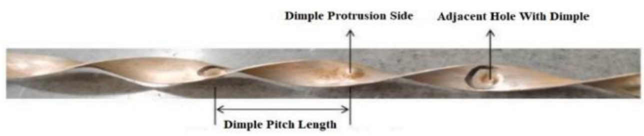


Figure 5. Helical smooth and dimpled configurations [30]

Singh and Kumar [31] investigated the effects of dimpled twisted tape inserts in a double pipe heat exchanger. Their experimental study revealed that the presence of dimples on twisted tapes substantially increased the Nusselt number, achieving a peak of 113.68 at a Reynolds number of 14,000. The friction factor also increased with the size and depth of the dimples, demonstrating that while heat transfer is enhanced, there is a corresponding rise in hydraulic resistance. Dhumal and Havaldar [32] investigated the thermal performance of double-tube heat exchangers using twisted and helical tapes. Their experimental data showed immense improvement in heat transfer, with the Nusselt number increasing by up to 315% compared to a plain tube. The empirical relationships provided in the study further validated their approach by accurately predicting the relationship between the Nusselt number and the friction factor. Nascimento and Garcia [33] studied the influence of shallow square dimples on thermal performance augmentation for compact heat exchangers under different vehicular applications. It is reported that these dimples increased the factor of heat transfer augmentation tremendously in the range of 1.37 to 2.28 according to their experimental tests. The work performed a series of calorimeter tests thus corroborating the performance enhancement with strong support of the use of dimpled surface in order to enhance heat transfer efficiency.

2.2.3 Numerical simulation and experimental works

Ali and Shehab [34] investigated the convection heat transfer in a double-pipe heat exchanger using a dimpled tube. Their numerical study showed that staggered dimple arrangements significantly improved heat transfer, with the thermal performance factor reaching as high as 9.07 for certain geometrical configurations, experimentally proving the potential of dimpled surfaces for enhanced hydrothermal performance. Mehrjardi et al. [35] investigated the performance of a shell-and-tube heat exchanger with augmented dimpled tubes. Their experimental work makes use of the P-NTU thermal analysis method with a suitably chosen turbulence model in developing predictive correlations of heat transfer efficiencies at surface conditions with and without dimples. They proved these correlations through detailed simulations including combined effects of dimple shapes under different baffle configurations and inlet mass flow rates. In that respect, they demonstrated the possibility for an elliptical and teardrop-shaped dimple, using a correlation-based approach, to enhance the performance evaluation criteria by up to 51.5% depending on the baffle arrangement. This huge improvement demonstrates the potential for substantially improved efficiency in heat exchangers fitted with dimpled tubes. Kumar et al. [36] conducted both numerical and experimental studies on the effects of dimpled ribs in heat exchanger tubes. They used the renormalization k-ε model in simulations with ANSYS 16.0 (Fluent) to model fluid and thermal dynamics within the tubes, aiming to better understand the turbulence effects induced by the dimples. The experimental validation closely matched the numerical data, within a ±10% error band, confirming the reliability of the simulation results. The study found that dimpled ribs enhanced heat transfer performance by up to 3.18 times compared to smooth tubes, especially when the ribs were closely spaced. This study demonstrated that such geometrical modifications could significantly improve both heat transfer and fluid flow behaviors within the tubes.

Song et al. [37] have investigated the application of a new configuration of fin with an ellipsoidal dimple-protrusion on a circle-tube-fin heat exchanger. For these investigators, according to their numerical results, such dimple-protrusions increased the heat transfer rate up to 29.01% and enhanced thermal performance factor by up to 16.1% with respect to the traditional designs. This basically occurred because it causes an enhanced secondary flow due to these dimple-protrusions. Maithani and Kumar [38] developed correlations for the Nusselt number and friction factor in heat exchanger tubes with dimpled surfaces. Their experimental study showed that specific geometrical parameters, such as the spacing and depth of the dimples, significantly enhanced heat transfer and thermal hydraulic performance by over four times compared to smooth tubes. These results were crucial in developing reliable predictive tools for designing more efficient heat exchangers. Al-Obaidi [39] investigated the impact of various dimple geometrical configurations in conjunction with internal twisted-tape inserts in circular tubes. The numerical results demonstrated that combining dimples with twisted tapes significantly enhanced the flow field dynamics and heat transfer characteristics. Specifically, the study showed that this combination led to increases in turbulence, which in turn enhanced the overall heat transfer, with a peak performance evaluation factor of 1.6 under optimal conditions.

Malapur et al. [40] performed a numerical study on the influence of internal dimples over heat gain in tube heat exchangers in the year 2023. They observed that the dimples enhance the heat transfer coefficient considerably compared to the plain tubes, but at the same time, they increase pressure drop. Their study showed that these dimples performed optimally at lower Reynolds numbers, in which most of the rise of the friction factor was offset by gains in heat transfer efficiency. Soltani et al. [41] explored the augmentation of heat transfer in a double-pipe heat exchanger using dimpled twisted tape inserts. Experimentally, they observed that these inserts substantially increased the Nusselt number and the friction factor, indicating enhanced thermal performance. The highest thermal performance factor recorded was 1.24, achieved with specific tape geometries, demonstrating the effective use of dimpled inserts in improving heat exchanger efficiency. The configuration of the double-pipe heat exchanger is equipped with intermittent louvered turbulence tubes and dimples, Dagdevir et al. [42] investigated the performance of a tube heat exchanger enhanced with trapezoidal dimples. Their numerical simulation revealed that the optimal configuration, featuring larger dimple diameters and aggressive trapezoid angles, increased the Nusselt number by up to 2.1 times compared to smooth tubes. This configuration also maintained a relatively low friction factor, making it an effective design choice for enhancing heat transfer without significantly increasing energy costs.

2.2.4 Summary of research articles

Table 2 summarizes all research articles explicitly accounted for above. This table organizes the entries by type of tube or pipe, the type of specific enhancement, the primary metric measured within the study, and a short highlight of the main findings. This results in a quite ready cross-reference between these different enhancements and how they impact heat exchanger performance under the varied conditions and configurations described above.

2.3 Scope of the present work

This study aims to enhance heat exchanger efficiency by exploring the design and performance impacts of helically dimpled tubes to address the gap between conventional and advanced heat exchanger designs. The simulation phase of this study will involve running numerous CFD simulations using ANSYS Fluent. Key parameters include hot water mass flow rates of 0.03, 0.06, 0.09, 0.12, and 0.15 kg/s, along with a hot water inlet temperature of 50℃ and a cold water inlet temperature of 22℃. These simulations aim to assess the effects of these parameters on heat transfer efficiency and pressure drop in a heat exchanger with helically dimpled tubes. The heat exchanger has a tube length of 600 mm, a coil diameter of 75 mm, a shell diameter of 150 mm, and a pipe diameter of 12.5 mm. The pitch is 50 mm, with 12 coils per exchanger, and a curvature ratio of 0.166. The dimples are spherical, staggered, with a diameter of 3.5 mm, a depth of 1.75 mm, and spaced 10 mm apart at a 90-degree angle. An experimental test rig is currently being designed to further validate these computational models and to probe the practical applications of this research based on the data supplied by these simulations. This proposed test setup replicates dimensionality and configurations that will be used in the simulations in order to project consistency and relevance. The experiments involve setting the mass flow rates of the fluids to their desired values and measuring some key performance metrics like heat transfer rates and pressure drops. Such experiments help in obtaining empirical data so that the results of the simulation could be validated and the models fine-tuned based on real-world observations. The integrated approach has enhanced the reliability of research results and produced practical insights directly useful for the design and operation of more efficient heat exchangers in industrial applications.

