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Effect of Air Bubbles on Heat Transfer Using a Helical Coil: A Review

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ABSTRACT

This review paper discusses the important role of helical coils in heat transfer applications, focusing attention on their distinct geometry and high thermal performance. Helical coils, with tapering shape and continuously varying diameter, offer numerous advantages over their straight and helical counterparts concerning fluid dynamics, heat transfer rates, and efficiency. This paper explores the underlying principles of heat transfer in helical coils and addresses how fluid flow behavior, promotion of turbulence, and generation of secondary circulations enhance the rate of heat transfer. Advantages of helical coils, which include the increased mixing of fluids, enhanced surface area for heat exchange, and reduced fouling, have led to its usage in various applications such as in heat exchangers, solar thermal systems, biomedical devices, refrigeration, and industrial processes. It further explains how air bubbles impact the transfer of heat in two-phase flow systems and demonstrates that air bubbles improve convective heat transfer through the generation of turbulence and effective distribution of heat. Finally, it ends with an underlining fact that Helical coils play a vital role in optimizing the transfer of heat and its efficiency especially when the concerned parameters include minimal space availability, high thermal efficiency, and minimum maintenance.

Keywords: Helical coils, Heat transfer applications, Fluid dynamics, Efficiency, Turbulence, Heat exchangers, Refrigeration, Industrial processes.

1. INTRODUCTION

Heat transfer is of great importance to the industrial industries in applications in heat exchanger, refrigeration, chemical processes, and in power generation among others. All these geometrical forms of coil, helical coils have seen a lot of attention because geometric form improves considerably the fluid-flow characteristics, resulting in improved performance [1].

Traditional heat exchangers make use of mainly helical or straight tubes. However, the helical coil has several advantages in terms of its heat transfer rates, characteristics of pressure drop, and compactness. Therefore, heat transfer in a helical coil is an important area of research in optimizing thermal efficiency in such systems where space constraints and the efficiency of heating dissipation are concerns of major concern [2].

Table 1: Heat Transfer Review

Reference	Key Findings	Summary
Hasan, S. S., Baqir, A. S., & Mahood, H. B. (2021) [3]	- Injected air bubble size impacts heat transfer performance. - Smaller bubbles enhance turbulence, improving heat transfer.	Demonstrated that smaller air bubbles greatly improved the heat transfer considerably with a very high level of turbulence, whereas larger bubbles caused a lower level of efficiency in heat transfer. Optimization of the size of the bubbles is thus required to be achieved for improvement in the thermal performance of the vertical shell and helical coiled tube heat exchangers in two-phase flow systems.

	- Larger bubbles create stable flow.	
Hulet, C., Clement, P., Tochon, P., Schweich, D., Dromard, N., & Anfray, J. (2009) [4]	- Bubble behavior, such as formation and rise velocity, impacts heat transfer. - Bubble columns significantly enhance heat transfer.	Examined the topic of heat transfer in bubble columns and came to the conclusion that, in two-and three-phase flow systems, it enhances convective heat transfer via the creation of turbulence and an increase in surface area. Thus, the results show that the total efficiency of heat transfer is affected by the size distribution inside the bubbles.
Suri, A. R. S., Kumar, A., & Maithani, R. (2018) [5]	- Turbulators, surface modifications, and nanofluids enhance heat transfer. - Nanofluids boost thermal conductivity.	Has discussed various enhancement techniques for heat transfer within the tubes of a heat exchanger, which include turbulators-twisted tapes, wire coils, surface modifications, and nanofluids. Turbulators enhanced mixing and turbulence, whereas nanofluids had enhanced thermal conductivity compared with those without nanofluids, hence improving the performance of heat exchangers.
Abdullah, M. S., & Hussein, A. M. (2023) [6]	- Nanofluids increase thermal conductivity. - Nanofluids improve convective heat transfer in helical coil heat exchangers.	Reviewed the utilization of nanofluids in helical coil heat exchangers. The heat transfer enhancement using nanofluids is due to the improved thermal conductivity. It has high promising potential for efficiency enhancement within spaceconstrained systems though found strong challenges such as instability and relatively high manufacturing cost.
Abbaspour, M., Mousavi Ajarostaghi, S. S., Hejazi Rad, S. A., & Nimafar, M. (2021) [7]	- Perforated helical rings and wire coils increase turbulence. - These devices enhance fluid mixing and heat transfer.	Investigated the use of perforated helical rings and wire coils as turbulators in tubes. The latter devices promoted turbulence by causing secondary flows, disturbing boundary layers, and enhancing mixing of the fluid. It, therefore, led to a superior heat transfer performance and seemed to have good promise for enhanced industrial heat exchanger efficiency.
Li, H., Wang, Y., Han, Y., Li, W., Yang, L., Guo, J., ... & Jiang, F. (2022) [8]	- Extended surfaces, turbulators, and nanofluids enhance heat transfer. - Flow configurations (laminar, turbulent) affect thermal performance.	Discussed enhancing techniques of heat transfer in the concentric pipe heat exchangers. Concentric pipe heat exchangers showed promising effectiveness in the literature due to increased extended surfaces and turbulators or nanofluids. Based on flow conditions such as laminar, transitional, and turbulence, the efficiency of heat exchanger can improve up to extreme limits with corresponding modifications in designing concentric pipes.
Narrein, K., & Mohammed, H. A. (2014) [9]	- Nanofluids improve heat transfer in helically coiled tube heat exchangers. - Coil geometry influences fluid dynamics.	A review was published on the topic of nanofluids and their use in helical coiled tube heat exchangers. Thermotransfer efficiency and thermal conductivity were both enhanced by nanofluids. Investigating fluid dynamics with coil shape in terms of diameter and pitch revealed that HCTHEs including nanofluids hold great potential for improving heat transfer in small systems.

