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# Computational Analysis of Thermal Performance Augmentation in Helical Coil Heat Exchangers via CuO/Water Nanofluid

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**Abstract:** Helical or spiral coiled heat exchangers, prevalent in industries such as power generation, heat recovery systems, the food sector, and various plant processes, exhibit potential for performance enhancement through optimal fluid selection. Notably, nanofluids, distinguished by their superior thermophysical properties, including enhanced thermal conductivity, viscosity, and convective heat transfer coefficient (HTC), are considered viable candidates. In this study, the thermo-physical attributes of helical coil heat exchangers (HCHEs), when subjected to nanofluids, were meticulously examined. During the design phase, Creo parametric design software was employed to refine the geometric configuration, subsequently enhancing fluid flow dynamics, thereby yielding a design improvement for the HCHE. Subsequent computational fluid dynamics (CFD) simulations of the heat exchanger were conducted via the ANSYS CFX program. A CuO/water nanofluid, at a $1\%$ volume fraction, served as the basis for the CFD analysis, incorporating the Re-Normalisation Group ($k-\varepsilon$) turbulence model. From these simulations, zones exhibiting elevated temperature and pressure were discerned. It was observed that the wall HTC value for the CuO/water mixture surpassed that of pure water by $10.01\%$. Concurrently, the Nusselt number, when the CuO/water nanofluid was employed, escalated by $6.8\%$ in comparison to utilizing water alone. However, it should be noted that a $5.43\%$ increment in the pressure drop was recorded for the CuO/water nanofluid in contrast to pure water.

**Keywords:** Computational fluid dynamics simulation; Turbulence model; Nanofluids; Helical coil heat exchangers; Thermo-physical properties; Efficiency augmentation

## 1 Introduction

In the field of thermal engineering, the importance of efficient heat transfer is underscored. Among the various technologies designed to facilitate this essential process, the HCHE has been identified as a significant advancement. Characterized by its extensive surface area, the HCHE enhances heat transfer rates beyond those of conventional systems.

The efficiency of the HCHE is attributed, in part, to its capability for promoting forced convection, further augmented by the induction of secondary flows. Within its coiled structure, fluid dynamics are altered, leading to improved fluid movement and thus, promoting enhanced heat transfer rates.

Across diverse industries, from power generation to heat recovery systems, and even within the food processing domain, the role of HCHEs has been acknowledged as pivotal. Their contribution to optimized energy transfer methods has been recognized and their widespread adoption across sectors attests to their functional relevance.

As depicted in Figure 1, the design of the HCHE showcases its innovative approach, with its distinctive coiling providing evidence of its enhanced potential. Figure 2 further elucidates the structure of the HCHE, providing insight into its operational principles.

Through extensive research and development, the HCHE has been demonstrated to be not just a mechanical device, but a solution pivotal to the enhancement of energy transfer across industries. As further studies on the HCHE continue, the breadth of its potential applications and its role in redefining heat transfer mechanisms will be more comprehensively understood.

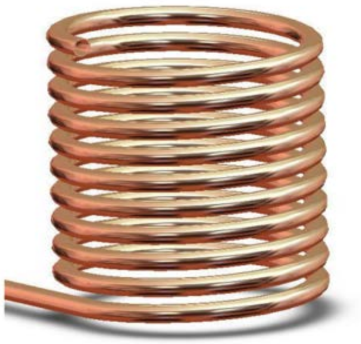

**Figure 1.** HCHE [1]

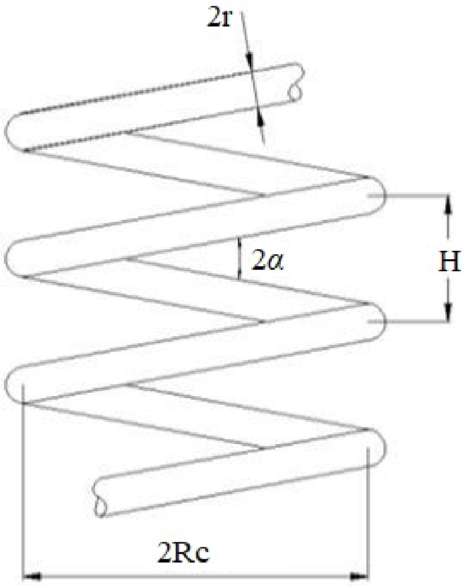


**Figure 2.** Geometry [2]

The following nomenclature is associated with the helical coil profile [2]:
• *2r*: Inner pipe diameter
• *2Rc*: Pitch Circle Diameter (PCD)
• *H*: Pitch
• $\Delta$: Curvature ratio
• $\lambda$: Non-dimensional pitch
• $\alpha$: Helix angle