Table 2. Summary on the important discussed research articles

Ref.	Tube/Pipe Type	Enhancement (Dimple) Type	Key Findings
[22]	Cylindrical	Crossed helical dimples	Increased heat transfer by 150-225%
[23]	Shell and tube	Elliptical dimples	40.6% increase in heat capacity
[29]	Helical coiled	Dimpled	Higher heat transfer coefficient compared to smooth tubes
[24]	Conical	Dimples	29.54% enhancement in PEC
[34]	Double-pipe	Dimples	Staggered dimples improve heat transfer by 50%
[30]	Double pipe	Dimples with twisted tape	Increased Nusselt number significantly
[31]	Double pipe	Dimpled twisted tape	High Nusselt number, increased friction factor
[25]	Helical dimpled	Helical dimples	Enhanced thermal performance by 120-270%
[26]	Helically coiled mini-tubes	Dimples	Dimples significantly increase Nusselt number
[35]	Shell and tube	Dimples	Elliptical and teardrop dimples elevate PEC
[32]	Double tube	Twisted and helical tapes	Nusselt numbers increase by 219%-315%
[36]	Heat exchanger tube	Dimpled ribs	Enhanced heat transfer and fluid flow
[37]	Circle tube-fin	Ellipsoidal dimple-protrusion	Increased heat transfer rate by up to 29.01%
[33]	Flat tubes	Shallow square dimples	Significant increase in heat transfer augmentation
[38]	Heat exchanger tube	Dimpled ribs	4.19 times enhancement in thermal performance
[27]	Helically grooved	Grooves	Improved thermal performance by up to 20%
[39]	Circular tube	Dimples with twisted tape	Enhanced overall heat transfer
[40]	Internally dimpled	Dimples	Enhanced heat transfer coefficient
[28]	Cross-combined ellipsoidal	Dimples	Increased heat transfer index by 24.8%
[41]	Double-pipe	Dimpled twisted tape	Substantial increase in Nusselt number
[42]	Enhanced tube	Trapezoidal dimples	Increased Nusselt number by up to 2.1 times

3. THEORETICAL WORK

3.1 Introduction

Performances of the heat exchangers mean much in many industrial applications and hence continuous development in the technology of transferring heat. Computational simulations will be executed in this part with the aid of ANSYS Fluent for thermal and hydraulic performance evaluation of helically dimpled tube shell-and-tube heat exchanger on account of its potential improvement over conventional geometries concerning both heat transport enhancement and flow resistance. The real value of these simulations lies in determining the quantitative fluid flow and heat transfer behaviors for various configurations and operational conditions that so far have been understood only qualitatively. They also optimize the designs of dimpled tubes for practical applications. The expected outcome is to establish theoretical gains in practice, with a view toward refining design parameters to support the most efficient solution to heat transfer problems in industry.

3.2 Overview of simulation methodologies

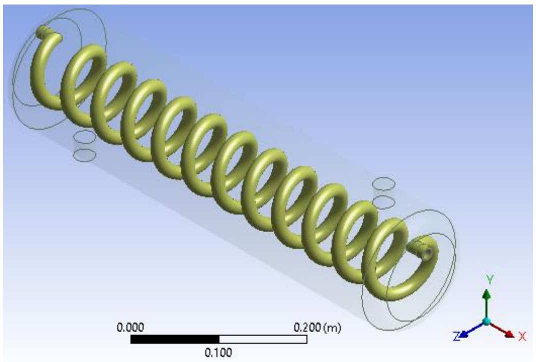
In the pursuit of optimizing heat exchanger performance, the choice of simulation methodology plays a critical role. For this study, FEA serves as the cornerstone of our computational approach [43, 44]. This method that is particularly when implemented via ANSYS fluent software offers a robust platform for simulating complex physical phenomena, which includes the thermal and fluid flow dynamics within heat exchangers equipped with helically dimpled tubes. ANSYS fluent facilitates detailed modeling of physical systems by solving the governing equations of fluid dynamics and heat transfer and this is why it is renowned for its comprehensive simulation capabilities. The software's ability to handle complex geometries and advanced boundary condition settings makes it an ideal tool for this research [45-48]. It supports a variety of solver techniques that are crucial for achieving accurate and reliable results in multiphysics simulations that include coupled thermal-fluid problems. The simulation process in ANSYS fluent involves several key steps that start from the creation of a detailed geometric model of the heat exchanger [15, 49]. The geometry of the helically dimpled tubes requires precise representation in the simulation environment to ensure that all relevant physical phenomena are captured. This is considered to be more complex than standard tube designs. Once the geometry is defined, appropriate material properties must be assigned to different components of the model. These properties include thermal conductivity, density, specific heat capacity, and viscosity, which influence the heat transfer and fluid flow behaviors within the system.

Meshing is the next critical step in preparing for simulation. The mesh must be refined enough to capture the intricate details of the helical dimples while also being computationally manageable. ANSYS fluent provides advanced meshing tools that allow for the creation of finely tuned meshes that conform to the complex surfaces of dimpled tubes [50]. The quality of the mesh directly affects the accuracy and convergence of the simulation results which generally makes this a focal point of the currently presented methodology. After setting up the model with the proper boundary conditions—such as inlet temperature, flow rate, and pressure—simulation parameters are consequently defined. These parameters include the contours of heat distribution after flow occurs, and other operational conditions under which the heat exchanger is expected to perform. The choice of solver settings depends on whether the simulation is steady-state or transient, which is a steady-state in the current thesis. These settings are collectively crucial for the capturing of the dynamic interactions between the heat transfer and fluid flow within the heat exchanger. By integrating these elements—geometry modeling, material property assignment, meshing strategy, and solver configuration—ANSYS fluent provides a comprehensive environment for the prediction of the performance of helically dimpled tube heat exchangers. This methodology supports the fundamental understanding of heat transfer enhancement mechanisms in addition to the fact that it aids in the design and optimization of more efficient heat exchanger systems.

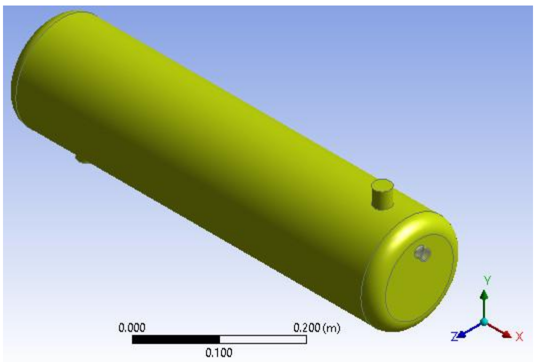
3.3 Modeling and configurations

3.3.1 Physical models of heat exchangers

The geometric modeling of heat exchangers forms the foundation for any computational simulation. For this study, two distinct configurations were modeled: a standard tube HE and a helically dimpled tube within an HE. Both of these configurations are designed with precise dimensions to facilitate comparative analysis of their thermal and fluid dynamics performance. The basic geometry of a traditional tube heat exchanger is characterized by simpler, smooth surfaces without any modifications. Table 3 details these dimensions of the traditional HE. The dimensions for this model include a total length (L) of 600 mm, coil diameter (Dcoil) of 75 mm, shell diameter (Dshell) of 150 mm, and pipe diameter (Dpipe) of 12.5 mm. The pitch (P) is set at four times the diameter of the pipe, equating to 50 mm, and the number of coils (N) is 12, leading to a curvature ratio (Dpipe/Dcoil) of 0.166. This configuration is collectively depicted in Figure 6.