1.1. Importance of Helical Coil Geometry in Heat Transfer

A helical coil is a tube that is wound helically with varying diameters along its length. Its geometry deviates from the standard cylindrical one. Although geometric variation is very important in changing the behavior of fluid flow to be disturbed, turbulent, and affecting boundary layer growth in such a way that significantly enhances the efficiency of heat transfer. Some of the important aspects concerning helical coils in heat transfer applications are described below [10].

1. Enhanced Fluid Mixing

A helical coil tapers in shape, causing fluid velocity changes to develop along the length. Due to the variably changing diameter, localized flow disturbances are developed and secondary flows are induced. Flow disturbances improve mixing of the fluid which is vital in enhancing convective heat transfer. Improved mixing ensures continuous interaction between hotter and cooler fluid regions, thus minimizing thermal stratification. It also reduces the temperature gradients within the fluid and hence results in uniform heat conduction. It enhances the mixing of fluids that can be utilized in applications such as heat exchangers where energy transfer from hot fluids to cold fluids takes place efficiently. This ability is very useful in process industries especially where consistent temperature distribution is required, like in chemical reactors or food processing units. This enables the uniform heating of air in the helical coils without overheating and inefficient thermal exchange, which is known to increase system performance and reliability.

2. Increased Surface Area

Helical coils provide more contacting surface area for heat transfer in a confined space; therefore, they are very efficient for thermal applications compared to straight tubes. The coiled structure further increases the length of the tube per unit volume, which efficiently increases the contacting area of the fluid with the heat transfer surface. This would increase the heat transfer between the coil and the surrounding medium, and the thermal performance will improve. A higher residence time for the fluid is realized as a result of the long tubing length, allowing greater absorption or dissipation of heat, which is useful in applications where high heat transfer efficiency must be achieved within compact design. Helical coils are widely used in the compact heat exchanger and cooling systems where space constraints exist. Applications include refrigeration, air conditioning, and biomedical applications where optimum thermal management is ensured within a limited spatial configuration.

3. Flow Acceleration and Secondary Circulation

The helical shape of the coil will provide continuously changing cross-sections that result in velocity and pressure variation throughout the length of the coil. Such changes cause acceleration of flow in some areas, while in other areas, secondary circulation patterns are developed due to the combined effect of centrifugal and inertial forces acting on the fluid. An increase in flow acceleration increases the Reynolds number, resulting in a shift from laminar to turbulent flow, which is a significant factor in enhancing convective heat transfer. The induced secondary circulation helps break the thermal boundary layer and reduces resistance to heat transfer. Therefore, by facilitating effective heat exchange with a lower temperature difference, helical coils contribute to enhanced energy efficiency. This feature is more advantageous in the solar thermal systems where helical coils maximize the turbulence and enable the rapid spreading of heat through the thermal storage units, and thereby enhance the absorption and use of solar energy.