The HCHE has been identified as a design of significant merit, presenting an array of advantages that contribute to its operational efficiency:

(1) Thermal Stability in Cryogenic Environments: One of the primary benefits of the HCHE is its ability to mitigate challenges related to thermal shock and expansion, especially in cryogenic contexts. The design of the helical coil has been observed to maintain stability amidst temperature fluctuations inherent to cryogenic operations, thereby bolstering its resilience against thermal adversities.

(2) Pressure Resistance without Structural Sacrifice: Beyond its aesthetics, the geometry of the helical coil is specifically structured to endure elevated pressures. Notably, this endurance is achieved without necessitating increased thickness or the addition of supplementary tube sheets. Such robustness underlines its structural integrity and showcases a novel approach to pressure-centric operations.

(3) Elevated Heat and Mass Transfer with Economical Production: In heat and mass transfer applications, the HCHE stands out for its efficiency. The manufacturing process, while relatively straightforward, has been found to be cost-effective. An added advantage to this design is the turbulent flow induced by the helical coil, which serves to reduce fouling and thus extend the exchanger's operational lifespan.

(4) Optimized Performance through Reduced Wall Resistance: The HCHE is not merely designed for facilitating

heat and mass transfer; it actively enhances these processes. The reduction in wall resistance, a characteristic of its design, results in heightened transfer performance. Maintenance, especially in cleaning the helical tube fluid flow area, is reported to be uncomplicated, further simplifying its upkeep.

In the context of heat exchange systems, the HCHE has emerged as a significant development, presenting characteristics that find applications across varied domains. Its various attributes exemplify innovation, offering solutions to challenges and turning potential inefficiencies into performance highlights. As the intricacies of this design are further explored, it becomes evident that a combination of efficiency, resilience, and structural simplicity sets the HCHE apart, redefining heat exchange paradigms.

A detailed experimental investigation on both parallel and counter flow HCHEs was conducted by Rennie and Raghavan [3]. In this study, operational variables, including the inner tube flow rate, were extensively probed. The utilization of Wilson plots was noted to enable a thorough assessment of HTC in both the annulus and the inner tube. Complementing this, Prabhanjan et al. [4] employed CFD techniques to assess HCHE performance intricacies. When HCHEs were contrasted against conventional straight tube heat exchangers in their study, a marked superiority in the helical design's efficiency was observed.

Delving into variations within the helical coil framework, Shokouhmand et al. [5] investigated the significance of different pitches and curvature ratios. Analyses of both parallel and counter flow configurations were undertaken, accompanied by an in-depth examination of Nusselt number and Reynolds number plots. The insights derived from this study not only enhanced the understanding of the domain but were also seen to corroborate established literature.

An augmentation to the ongoing dialogue on HCHEs was presented by Ghorbani et al. [6], where a rigorous experimental approach was adopted. Variations in tube-to-coil ratios and Reynolds numbers were subjected to analysis. From this, tube diameter, coil pitch, and mass flow rates were identified as instrumental parameters influencing the heat exchanger's effectiveness.

Further specializing in refrigerant dynamics, the condensation process of the R-134a refrigerant within HCHE was scrutinized in study [7]. A significant enhancement, ranging between $4\%$ to $13.8\%$, was discerned in condensation HTC within the helical section compared to its straight counterpart. Another research effort highlighted the influence of the cooling medium temperature on R-407C condensation rates [8], covering a broad spectrum of mass fluxes for R-407C and coolant water. Here, the helical coiled tube's superiority over conventional smooth tubes in accelerating condensation rates was observed.

In a precision-driven study, Jayakumar et al. [9] employed CFD through the FLUENT software, exploring variables such as mass flow rates and operating fluid temperatures. The findings from this investigation were seen to align with empirical data, culminating in the formulation of an empirical correlation for the inner HTC.