(a)



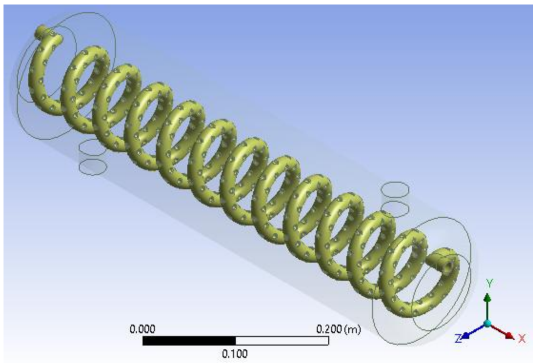
(b)

Figure 6. Traditional shell-and-tube of helical coils: (a) Helical copper tube, (b) Shell

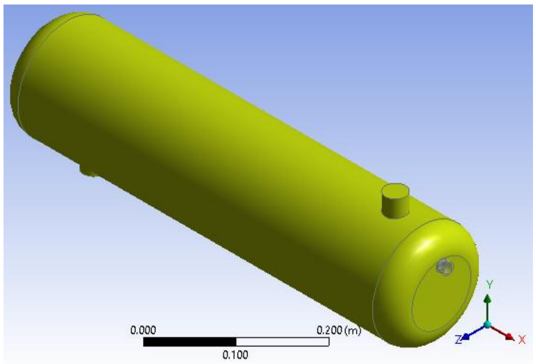
Table 3. Heat exchanger dimensional properties

Parameter	Value
Length (L)	600 mm
Coil Diameter (Dcoil)	150 mm
Shell Diameter (Dshell)	250 mm
Pipe Diameter (Dpipe)	12.5 mm
Pitch (P)	50 mm
Number of Coils (N)	12
Curvature Ratio	0.166

This configuration introduces spherical dimples staggered along the tube surface to enhance the heat transfer capabilities by disrupting the flow pattern and increasing surface area. The helical dimple properties are in Table 4 and are meticulously set with a diameter of 3.5 mm, depth of 1.75 mm, dimple spacing of 10 mm, and an angle of 90 degrees between each dimple. This modified design aims to intensify the turbulence within the flow, thereby potentially guarantees an increment in the heat transfer rate. The geometric representation of this configuration is shown in Figure 7, in addition to the dimples. Figure 8 illustrates the dimples in a zoomed in configuration.



(a)



(b)

Figure 7. Helically-dimpled shell-and-tube HE of helical coils: (a) Helical copper tube, (b) Shell

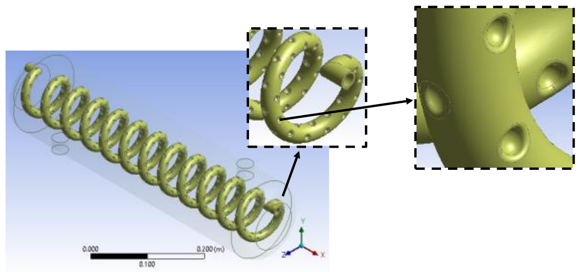


Figure 8. Dimples' configuration

Table 4. Dimple properties

Parameter	Value
Diameter	3.5 mm
Depth	1.15 mm
Spacing	15 mm
Angle	90 degrees

3.3.2 Effect of dimples geometry

The geometric configuration of dimples on the inner tube of the heat exchanger significantly influences the heat transfer performance. The Table 5 below summarizes the effects of different dimple parameters, such as diameter, depth, spacing, and distribution angle, on the overall performance of heat transfer.

3.4 The assumptions and governing equations

Fluid Flow Fluent was used for the ANSYS simulation with 1000 interactions for convergence. The governing equations are a set of partial differential equations for continuity, momentum, and energy equations, as shown below:

Continuity equation:

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

Momentum equation:

u-**momentum** (x-direction):

$$\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right] \tag{2}$$

v-momentum (y-direction):

$$\frac{\partial(\rho uv)}{\partial x}+\frac{0\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y}+\mu\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right]+\rho g \tag{3}$$

w-momentum (z-direction):

$$\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial p}{\partial z}+\mu\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right] \tag{4}$$

Energy equation:

$$\frac{\partial(\rho uT)}{\partial x}+\frac{\partial(\rho vT)}{\partial y}+\frac{\partial(\rho wT)}{\partial z}=\Gamma_{eff}\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right] \tag{5}$$

$$\Gamma_{eff}=\frac{\mu_{eff}}{Pr_{eff}} \tag{6}$$

where, Γ_{eff} is the effective diffusion coefficient, μ_{eff} is the effective viscosity coefficient, and Pr_{eff} : is the effective Prandtl number.

3.5 Mathematical model

The standard k–ε model uses the following transport equations for k and ε:

Turbulence kinetic energy (k):

$$\frac{\partial(\rho uk)}{\partial x}+\frac{\partial(\rho vk)}{\partial y}+\frac{\partial(\rho wk)}{\partial z} = \frac{\partial}{\partial x}\left(\frac{\mu_t}{Pr_k}\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\mu_t}{Pr_k}\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\mu_t}{Pr_k}\frac{\partial k}{\partial z}\right)+P_k+G_k-\rho\varepsilon \tag{7}$$

Dissipation rate (ε):

$$\frac{\partial(\rho u\varepsilon)}{\partial x}+\frac{\partial(\rho v\varepsilon)}{\partial y}+\frac{\partial(\rho w\varepsilon)}{\partial z} = \frac{\partial}{\partial x}\left(\frac{\mu_t}{Pr_\varepsilon}\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\mu_t}{Pr_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\mu_t}{Pr_\varepsilon}\frac{\partial \varepsilon}{\partial z}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(P_k+G_k)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{8}$$

where:

Pr_k: is the turbulent Prandtl number for k (empirical constant).

Pr_ε: is the turbulent Prandtl number for ε (empirical constant).

G_k: is the kinetic energy generation by buoyancy.

$$P_k=\mu_t\left(2\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right]+\left(\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}+\frac{\partial u}{\partial z}\right)^2\right) \tag{9}$$

$$G_k=\frac{\mu_t}{Pr_t}g\beta\frac{\partial T}{\partial y} \tag{10}$$

Table 5. Dimple properties for the optimal choice

Parameter	Variation Tested	Optimal Value	Effect on Heat Transfer Performance
Dimple Diameter	Various (e.g., 2 mm to 5 mm)	3.5 mm	Larger diameters increase surface area and turbulence but may raise pressure drop. A diameter of 3.5 mm provides the best balance between improved heat transfer and acceptable pressure loss.
Dimple Depth	Various (e.g., 0.5 mm to 2 mm)	1.15 mm	Deeper dimples enhance boundary layer disruption, improving convective heat transfer. Excessive depth, however, results in higher pressure losses. The chosen depth of 1.15 mm ensures maximum heat transfer without severe penalties in flow resistance.
Dimple Spacing	Various (e.g., 5 mm to 20 mm)	15 mm	Closer spacing intensifies turbulence but increases pressure drop, while wider spacing reduces turbulence. A 15 mm spacing ensures optimal interaction between dimples, promoting turbulence without exc essive flow resistance.
Dimple Distribution	Staggered vs. Inline	Staggered	Staggered distribution promotes more effective interaction between dimple-induced disturbances, leading to better turbulence generation and enhanced heat transfer.
Distribution Angle	90° vs. 120°	90°	A 90-degree distribution angle results in higher heat transfer rates and more uniform turbulence compared to a 120-degree angle, which produced moderate heat transfer performance

3.6 Mesh generation and properties

In CFD, the mesh serves as the framework upon which the simulations are built. Proper mesh generation is crucial as it directly influences the accuracy, convergence, and computational efficiency of the simulations. For the current study, the meshing strategy was tailored to accommodate both the normal and helically dimpled tube configurations within the heat exchanger. Here, this subsection discusses the mesh preferences selected, the resulting mesh statistics, and provide a visualization of the meshing applied to both configurations. To ensure that both the standard and dimpled tube configurations were appropriately modeled, specific meshing preferences were applied consistently across both setups. The physics and solver preferences were set to cater specifically to CFD applications with Fluent as the chosen solver, optimizing the interaction dynamics between the fluid flow and the tube surfaces. The choice of linear element order and a patch confirming algorithm was aimed at enhancing the mesh quality around the complex geometries, especially necessary in the case of the dimpled tubes where precision in capturing the dimple contours is critical. The method of tetrahedrons was selected for mesh generation, as detailed in Table 6 below. Tetrahedral meshing is particularly advantageous for complex geometries as it can easily conform to irregular shapes, which is essential for accurately modeling the spherical dimples on the helical tubes. This approach helps in capturing the intricate details of the dimples, which are crucial for studying their impact on fluid flow and heat transfer.