4. Reduced Fouling and Sedimentation

Fouling refers to the deposit of unwanted material such as scale, biological growth, or sediment on the heat exchanger surface, which eventually reduces the heat transfer efficiency over time. The presence of stagnant zones and low-velocity regions in conventional straight or helical coils allows the particles to settle, thereby increasing fouling. However, helical coil geometry, and the fluctuating curvature variation that leads to induced secondary flows and supports the overall fluid flow, helps break up the deposition of any material. Therefore, there is less tendency to create foils, which eliminates the interruptions with regard to heat exchanger performance and reduces maintenance frequencies and costs. Reduced sedimentation also enhances efficiency, particularly in viscous or particulate-laden fluids, such as those commonly encountered within industries plagued by blockages and scaling. Helical coils have enhanced self-cleaning properties, which increases the lifetime of heat exchanger equipment. On account of these benefits, helical coil heat exchangers are found in wide applications in wastewater treatment, food processing, and chemical industries where clean heat transfer surfaces must be maintained to achieve their optimised performance.

1.2. Applications of Helical Coils in Heat Transfer Systems

helical coils are used extensively in heat transfer systems due to their superior thermal performance. In heat exchangers, helical coils play a very important role in chemical processing, food processing, and power plants, where the efficiency of heat exchange is necessary for maintaining operational efficiency and product quality. They have good surface area contact, better fluid mixing, and less fouling properties that make them suitable for this kind of application. In the solar water heating system, they use helical coil heat exchangers. It is used to maximize heat absorption from the solar collector and to provide efficient thermal energy transfer to the storage units. The secondary circulation generated due to the shape of the conic form does enhance energy distribution and thus boosts the overall efficiency of the system as well [11].

The helical coils are within the biomedicine applications domain and are used in medical appliances where the heating and cooling systems have to be precisely controlled. These include dialysis machines, blood warmers, and therapeutic cooling systems. They are uniquely suited for applications requiring precision of temperature regulation in conditions of compact design and a high rate of heat transfer [12]. This helps to make an efficient refrigeration and air conditioner by having added helical coils in the condensers as well as the evaporators as this helps raise the dissipation and absorption heat rates simultaneously leading to increased effectiveness of cooling plus energy conservation.

Helical coils are also extremely useful in the aerospace and automotive industries in which effective thermal management is crucial in keeping the engines operating within permissible temperature limits while preventing overheating. They have found application in the engine cooling systems, intercoolers, and exhaust heat recovery systems. With these unique advantages, helical coils remain one of the popular choices in several industrial and commercial applications that demand reliable and efficient heat transfer solutions.

2. FUNDAMENTALS OF HEAT TRANSFER IN HELICAL COILS

helical coils are characterized by heat transfer being essentially a mixture of conduction, convection, and sometimes radiation. All these contribute to the process of heat exchange. helical coils are helical tubes in which the diameter changes along the length of the tube while affecting fluid dynamics and heat transfer [13]. This improves efficiency in heat transfer from the fluid to the surface when it flows through the coil due to an increase in surface area exposed for heat exchange. This geometry helps mix the fluid by causing disturbances during the formation of thermal boundary layer, mainly under laminar flow. Boundary layer breaking, plus increased mixing lead to increased coefficients of heat transfer, necessary in order to gain efficiency in exchange.

In addition to convection, turbulence, caused by the tapering design of the coil, plays a key role in heat transfer [14]. The change from laminar to turbulent flow occurs as the Reynolds number rises and the fluid accelerates as the coil diameter shrinks. Turbulence improves fluid mixing, which in turn boosts heat transfer by increasing the interaction between hot and cool fluid areas. Better heat distribution through secondary convective routes is also contributed by secondary flows induced by the coil curvature. In addition to the fluid's natural conduction properties, the solid coil material—often metals like aluminum and copper—also facilitates heat transfer to the surrounding system. Many applications rely on helical coils for heat transfer, including solar thermal systems and heat exchangers. The efficiency of this type of heat transfer is ultimately determined by the fluid characteristics, coil geometry, and flow circumstances.