Furthering the discussion, Ghorbani et al. [10] focused on tube coil heat exchangers under steady-state and turbulent flow conditions. This study revealed heat transfer subtleties within these configurations and established the correlation between effectiveness and mass flow rate. Notably, parallels between the NTU (Number of Transfer Units) relation of mixed convection heat exchangers and that of pure counter-flow variants were unveiled.

Salimpour [11, 12] extended the empirical lens to helical tube heat exchangers, emphasizing their thermal characteristics. In their comprehensive experiments, correlations between inlet/outlet temperatures and efficacy were derived. Their further studies, which utilized engine oil as the working fluid, offered a broader perspective on the thermal dynamics at play, encompassing diverse pitch values for the coil.

Through mathematical modeling, insights into the heat transfer characteristics of spiral coil heat exchangers were developed by Naphon [13], Naphon and Suwagrai [14]. Their model, founded upon concentric spirally coiled tubes and utilizing water and air as working fluids, employed the Newton-Raphson algorithm, ensuring mass and energy conservation. A notable correlation between their numerical predictions and empirical data was observed. Furthermore, a deeper understanding was provided by their exploration of curvature ratios, highlighting the interaction between fluid dynamics and geometric properties.

A numerical lens was used by Zamankhan [15] to delve into the complexities of helical tabulators, employing CFD techniques. Glycol water was analyzed at varying concentrations, providing insights into turbulence's role in heat flow. A nonlinear association between Reynolds and Prandtl numbers and heat transfer was unearthed through the study's turbulence models, which included k-epsilon, k-omega, and large eddy simulation.

By combining numerical techniques with experimental methods, Kharat et al. [16] offered insights into the influence of "tube diameter" and "coil diameter" on heat transfer properties. Empirical correlations were drawn, forming a foundation for understanding HTC. The use of phase change materials like Paraffin as a latent heat storage medium signaled a novel method for efficient thermal energy storage, aligning with broader sustainability objectives [17].

These studies collectively provide a layered understanding of the thermal characteristics and performance attributes of HCHEs. Such research not only offers a synthesis of existing knowledge but also acts as a cornerstone for future endeavors in thermal engineering.

Despite advancements in heat exchanger technology, a discernible gap exists between the capabilities of nanofluids and the design of HCHEs. While the potential of nanofluids to augment thermal conductivity has been recognized, their specific effects on HCHE performance remain understudied.

This study aims to bridge this chasm. Key objectives are outlined:

(1) Comprehensive assessment of the thermal attributes of HCHEs when integrated with a CuO/water nanofluid of 1% volume fraction.

(2) The utilization of advanced design software and CFD simulations to decipher HCHE behavior when merged with nanofluids.

(3) Determination of whether enhanced heat transfer efficiency is achieved through nanofluid integration within the HCHE design compared to traditional methods.

The research seeks to address: How do nanofluids impact the thermal attributes and overall efficacy of HCHEs? The hypothesis suggests that the strategic incorporation of CuO/water nanofluid at a precise 1% volume fraction may substantially enhance the thermal conductivity and heat transfer efficiency of HCHE. The distinct thermophysical properties of nanofluids might forge a synergy, surpassing traditional heat exchange benchmarks and leading to superior heat transfer performance.

In the evolving landscape of heat exchangers, an opportunity arises to intersect the properties of nanofluids with the design intricacies of HCHEs. Despite the acknowledged potential of nanofluids in thermal conductivity enhancement, their specific dynamics within HCHE remain relatively unexplored. This presents a call for an integrated investigation, merging design precision, fluid dynamics, and nanofluid behavior within HCHE. The research blueprint, designed using Creo parametric software, ventures into CFD via the ANSYS CFX program. Precision is maintained with the study's selection of a CuO/water nanofluid at a 1% volume fraction. Analysis under the Re-Normalisation Group $(k-\varepsilon)$ turbulence model is anticipated to reveal interactions between nanofluids and HCHE, potentially revolutionizing traditional heat exchange methodologies. The choice of the Re-Normalization Group $(k-\varepsilon)$ turbulence model likely resonates with its suitability for the specific research goals, considering its track record in predicting turbulent flow behavior across various contexts.

## 2 Methodology

In CFD analysis, the Navier-Stokes (N-S) equation is fundamentally recognized as a pivotal framework, illuminating the intricate aspects of fluid dynamics [18]. The N-S equation, derived from the transport theorem and the conservation of momentum, serves as a primary directive in CFD explorations [18].