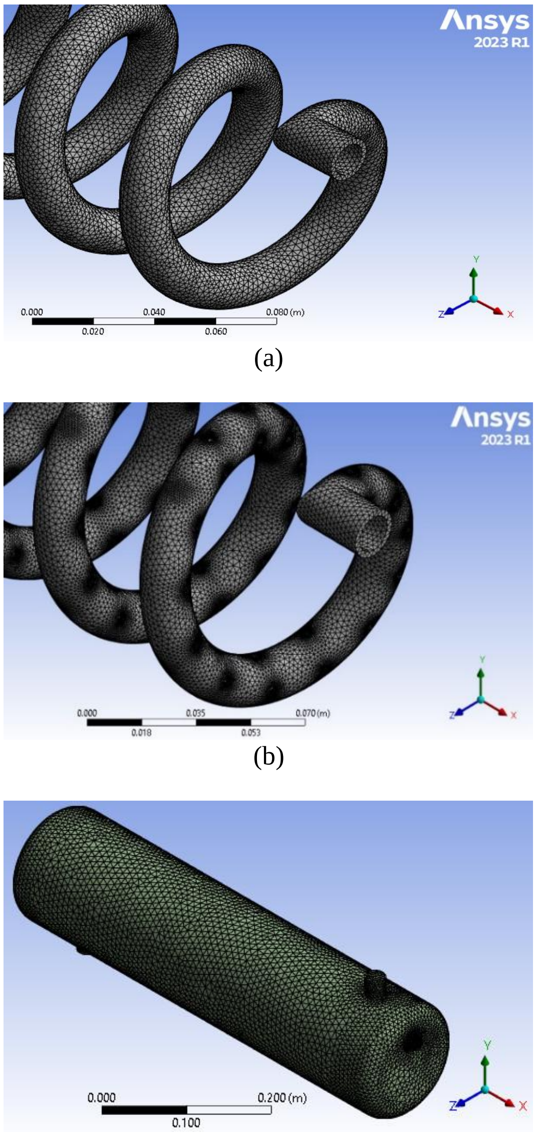
Table 6. Mesh selected preferences and resulted elements

Configuration	Property	Value
Both	Physics Preference	CFD
	Slolver Preference	Fuent
	Element Order	Linear
	Algorithm	Patch Confirming
	Method	Tetrahedrons
Normal	Nodes	332,052
	Elements	1,583,917
Dimpled	Nodes	1,367,135
	Elements	6,757,590

Figure 9 illustrates the mesh generated for both the normal and helically dimpled tube configurations. Figure 9(a) displays the mesh for the tube without dimples, showing a smoother and less dense mesh structure, which is sufficient given the simpler geometry. On the other hand, Figure 9(b) shows the inner tube with the dimple configuration, where a significantly denser mesh is observed. This is essential for capturing the small-scale features and complexities introduced by the dimples, which affect the fluid dynamics within the tube. Finally, the mesh for the outer shell, which is consistent for both cases is depicted in Figure 9(c). The figure demonstrates that the primary focus of mesh refinement was on the inner configurations where the heat transfer enhancements are expected.

3.7 Simulation setup and execution

The setup and execution of the simulations are pivotal steps in leveraging the computational models to derive insightful data on the thermal and flow dynamics within the helically dimpled tube heat exchanger. This section details the simulation parameters, boundary conditions, and specific conditions under which the simulations were executed. Therefore, it ensures that all relevant aspects are defined to mirror the operational characteristics of the heat exchanger realistically. To accurately simulate the operational environment of the heat exchanger, specific boundary conditions were applied at the inlets and outlets of both the hot and cold water flows. The following Table 7 summarizes these parameters by providing a clear framework for the simulation inputs.



(a) (b) (c)

Figure 9. Mesh depiction: (a) Tube without dimples, (b) Inner tube with the dimple configuration, (c) Outer shell mesh for both cases

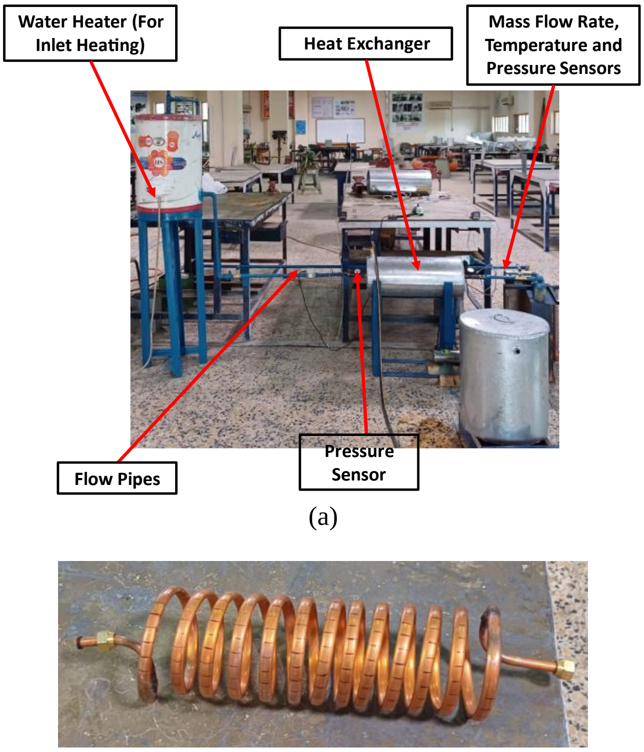
Table 7. Simulation parameters

Parameter	Value
Hot Water Inlet Temperature	50℃
Cold Water Inlet Temperature	22℃
Cold Water Inlet Mass Flow Rate	0.05 kg/s
Hot Water Inlet Mass Flow Rates	0.03, 0.06, 0.09, 0.12, 0.15 kg/s
Exit Conditions	Pressure outlet

These parameters are chosen to represent typical operating conditions for a heat exchanger in an industrial setting. Different mass flow rates for hot water are particularly important for assessing the performance under varying thermal loads, which helps in understanding the heat exchanger's capacity to handle different operating scenarios.

4. EXPERIMENTAL APPROACH

This section presents the experimental validation of the computational analyses, detailing the construction and operation of a custom-built test rig designed to replicate the simulated conditions of a shell-and-tube heat exchanger with helically dimpled tubes. Key components—including water tanks, heater, pump, and the heat exchanger—were assembled to create precise conditions for validation. Integrated sensors measured variables like mass flow rate, temperature, and pressure, enabling comparison with predicted outcomes. The experimental procedure was conducted rigorously to ensure reliable data, providing essential insights that substantiate the theoretical findings on enhanced heat transfer and fluid dynamics.



(a)

(b)

Figure 10. Experimental setup: (a) Test rig, (b) Helical tube

The experimental test rig was meticulously designed and constructed to facilitate precise measurements of heat transfer characteristics in a shell-and-tube heat exchanger equipped with helically dimpled tubes. The fabrication aimed to replicate the conditions simulated in the computational models, ensuring the validity and reliability of the experimental results. Figure 10 provides a detailed view of the water flow methodology within the heat exchanger where Figure 10(a) is the test rig and Figure 10(b) is the helical tube. This close-up look helps in understanding the flow dynamics and it also highlights the paths that hot and cold water take within the system, which is important for the optimization of the experimental setup and ensuring accurate data collection. Moreover, Figure 11 illustrates a schematic of the experimental test procedure by using color coding (blue for cold water and red for hot water) to simplify the understanding of the operational sequence. This schematic is added for the purpose of serving as a quick reference for the setup and operational flow of the experiment. It consequently ensures clarity in the experimental methodology and aiding in troubleshooting and system checks. The assembly of the test rig involved careful consideration of the connectivity and accessibility of each component, with valves and pumps strategically placed to facilitate precise control over the experimental conditions. The test rig's design allows for adjustments and modifications and provides the flexibility needed to explore a range of experimental conditions and configurations.