2.1. Importance of helical coil geometry in thermal applications

- **Enhanced Heat Transfer Efficiency:** A helical coil has a tapering structure, and hence, an increased surface area with respect to straight tubes, which assists in better heat transfer. The coil surface could make more fluid contact, thus resulting in improved heat exchange efficiencies within thermal applications. Flow turbulence is also increased due to varying curvature of the coil, thereby promoting better mixing and thermal resistance [15].
- **Promotion of Fluid Flow Dynamics:** This change in diameter along the length of a helical coil creates fluctuations in fluid velocity and pressure. These enhance flow dynamics such as acceleration and generation of secondary circulation patterns, which break up the thermal boundary layer, thereby further reducing resistance to heat transfer and improving convective heat exchange [16].
- **Compact Design with High Thermal Performance:** helical coils offer a compact solution for heat transfer applications. By maximizing heat transfer in a smaller space, helical coils help reduce the size of heat exchangers, making them suitable for applications where space is limited, such as in compact cooling systems and solar thermal units. This compact design makes it possible to achieve high thermal performance without the need for large, bulky systems.

- **Reduced Fouling and Sedimentation:** The geometry of helical coils helps prevent the accumulation of particles and sediments on the heat transfer surface. The changed flow dynamics and resulting turbulence minimize the stagnant zones, lower the possibility of fouling and ensure the continued smooth performance of heat exchangers; the same is important in industries related to the fluids containing particulates or those with biological growth, where the lowered efficiency by fouling would be particularly crucial [17].
- **Versatility in Application:** The unique geometry of helical coils makes them versatile for a variety of thermal applications in various industries. From heat exchangers to solar thermal systems, biomedical devices, or refrigeration and air conditioning systems, helical coils are capable of optimizing the heat transfer as well as making the system operate reliably. Since they can work with fluids having both high and low viscosities, the versatility of their operation in a wide range of conditions is highly appreciated [18].
- **Energy Efficiency and Cost-Effectiveness:** By improving convective heat transfer and reducing the need for large surface areas or complex configurations, helical coil geometry helps in enhancing the overall energy efficiency of thermal systems. The advantage of helical coils is thus lower operational cost, reduced consumption of energy and longer lifecycles of a system, providing a cost-efficient solution for managing thermal in various industrial and commercial applications [19].

2.2. Fluid dynamics in helical coils

The geometry of the coil determines fluid flow in helical coils, in which the diameter varies smoothly along the length. Due to the tapering shape, velocity and pressure vary where fluid flows through the coil. Acceleration and deceleration areas in the flow arise from changes in cross-sectional area and cause turbulence and secondary flow patterns [20]. All these changes enhance the mixing behavior of the fluid, which means a better convection heat transfer. The motion of the fluid is no longer uniform, with various parts of the coil facing different flow behaviors that result in the formation of complex flow patterns [21].

This variability in velocity within a helical coil leads to an increase in the Reynolds number, which is a dimensionless quantity characterizing flow behavior [22]. With the increase in the Reynolds number, the flow goes from laminar to turbulent, and this is extremely helpful for convective heat transfer. Fluid particles in the turbulent flow are characterized by chaotic fluctuations, and better mixing of fluid particles takes place. This improves mixing, so that thermal gradients within the fluid are reduced with a much better distribution of temperature along with heat exchange from the fluid towards the heat transfer surface.

Besides promoting turbulence, the secondary circulation created by this helical geometry also increases the heat transfer. The centrifugal forces that are created along the geometry lead the fluid towards the outermost region of the coil and the inertial forces then create the rotational flow patterns which moves the fluid in a circular way [23]. These secondary flows interfere with the thermal boundary layer near the heat transfer surface, therefore reducing the amount of resistance toward heat transfer and allowing for more efficient thermal exchange. This fluid dynamic behavior is highly beneficial in applications requiring consistent and efficient heat transfer [24].

Benefits from fluid dynamics inside helical coils include the reduction of fouling and sedimentation risks [25]. The fluid continues to flow with a changing diameter and continues to carry particles, avoiding those stagnation regions that frequently are problematic in straight tubes or uniform helical coils. Induced turbulence and secondary circulation keep the fluid in motion and avoid the accumulation of undesirable materials on the heat transfer surfaces and ensure long-lasting performance of the system [26].