Eq. (1) illustrates the transformation of the mass conservation equation into the continuity equation, representing a crucial progression in fluid dynamics analysis [19]. Subsequently, the energy equation is addressed, defined by the mathematical structure in Eq. (3) [20].

The intricacies of fluid behavior are deciphered through these equations, providing a mathematical interpretation of fluidic motions. Through a comprehensive study of the N-S equation, the core principles of fluid dynamics are elucidated.

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho U_1}{\partial x_1}+\frac{\partial \rho U_2}{\partial x_2}+\frac{\partial \rho U_3}{\partial x_3}=0 \tag{1}$$

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial x}=0 \tag{2}$$

From Newton's $2^{\text{nd}}$ law, the momentum balance equation is given by [21]:

$$\rho\left(u\frac{\partial U}{\partial x}+v\frac{\partial V}{\partial x}\right)=-\rho g-\frac{\partial p}{\partial x}+\mu\frac{\partial 2y}{\partial x2} \tag{3}$$

$$\rho Cp\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\frac{\partial 2T}{\partial y2} \tag{4}$$

A notable characteristic of the helical coiled-tube design is its inherent ability to produce centrifugal forces without the requirement for moving mechanical components [22]. This capability underscores its relevance within fluid dynamics studies.

For the analytical procedure, the helical coil design was constructed with precision using the Creo sweep tool. This construction process, as represented in Figure 3 [23], stands pivotal to the research's accuracy. It was ensured that the design of the helical coil remained consistent, precise, and detailed.

**Figure 3.** CAD design of coil

Specifications for this research were anchored in established literature [24]. Parameters and elements were defined based on an amalgamation of previous studies, augmenting the research's precision and credibility.

Upon its construction, the helical coil design was imported into the ANSYS Design Modeler, a crucial step demanding precision [25, 26]. At this stage, the geometric complexities of the design were thoroughly examined, focusing on features like hard edges and patches. A comprehensive assessment of geometric fidelity was conducted to ensure the foundation for precise simulations was established.

Within the coil's core, the generated fluid domain was integrated. This procedure captured the intricate interactions of fluid forces within the coil's confines. As represented in Figure 4, the imported CAD design, now integrated with the fluid domain, exemplified the synthesis of precise engineering and fluid dynamics.

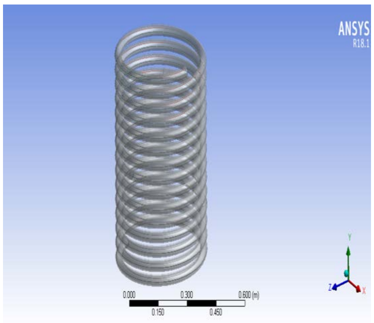


**Figure 4.** Imported CAD design with integrated fluid domain

For CFD analyses, the creation of an accurate computational mesh for the domain is paramount. The mesh acts as the foundation for fluid dynamics simulations, with the accuracy of results directly correlating to its quality. As referenced in previous studies, finer meshes often yield better results, though they require more computational resources [18, 27].

In this study, the helical coil model was discretized using hexahedral elements as shown in Figure 5. This process resulted in 696,899 nodes and 548,972 elements, forming the base for subsequent analyses. The boundary between fluid and solid regions was clearly defined. Characteristics of the fluid domain, including material properties, shape, and the selected turbulence model, were detailed. This comprehensive representation of the fluid domain can be observed in Figure 6.

The fluid inlet velocity was set at 1.2 m/s, directing the fluid into the domain of analysis. The fluid outlet parameters were delineated to represent the trajectory of the fluid through the system. An inlet fluid temperature of 300K was maintained, accompanied by medium turbulence intensity, reflecting the interrelation of temperature and flow dynamics. With a relative pressure set at zero, the system allowed the fluid to exit, each parameter carefully defined for accuracy.

Specific parameters governing the fluid's behavior were integrated into the analysis. A wall heat flux of 400W was established, influencing the system's energy exchange. For this study, the fluid's velocity was set at 0.05 m/s, reflecting the calibrated flow dynamics. Figure 7 illustrated the boundary conditions that govern fluid flow at both intake and outflow points, representing the fluid dynamics within the system. In complement to this, Table 1 presented the properties that characterize the fluid's behavior throughout the analysis.