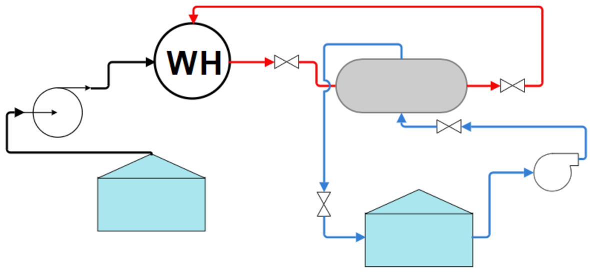


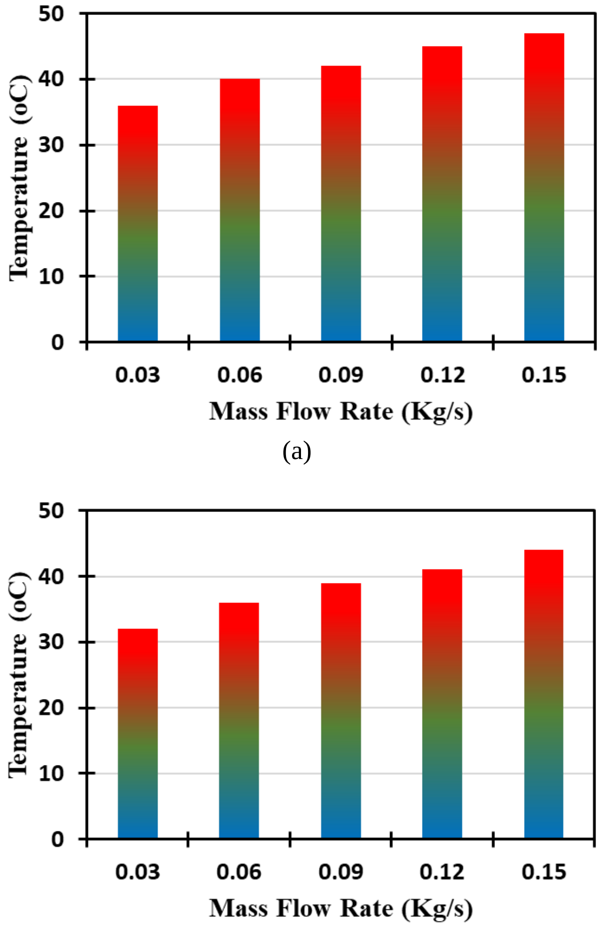
Figure 11. Scheme of the experimental test procedure

5. RESULTS AND DISCUSSION

This section presents and discusses the results from experimental tests and numerical simulations on both normal and helically dimpled tube heat exchangers, focusing on evaluating the helical dimples' impact on heat transfer under varying mass flow rates. The analysis compares temperature change, pressure drop, and overall performance, highlighting key trends and validating computational predictions. The findings provide insights into how the helical dimples improve efficiency by disrupting boundary layers and promoting turbulence. Finally, the section compares experimental and simulation results, offering recommendations for optimizing design and operational parameters for enhanced heat transfer efficiency and reliability.

5.1 Experimental results

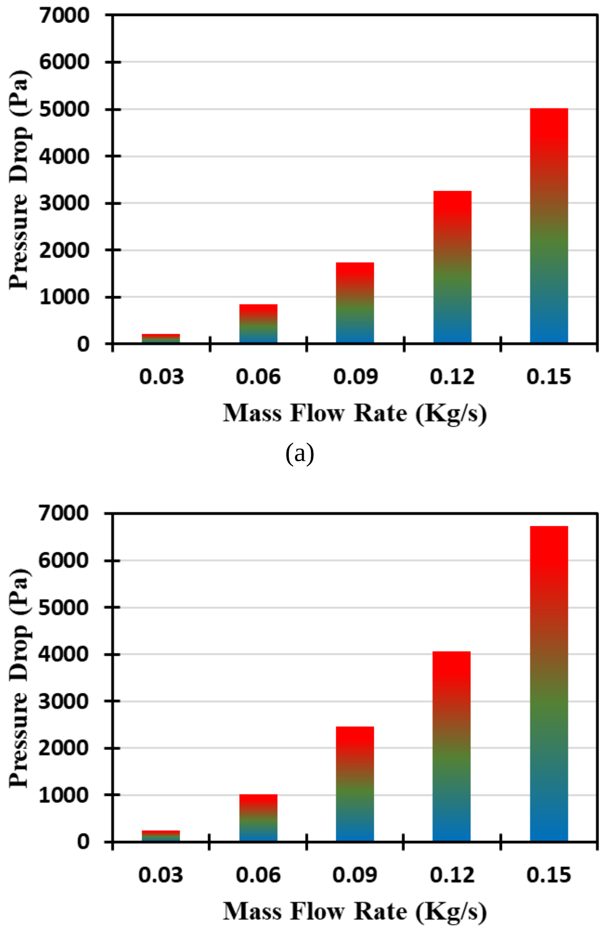
This section delineates the experimental outcomes obtained from the testing of both the traditional and dimple-added helical-tubed heat exchangers. The primary focus here is on the temperature and pressure measurements collected under varying operational conditions, which are crucial for assessing the thermal performance and the efficacy of the helical dimpling enhancement on heat transfer processes. The experimental results concerning temperature changes are critical for understanding the impact of helical dimpling on heat transfer efficiency, as depicted in Figure 12. Figure 12(a) and Figure 12(b) visually show the findings, with clear distinctions in temperature reductions across the range of tested flow rate. The data indicates that at every given mass flow rate, the dimple- From the data, we observe a clear trend: as the mass flow rate increases, so does the exit temperature of the water in both heat exchanger designs. This trend indicates that higher flow rates, while increasing the rate of heat transfer by mass, do not allow sufficient time for the water to fully absorb heat, thus exiting the system at higher temperatures. For example, in the traditional heat exchanger, the exit temperature increases from 36℃ at a flow rate of 0.03 kg/s to 47℃ at 0.15 kg/s. Similarly, in the dimple-added heat exchanger, temperatures increase from 32℃ to 44℃ under the same conditions. The lower temperatures observed in the dimple-added heat exchanger across all flow rates highlight the efficiency of dimples in enhancing heat transfer. The dimples increase the surface area and create turbulent flows that disrupt the boundary layer formation, facilitating higher rates of heat transfer even as flow rates increase. For instance, at a flow rate of 0.15 kg/s, the dimple-added model shows a 3℃ lower exit temperature compared to the traditional model, which is a significant improvement in thermal performance.



(b)

Figure 12. The experimental-based hot exit water temperature bars across the inner tube of the HE under all working condition of variant mass flow rates: (a) Traditional, (b) Dimpled

Next, we analyze the pressure drops recorded during the experimental testing of both the traditional and dimple-added helical-tubed heat exchangers. Pressure drop is an essential parameter for evaluating the hydraulic performance of heat exchangers, as it impacts the pump power requirement and overall system efficiency, as Figure 13 illustrates. The data presented in Figures 13(a) and 13(b) show an expected trend where the pressure drop across the heat exchanger increases with the mass flow rate. This is due to the increased resistance encountered by the flowing fluid, particularly as it navigates through the helical and dimpled tubes. From the traditional heat exchanger data, we see a pressure drop from 211 Pa at a flow rate of 0.03 kg/s to 5012.09 Pa at 0.15 kg/s, indicating a substantial increase as the flow rate rises. Similarly, in the dimple-added heat exchanger, the pressure drop starts at 247.1 Pa at the lowest flow rate and escalates to 6736 Pa at the highest flow rate. Notably, the dimple-added heat exchanger exhibits higher pressure drops at corresponding flow rates compared to the traditional model. For instance, at a flow rate of 0.15 kg/s, the pressure drop in the dimple-added model is approximately 34% higher than in the traditional model. This increase in pressure drop for the dimple-added heat exchanger can be attributed to the enhanced surface roughness and geometric complexity introduced by the dimples. While dimples improve thermal performance by increasing turbulence and surface area for heat transfer, they also add to the hydraulic resistance, thereby elevating the pressure drop.