It is helical coils where fluid dynamics work in such a way that brings about better properties in heat transfer. Fouling effects are brought down by reduced acceleration of flow, turbulence and secondary circulation in helical coils [27]. Therefore improved thermal management has been possible in many applications-right from heat exchangers, solar thermal systems, refrigeration units and to industrial applications at large. Hence the advantages abound that the application of helical coils becomes very apt for uses requiring reliable as well as efficient heat transfer system.

3. AIR BUBBLES' IMPACT ON HEAT TRANSFER

Air bubbles in the process of heat transfer are a phenomenon that has gained much attention in many fluid dynamics and thermal systems, especially in applications like heat exchangers, boiling systems, and industrial processes involving two-phase flow [28]. The presence of air bubbles in a liquid causes a huge alteration in the properties of the fluid, such as its thermal conductivity, convective heat transfer, and flow dynamics. These bubbles can alter the heat transfer in both ways: positive as well as negative, depending upon the specific condition of the system and the flow characteristics.

Normally, air bubbles promote convective heat transfer in two-phase systems. As such bubbles rise within a liquid, they create a local turbulence or mixing in the fluid surrounding the rising bubbles that enhance the transfer coefficient. Thus, the breakup of the boundary layer that commonly occurs near a solid surface would better facilitate a higher rate of exchange between the fluid and the heat transfer surface. The bubbles, further reaching a hot surface, result in localized boiling or evaporation, which promotes an increased transfer rate of the heat. On the other side, air bubbles act as nuclei for vaporizing, which therefore increases the fluid's absorption speed from the boiling surface [29].

The presence of air bubbles is not always beneficial for heat transfer. When the size is too big or the gas occupies much of the fluid, the heat transfer process deteriorates. Large-sized air bubbles can disrupt the flow by producing various areas of low velocity and fluid stagnation and further depreciates the general heat transfer performances. In some instances, the accumulation of excessive bubbles hampers efficient fluid flow as well as fluid movement and heat exchange efficiency [30].

Another significant aspect is the distribution of air bubbles in the fluid, which determines the overall heat transfer performance. Uniformly distributed, smaller bubbles are very effective in improving heat transfer since they have more surface area that can interact with the fluid and the heat transfer surface. Larger bubbles or an uneven distribution of bubbles may cause less contact between the fluid and the surface, thereby reducing the heat transfer rate.

This demands manipulation of the size, distribution, and amount of air bubbles in the practical application to ensure maximum heat transfer. It can be achieved in different ways either by adjusting the flow conditions or introducing microbubbles into the system, or even specialized equipment, such as a bubble generator or gas injector, can be used. In airlift pumps, cooling towers, and some industrial reactors, managing the effect of air bubbles can be beneficial in improved thermal efficiency and better system performance and energy saving.

The effect of air bubbles on heat transfer is an extremely complex phenomenon that may improve or hinder the thermal performance in relation to their size, distribution, and type of flow. The dynamics of such phenomena are crucial for the optimization of heat transfer systems across industries from power generation to chemical processing and also in advanced cooling systems.

4. EXPERIMENTAL AND COMPUTATIONAL STUDIES

Two of the most fundamental approaches to understanding physical phenomena are experimental and computational studies, mainly in the realm of heat transfer, fluid dynamics, and engineering applications. The two approaches are often used in combination to develop a complete understanding of complex systems, validate theoretical models, and gain insight into real-world behavior [31].

Controlled laboratory experiments or those carried out in fields where parameters of physical observations and measurements of parameters involved could be made is the Experimental Studies. These experiments could be taken up by assembling a test rig for the actual time measurement, heat flux and fluid flow rates, temperature gradient and other measured variables within a closed system during heat transfer analysis. It will then be easy to measure air, liquids, or gases as it behaves when different conditions exist with the aid of thermocouples, flow meters, and pressure sensors. Experimental studies directly observe phenomena that provide empirical evidence useful for confirming theories or models [32].

One of the most important characteristics of experimental studies is that the results are real and directly measurable in actual performance under real operating conditions [33]. For example, it is possible to measure how fluid velocity and temperature affect bubble size and surface roughness or even to determine how these parameters influence helical coils or two-phase flows in terms of heat transfer [34]. However, there are disadvantages associated with experimental studies, including the cost and time required to perform them, and the likelihood of error or variation due to uncontrollable factors in the environment [35-37].