As illustrated in Figure 8, the demarcation between fluid and solid domains was emphasized, with copper as the material of choice. In this domain, thermal energy was identified as the primary variable, activating the specified

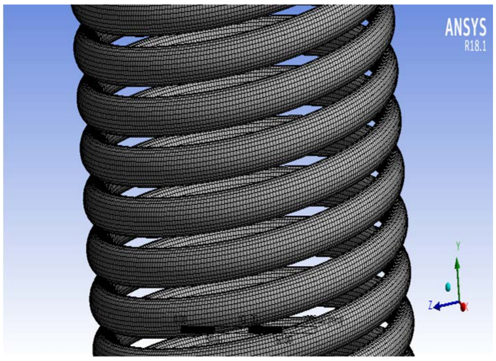


**Figure 5.** Discretized coil design

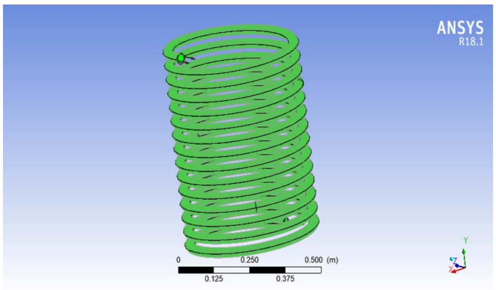


**Figure 6.** Detailed fluid domain characteristics

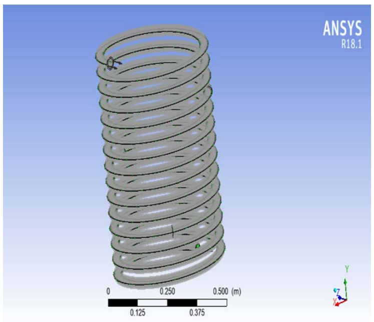


**Figure 7.** Boundary conditions

**Table 1.** CuO/water properties (1% volume fraction)

| Fluid | Thermal Conductivity (W/mK) | Specific Heat | Density | Viscosity (N·m/s$^2$) $* 10^{-3}$ |
|---|---|---|---|---|
| Water | 0.602 | 4182 | 998.54 | 1.006 |
| CuO/ water | 0.620 | 3262.9 | 1051.7 | 1.477 |

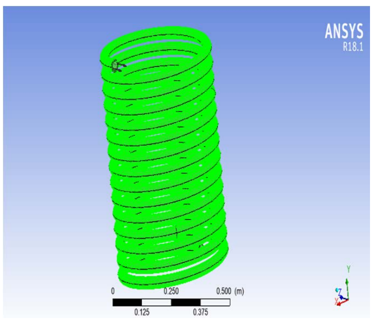


**Figure 8.** Copper domain definition

energy model. The interfaces between fluid and solid were defined, each characterized as either fluid or solid type [28]. These interfaces enabled the heat exchange, facilitating the transfer of thermal energy between the two domains. Specific solver options were then selected for the simulation, with iteration numbers, RMS (Root Mean Square) residual objectives, and the "upwind scheme" option being prioritized. These options were crucial in guiding the course of the CFD simulation, ensuring precision and convergence. As the simulation progressed, RMS residual plots provided visualization of turbulence generation and heat transfer dynamics. These plots offered more than graphical representation; they encompassed key analysis components such as mass conservation and momentum in the x, y, and z directions, elucidating the intricate fluid dynamics at play.

## 3 Results and Discussion

The study transitioned into the presentation and interpretation of results, unveiling patterns and implications derived from the analysis. Contour plots were employed to visually interpret the interplay of pressure and temperature within both water and Nanofluids. As depicted in Figure 9, the pressure distribution in water was emphasized.