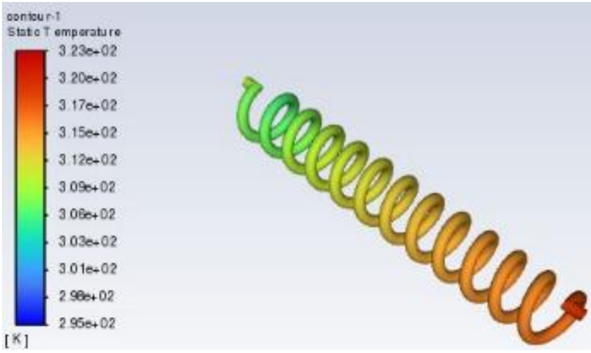


(b)

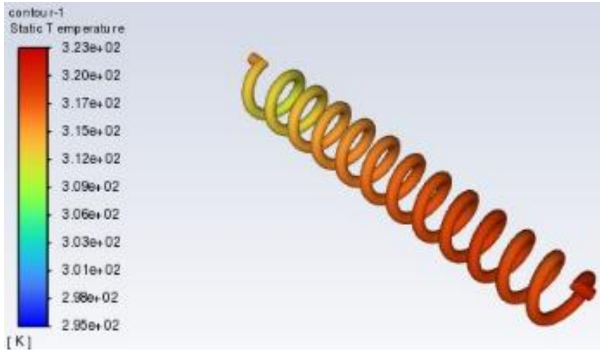
Figure 13. The experimental-based pressure drop bars across the inner tube of the HE under all working condition of variant mass flow rates: (a) Traditional, (b) Dimpled

5.2 Numerical simulation results

This section presents the numerical simulation results of the heat transfer performance for both traditional and dimple-added helical-tubed heat exchangers. The simulations were conducted to evaluate the impact of mass flow rate variations on the hot water exit temperatures under controlled conditions, aiming to complement and compare with the experimental results. The temperature analysis from the numerical simulations offers critical insights into how different configurations of heat exchangers react under various operational conditions. The results are presented in Figures 14, 15 and 16, to provide a comprehensive view of temperature dynamics within these systems. The simulation results demonstrate a clear trend of increasing hot water exit temperatures with increasing mass flow rates for both heat exchanger types. In the traditional model, temperatures gradually rise from 34.9℃ at a flow rate of 0.03 kg/s to 47.7℃ at 0.15 kg/s. This increment highlights the reduced heat transfer efficiency at higher flow rates due to decreased residence time of water within the heat exchanger. Conversely, the dimple-added model exhibits consistently lower exit temperatures across all mass flow rates compared to the traditional model, confirming the enhanced heat transfer capabilities of the dimples. For instance, at the highest flow rate of 0.15 kg/s, the dimple-added heat exchanger achieves a temperature of 44.4℃, which is significantly lower than the 47.7℃ observed in the traditional model.



(a)



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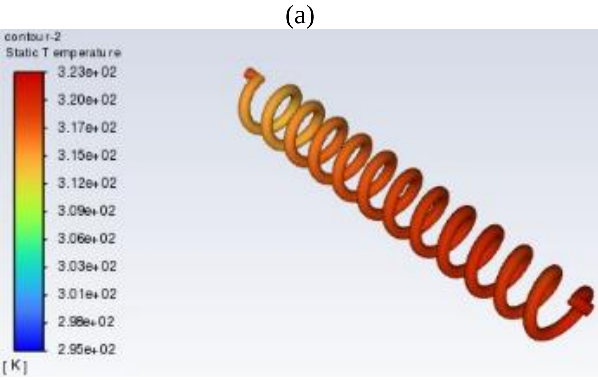
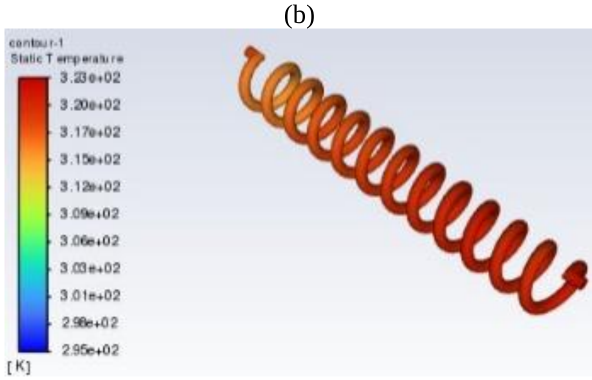


(c)



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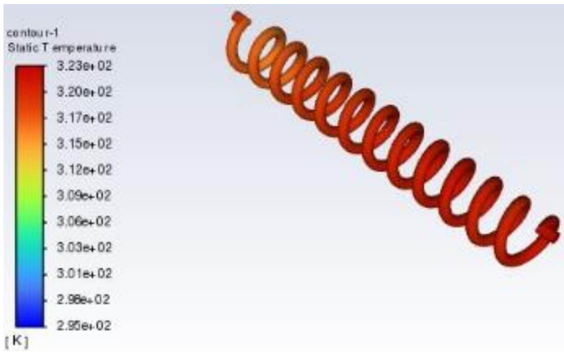
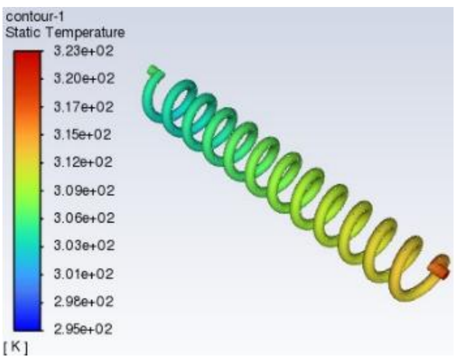
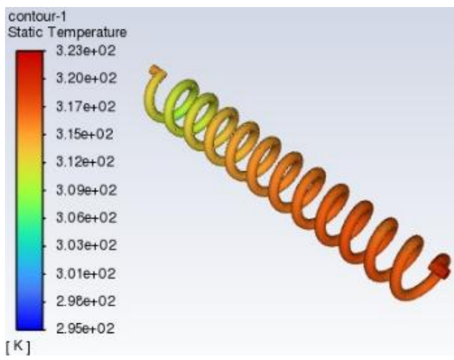


(e)

Figure 14. Traditional helical-tubed HE temperature profile across varying mass flow rates of: (a) 0.03 kg/s, (b) 0.06 kg/s, (c) 0.09 kg/s, (d) 0.12 kg/s, (e) 0.15 kg/s



(a)



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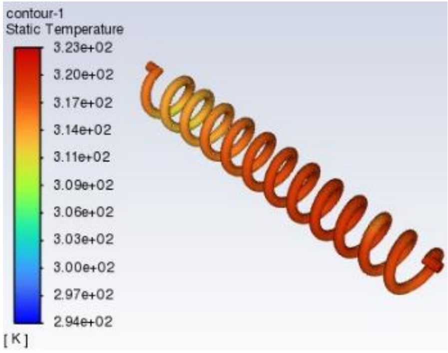

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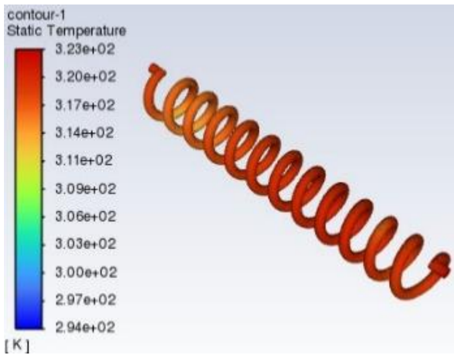