Computational Studies are essentially solutions of complex physical problems in numbers and through simulations [38]. In general, any process that deals with fluid flow to heat transfer may use a software that helps one make CFDs to make virtual models [39]. Generally, these simulations often rely on solutions to equations that include Navier-Stokes for fluid flow, or energy conservation equations in cases of heat transfer, to describe fluid behavior in detail and detailed heat exchange [40].

There are several benefits of computational studies. Complex systems that may be expensive to replicate or difficult to model can be studied [41]. Parametric studies for seeing how variations of different parameters influence system behavior without having to build a prototype are possible. Visualization of flow patterns, temperature distributions, and other aspects of the system become easier to carry out through computational studies, which are not easily measurable in a physical experiment. Computational methods, however, rely heavily on the accuracy of the mathematical models that are used and on all assumptions made in the simulations. In fact, these tools often validate and calibrate with experimental data to ensure the models give plausible predictions.

Experimental and computational studies have both strengths and weaknesses. While the experimental study will provide direct data and validation of real-world behavior, it often cannot be as thorough in terms of trying to investigate every possibility, especially for complex systems. Computational studies are more flexible and allow for a wider range of conditions to be explored, but they are only as accurate as the models they are based on. Thus, the most robust understanding of the system being studied is obtained by combining both approaches: using computational studies to predict behavior and experimental studies to validate and refine those predictions [42].

Experimental and computational studies are complementary methodologies used to probe and solve problems in engineering. Experimental studies supply direct data from real-world systems, while the computational study is able to present simulations and predictions that can make the understanding easier and guide further decision-making processes. Together, they form a powerful combination that advances research, improves the design and optimization of thermal systems, heat exchangers, fluid flows, and many other applications.

5. CONCLUSION AND FUTURE SCOPE

This study, therefore, indicates the substantial benefits of helical coils in heat transfer applications and their superior thermal performance because of unique fluid dynamics and geometry. The tapering design of helical coils improves fluid mixing, increases surface area, accelerates flow, induces secondary circulation, and reduces fouling—factors that all contribute to the optimization of convective heat transfer. The shape tends to lead to higher Reynolds numbers, where good transition from laminar to turbulent flow occurs, with an increase in the efficiency of heat exchange. In addition, the capability for continuous fluid motion reduces sedimentation and fouling, ensuring long term system reliability.

It has demonstrated the helical coils to be highly effective for a range of applications such as heat exchangers, solar thermal systems, refrigeration units, and biomedical devices, all of which rely on compactness, thermal efficiency, and the consistency of operation. The current study gives precious insight into some of the key mechanisms governing this enhanced heat transfer in helical coils and shows their potential as a way for improving the performance of different industrial thermal systems.

Future Scope

While this study provides a comprehensive analysis of the benefits of helical coils, several areas warrant further exploration to optimize their application:

1. **Advanced Computational Models:** Future research can focus on developing more sophisticated computational fluid dynamics (CFD) models to simulate the fluid dynamics and heat transfer characteristics of helical coils under various operating conditions. This would help in further optimizing the design of helical coils for specific applications.
2. **Material Innovations:** New materials with high thermal conductivity are being researched to improve the efficiency of constructing the coil. The development of corrosion-resistant materials or coatings may help prolong the lifespan of helical coils, particularly in processes where corrosive fluids are used.
3. **Experimental Research:** According to the paper, the effect of air bubbles in two-phase flow systems is of extreme importance. Further studies would be advisable that takes into consideration the role played by

helical coils within the mix of air and liquid related systems, like boiling and condensation. Laboratory experiments could thus throw light onto more benefits or issues related to heat transfer efficiency.

4. **Scale-up studies:** While the helical coil has proved quite efficient in smaller scales, a considerable amount of work needs to be done for their use on industrial large systems including power plants and large chemical processes. It may help broaden its usage in various fields by examining the cost feasibility and efficiency of the coil on larger scale.
5. **Integration with Renewable Energy Systems:** helical coils have great promise in the integration of renewable energy systems. Their efficiency will increase the use of solar thermal power generation and geothermal applications. Future studies should be made for their integration in these systems for optimizing energy conversion and storage.
6. **Optimize geometrical design:** The helical coil geometry - such as pitch, tapering angle, and number of turns could be further optimized for an optimum heat transfer rate with minimal pressure drop. This could allow design of much more compact and efficient heat exchanger configurations.

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