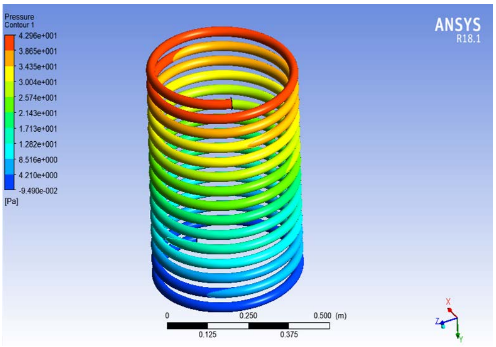


**Figure 9.** Pressure distribution in water

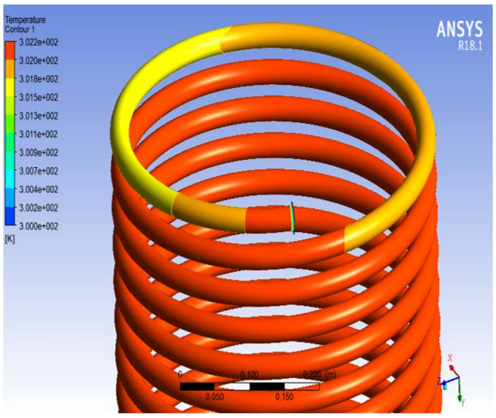


**Figure 10.** Temperature variation for water

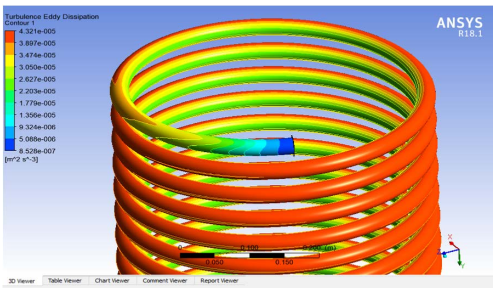


**Figure 11.** Turbulence eddy dissipation in water

Depicted in Figure 9, when water is the chosen fluid, the pressure gradient is most pronounced near the entry point, highlighted in red. At this specific juncture, the pressure reaches 42.96 Pa. As the fluid progresses along the tube, the pressure gradually diminishes along the wall. Figure 10 shifts focus to temperature, utilizing water as the fluid medium. The temperature plot starts at the coil's fluid intake, gradually intensifying as the fluid progresses towards the exit. Turbulence also plays a role in the exploration. Figure 11 presents the turbulence eddy dissipation plot, shedding light on the fluid's inner dynamics. On the outer face of the coil, turbulence is vibrant, represented by high magnitudes. In contrast, within the coil's interior, a sense of calm prevails, depicted through shades of green and yellow. Impressively uniform across all coils, the turbulence eddy dissipation maintains a consistent value of $2.203\mathrm{e}-5\ \mathrm{m}^2/\mathrm{s}^3$, underscoring the coherence in this aspect. Through these visual representations, the journey evolves beyond numbers and equations, unveiling the intricate choreography of pressure, temperature, and turbulence within the fluid's domain.

In the scenario where water served as the fluid medium, a pronounced pressure gradient was observed at the entry point, as evidenced by the highlighted region in Figure 9, where pressure was recorded at 42.96 Pa. As the flow advanced through the tube, a decline in pressure was noted along its walls. The temperature dynamics, with water as the fluid medium, were illustrated in Figure 10. Starting at the intake of the coil, an escalation in temperature was observed as the fluid neared the exit.

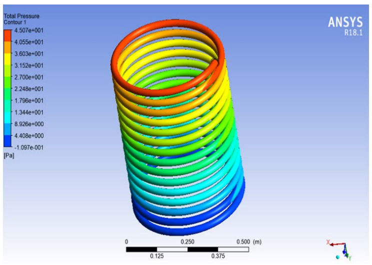


**Figure 12.** Pressure plot CuO/water

Turbulence dynamics were not overlooked in this investigation. Figure 11 provides a visual depiction of turbulence eddy dissipation. A pronounced turbulence was observed on the coil's exterior, indicated by higher magnitude regions. In contrast, reduced turbulence characterized the coil's interior, demonstrated by shades of green and yellow. Remarkably, throughout all coils, a consistent value of $2.203\mathrm{e}-5\ \mathrm{m}^2/\mathrm{s}^3$ was recorded for the turbulence eddy dissipation, highlighting uniformity in this aspect. The pressure dynamics of the Nanofluid were explored as shown in Figure 12.