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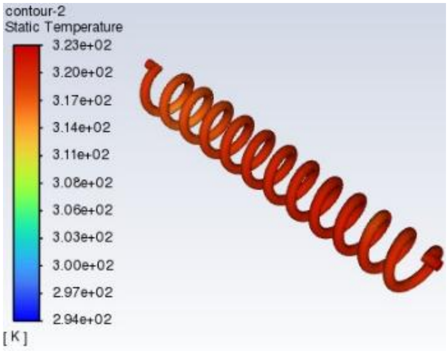
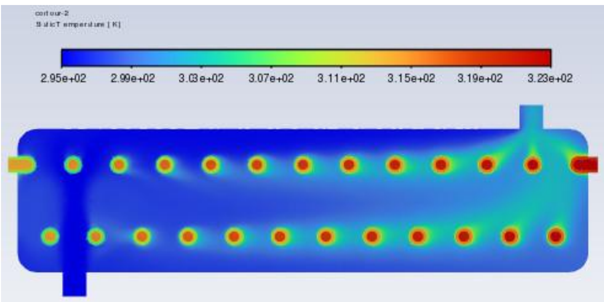
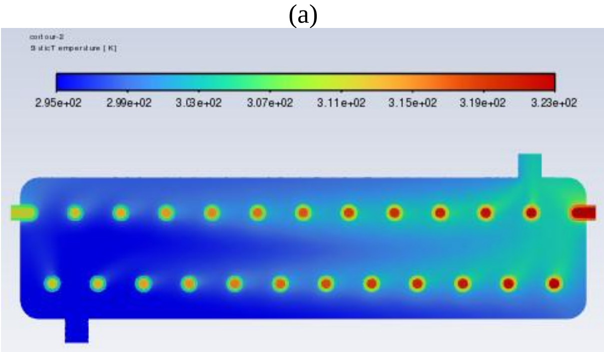


(e)

Figure 15. Dimpled helical-tubed HE temperature profile across varying mass flow rates of: (a) 0.03 kg/s, (b) 0.06 kg/s, (c) 0.09 kg/s, (d) 0.12 kg/s, (e) 0.15 kg/s



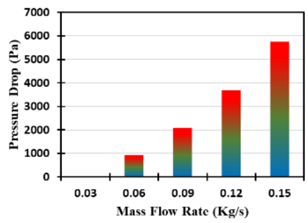
(a)



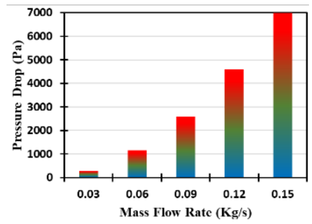
(b)

Figure 16. Cross-section for the temperature profile contours of the full HE under optimum working condition of 0.03 kg/s mass flow rate: (a) Normal HE, (b) Dimples HE

Figure 14 and Figure 15 illustrate the temperature profiles for both types of heat exchangers across the tested flow rates. These figures reveal the thermal behavior within the heat exchangers, showing more uniform temperature distribution and enhanced heat dissipation in the dimple-added model. Figure 15 provides a comparative visualization of temperature contours in the heat exchangers under the optimal condition of a 0.03 kg/s mass flow rate. This figure highlights the stark contrast in heat distribution patterns between the normal and dimple-enhanced models, with the latter showing more effective heat transfer characteristics.



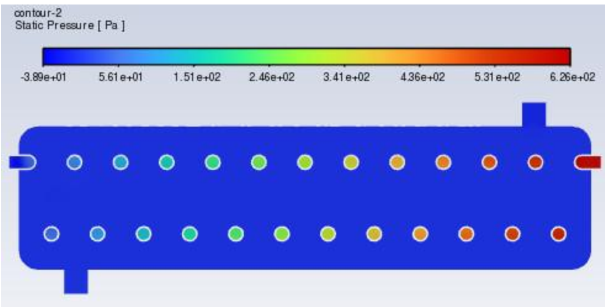
(a)



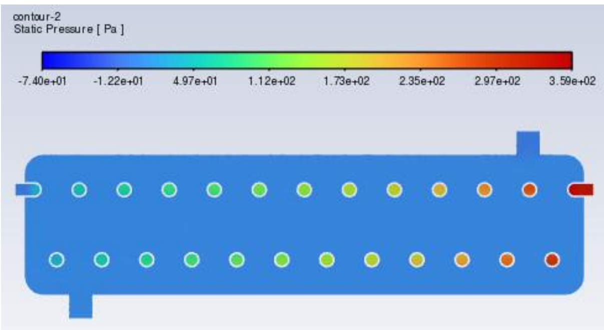
(b)

Figure 17. The simulation-based pressure drop bars across the inner tube of the HE under all working condition of variant mass flow rates: (a) Traditional, (b) Dimpled

Forward, the focus is on the pressure drops experienced within the traditional and dimple-added helical-tubed heat exchangers, as determined through numerical simulations. Pressure drop is a critical metric in assessing the hydraulic efficiency of heat exchangers and their impact on overall system performance. Figure 17, namely Figures 17(a) and 17(b) visually represent the pressure drops across the traditional and dimple-enhanced heat exchangers, respectively, under varying flow conditions. The dimple-added model consistently exhibits higher pressure drops at equivalent flow rates compared to the traditional model, indicative of the increased hydraulic resistance introduced by the dimples. For example, at the highest flow rate of 0.15 kg/s, the pressure drop in the dimple-added model is 25% higher than in the traditional model. Figure 18 offers a detailed view of the pressure drop contours within both heat exchangers under the optimum working condition of a 0.03 kg/s mass flow rate. This comparison vividly illustrates the impact of dimples on fluid dynamics which shows a more pronounced pressure gradient in the dimple-enhanced model compared to the normal model. The dimple-induced turbulence, while beneficial for heat transfer by disrupting boundary layer formation, consequently increases the pressure drop, highlighting a trade-off between thermal performance and hydraulic efficiency.



(a)



(b)

Figure 18. Cross-section for the pressure drop contours of the full HE under optimum working condition of 0.03 kg/s mass flow rate: (a) Normal HE, (b) Dimples HE

5.3 Comparative analysis

This section provides a detailed comparative analysis of temperature and pressure results obtained from both experimental and numerical simulations for traditional and dimple-added helical-tubed heat exchangers. The objective is to assess the effectiveness of dimple enhancements under varying operational conditions and to validate the simulation models against experimental outcomes.

Comparative analysis of temperature data highlights the differences in heat transfer efficiency between the traditional and dimple-added heat exchangers under various flow rates. The experimental results, as depicted in Figure 19, show a consistent trend where the dimple-added heat exchanger maintains lower exit temperatures across all flow rates compared to the traditional model. For instance, at a flow rate of 0.15 kg/s, the exit temperature in the dimple-added model is about 6.4% lower than in the traditional model. This indicates a more effective heat transfer due to the increased turbulence and surface area provided by the dimples. Similarly, Figure 20, based on simulation data, mirrors the experimental findings with the dimple-added model demonstrating superior performance. The simulation shows a consistent temperature reduction in the dimple-added heat exchanger, which underlines the accuracy of the computational model in predicting the thermal behavior of these configurations. Figure 21 compares the experimental and simulation results side by side for both heat exchanger types. This comparison not only validates the simulation model but also underscores the reliability of the experimental setup. The close alignment between the two data sets across all conditions confirms the robustness of the findings and supports the conclusion that dimples significantly enhance the thermal performance of heat exchangers. These comparative analyses affirm that the use of dimpled tubes in heat exchangers can lead to substantial improvements in temperature management, which is critical for energy efficiency in industrial applications. The consistency between experimental and simulation results further provides confidence in the use of computational tools for designing and optimizing heat exchanger performance.