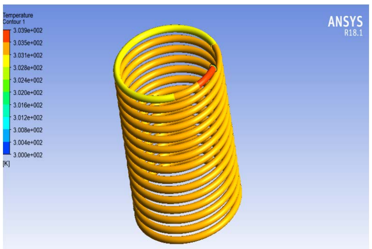


**Figure 13.** CuO/water temperature plot

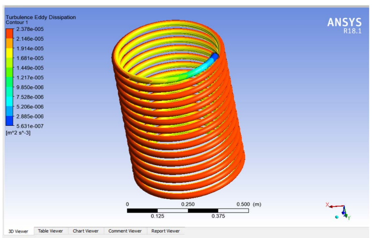


**Figure 14.** Turbulence eddy dissipation with CuO/water as fluid

In the continuation of the analysis, the temperature dynamics of the Nanofluid were explored as shown in Figure 13. An observed trend indicated a rise in temperature magnitude as the fluid progressed toward the coil exit. A temperature of approximately 303.9 K was recorded on the outer coil surface, emphasizing a significant thermal attribute of the system. Within the same figure, the turbulence eddy dissipation for CuO/water was presented, offering insights into the turbulence dynamics. A closer inspection of the coil's interior, characterized by shades of green and yellow, revealed reduced turbulence magnitudes. A consistent turbulence eddy dissipation of 1.681e-5 $m^2/s^3$ was recorded across all coils, further illustrated in Figure 14.

The Wall Heat Transfer Coefficient (WHTC) and Nusselt number were calculated for both water and CuO/water nanofluid. A distinct observation was made: the CuO/water nanofluid exhibited a higher HTC than water, as detailed in Table 2.

**Table 2.** Thermal characteristics comparison [29]

| Fluid Type | WHTC $(W/m^2K)$ | Hydraulic Diameter | Nusselt Number |
|---|---|---|---|
| Water | 344.26 | 0.0275 | 15.72 |
| CuO/water | 378.69 | 0.0275 | 16.79 |

Furthermore, the HTC for CuO/water exceeded that of water by 10.01%, suggesting a significant improvement. Concurrently, the Nusselt number recorded a 6.8% enhancement. Differences in pressure between CuO/water nanofluid and water were elucidated in Table 3.

**Table 3.** Fluid flow characteristics comparison

| Fluid Type | Pressure In | Pressure Out | Pressure Drop (Pa) |
|---|---|---|---|
| Water | 43.99 | 1.27 | 42.72 |
| CuO/ water | 46.37 | 1.33 | 45.04 |

An increase in friction between the fluid and tube was inferred upon the introduction of Nanofluids, manifested as an augmented pressure drop across the helical tube. This observation implied that HCHEs require increased pumping power to compensate for this amplified pressure drop. When CuO/water nanofluid was compared to water, a discernible pressure loss increase of 5.43% was noted.

## 4 Conclusion

In an endeavor to amplify thermal performance within coil heat exchangers, the role of CFD has been reaffirmed as being integral, facilitating rapid and adaptable evaluations. Through the adoption of the Re-Normalization Group $(k-\varepsilon)$ turbulence model, satisfactory predictions, especially pertaining to fluid flow dynamics in the HCHE, were made for both CuO/water nanofluid and water. A marked increase of 10.01% in the WHTC for CuO/water, in comparison to water, accentuates the pronounced potential of superior heat transfer following the introduction of Nanofluids. Concurrently, a surge of 6.8% in the Nusselt number when using CuO/water nanofluid exemplifies the potential efficiency enhancements of such fluid incorporation. Nevertheless, a consequential observation was the 5.43% elevation in pressure drop with CuO/water nanofluid, indicating significant shifts in the system's fluid dynamics.

While these findings are instructive, certain limitations inherent to the study were recognized. The predominant focus on CuO/water nanofluid narrowed the investigative scope within the vast spectrum of Nanofluids. Hence, there emerges a prospective avenue for expanded research into other Nanofluids, notably Aluminium oxide and zinc oxide, to achieve a more encompassing understanding of their thermal dynamics. A compelling direction for prospective studies centers on the design intricacies of HCHEs. Investigations into the effects of embedding artificial roughness in tube structures could be particularly enlightening, given the potential to enhance heat transfer efficiency. Such explorations might hold the key to magnifying the design's efficacy, thereby aligning with the paramount aim of refining heat exchange procedures.

In anticipation of future endeavors, it is suggested that the optimal configuration of artificial roughness in tube structures be probed, to ascertain the most effective means of bolstering heat transfer efficiency. Equally, delving into Nanofluids like Aluminium oxide or zinc oxide might elucidate aspects of their thermal conductivity, viscosity, and convective heat transfer traits in varied heat exchange configurations. In summation, the insights derived from this study not only shed light on pivotal considerations but also beckon further probing, setting the stage for the advancement of knowledge in the domains of HCHEs and Nanofluid applications.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare no conflict of interest.

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