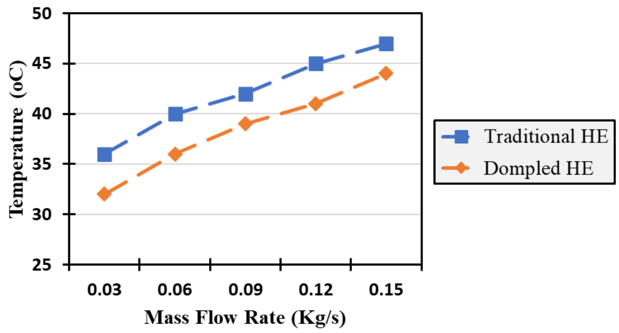


Figure 19. The experimental-based temperature recordings across the exit of the inner tube of the traditional vs. dimpled HE under all working condition of variant mass flow rates

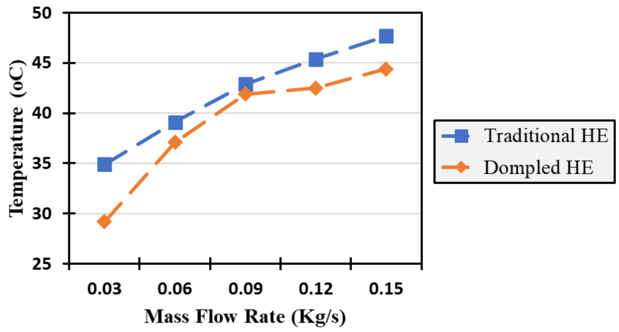


Figure 20. The simulation-based temperature recordings across the exit of the inner tube of the traditional vs. dimpled HE under all working condition of variant mass flow rates

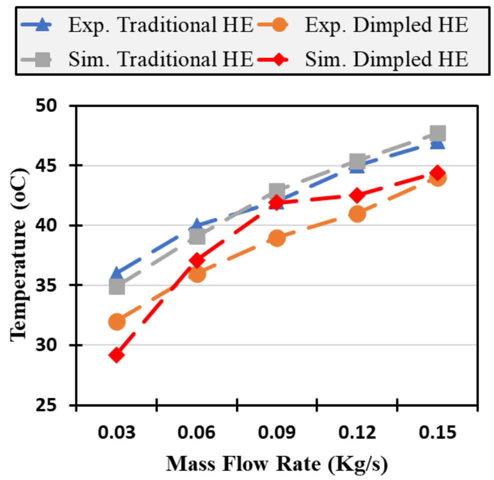


Figure 21. The experimental-simulation temperature recordings across the exit of the inner tube of the traditional vs. dimpled HE under all working condition of variant mass flow rates

Furthermore, the focus shifts to the comparative analysis of pressure drops recorded experimentally and via simulations for both traditional and dimple-added helical-tubed heat exchangers. This analysis highlights the hydraulic impact of employing dimples within the heat exchanger design. The experimental data, as presented in Figure 22, indicate that the pressure drop in the dimple-added heat exchanger is consistently higher across all flow rates compared to the traditional model. For example, at the highest flow rate of 0.15 kg/s, the pressure drop in the dimple-added heat exchanger is 26.2% higher than in the traditional heat exchanger (6736 Pa vs 5012.09 Pa). This increase reflects the enhanced turbulence and resistance caused by the dimples, which, while improving heat transfer, also contributes to a higher hydraulic load. The simulation outcomes, detailed in Figure 23, corroborate the experimental findings. The simulated data show a similar trend, with the dimple-added model exhibiting an increased pressure drop. This alignment between experimental and simulated data highlights the accuracy of the simulations in capturing the fluid dynamics within the heat exchangers. At a flow rate of 0.15 kg/s, the simulation shows a 25.1% increase in pressure drop for the dimple-added model compared to the traditional one (7188 Pa vs 5743 Pa). Figure 24 integrates both experimental and simulation results, providing a side-by-side comparison that emphasizes the consistency across methodologies. This comparative view underlines the predictive reliability of the simulations and the empirical robustness of the experimental setup. Notably, the results affirm that the increase in pressure drop due to the dimples is a consistent outcome, validating the trade-off between enhanced thermal performance and increased fluid resistance.

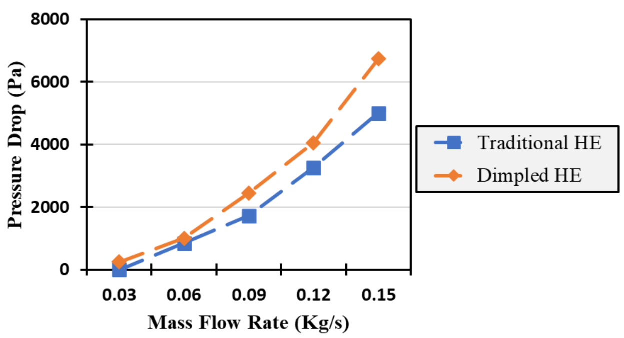


Figure 22. The experimental-based pressure drop calculations across the inner tube of the traditional vs. dimpled HE under all working condition of variant mass flow rates

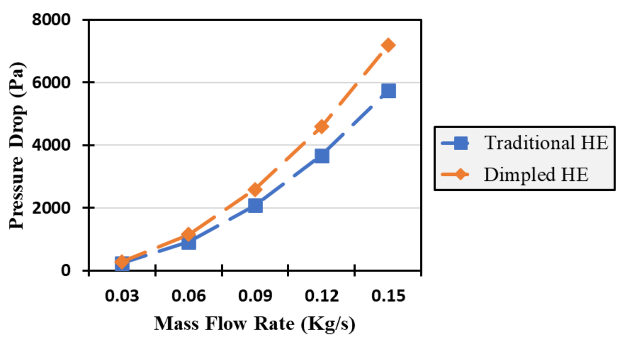


Figure 23. The simulation-based pressure drop calculations across the inner tube of the traditional vs. dimpled HE under all working condition of variant mass flow rates

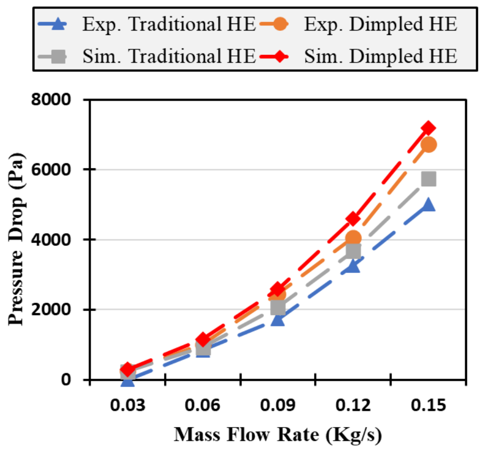


Figure 24. The experimental-simulation pressure drop calculations across the inner tube of the traditional vs. dimpled HE under all working condition of variant mass flow rates

6. CONCLUSION

This research conducted a highly comprehensive journey in an effort to enhance knowledge and performance regarding heat exchangers based on the impacts achieved with the introduction of helically dimpled tubes. With this chain of systematic approaches, much finding and development have been recorded.

1. The comprehensive literature survey established a robust foundation, emphasizing the need for innovative designs to enhance heat exchanger efficiency. The review highlighted significant gaps, particularly in the understanding of the impact of surface modifications such as dimples on heat transfer and fluid dynamics.
2. A new test apparatus was designed and constructed that allowed detailed investigation of the performances of both traditional helical and helically-dimpled tube heat exchangers. This was crucial to establish performance in real-world conditions and validation of theoretical models.
3. Extensive numerical simulations using ANSYS Fluent mirrored the experimental setup and extended the findings by providing detailed insights into the fluid flow and heat transfer mechanisms within the heat exchangers.
4. The experimental results were systematically compared with simulation outcomes which shows high compatibility and confirming the reliability of the numerical models used in this study.
5. It was observed that if dimples were incorporated in the design of the tube, the turbulence in the flow can be taken to a much higher extent, and hence a much higher pressure drop. This was the case in all types of data sets created, be they real or simulated.
6. Dimpled tubes demonstrated a more considerable reduction in hot water exit temperatures, particularly noticeable at the lowest mass flow rate tested (0.03 kg/s). The greatest temperature reduction achieved was notably more effective in dimpled tubes compared to traditional designs and underscores the benefits of surface-induced turbulence.
7. The comparative studies between traditional and dimpled tubes revealed that at a mass flow rate of 0.03 kg/s,

dimpled tubes are capable of significantly reducing exit temperature, with the lowest temperature recorded being in sharp contrast to traditional designs. Besides, comparative analysis of experimental and ANSYS results showed differences in estimated temperature and pressure readings within 10%, which validates the simulation approach as a reliable predictor of real-world performance.

8. The research suggests that further enhancements in heat exchanger performance can be achieved by optimizing dimple configurations. This opens avenues for tailoring heat exchanger designs to specific industrial needs for improved energy efficiency.
9. The limitations are acknowledged within the limited studied mass flow rate values where further investigations are proposed for future directions.

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