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Research Article

Enhancement of Heat Transfer in Helical Coils via Air Bubbles Injection: A Review

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ABSTRACT

This review paper is on Helical coil heat exchangers, which are extensively used in industrial processes, as they have the advantage of compact structure and high heat transfer efficiency. Injection of air bubbles in the working fluid is one promotional method to enhance heat transfer in such systems. The introduction of this technique enables flowing gas–liquid two phase which greatly disrupts thermal boundary layers and improves convection heat transfer. The air bubbles presence has been shown to facilitate fluid mixing and turbulence particularly in curved geometries and hence increase heat transfer coefficients. It is found that the improvement depends on bubble size, injection rate, coil diameter, and flow orientation. Particularly, by deriving optimal bubble flow, energy savings and performance improvement over current best can be accomplished at little to no design modification. Despite that, bubbles remain to be controlled in the distribution, while pressure drops are undesirable. Next, future research will be aimed at optimizing operating parameters and developing models for predicting bubble behavior. As a whole, air bubble injection is a cost effective scalable method of increasing heat transfer in helical coil systems deployed in refrigeration, chemical processing, and heat recovery applications.

Keywords: Helical coils, Heat transfer applications, Air bubbles, Fluid dynamics, Efficiency, Heat exchangers, Refrigeration.

1. INTRODUCTION

The helical coil heat exchangers have superior heat transfer, compactness, and capability to handle high pressure fluid, and therefore they are widely applied in chemical, energy, and HVAC companies. Because tubes are curved, they generate secondary flow patterns that increase thermal performance over and above straight tubes. Nevertheless, due to the increasing demand for energy efficient systems, there is a constant need to increase the heat transfer efficiency of such systems without compromising structural changes.[1]

Injection of air bubbles has become an attractive technique for further augmenting heat transfer in helical coils. Turbulence and mixing are augmented by the introduction of gas bubbles into a liquid flow through intensification of thermal boundary layer disruption and enhanced convective heat transfer rates. This provides a cheap, mass producible method with minimal mechanical alterations required. Investigations for optimizing injection parameters, understanding bubble dynamics, and quantifying its effect on performance under varying flow conditions are all receiving more and more attention in the research field.[2]

2. REVIEW IN HEAT TRANSFER WITH AND WITHOUT AIR BUBBLES INJECTION

2.1 Heat transfer from a helical coil without air bubbles injection:

Fouda et. al [3] Accurate thermal conductivity and thermal conductance across the interface between bulk and thin film materials must be known for correct quantification of heat transfer in the bulk and thin film materials. Steady state techniques, such as the guarded hot plate and heat flow meter methods are used for bulk materials measurements that require large samples sizes and long measurement times. Faster measurements can be made using transient methods such as the laser flash technique by measuring the temperature response to a heat pulse with high-throughput testing. In contrast, thin film materials demand more sensitive and precise techniques due to their small dimensions and interface-dominated thermal transport. The 3-omega method is widely used for thin films, utilizing an AC current to induce Joule heating and analyzing the resulting voltage response to extract thermal properties.

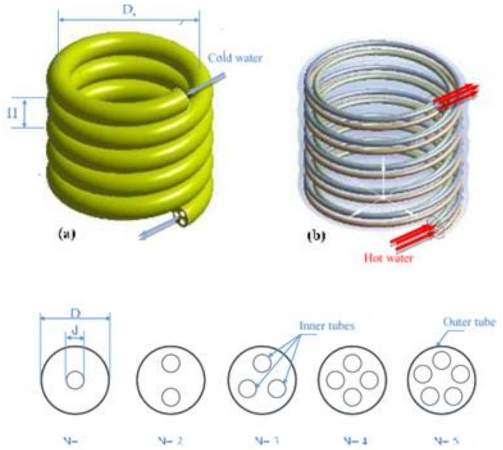

Fig. 1. Physical model: (a) Geometry of multi tubes in tube helical coil, (b) Inner tubes configuration (c) section views of the studied coils.

Sajjad Z.et. al. [4] Studied The condensing Magnetohydrodynamic (MHD) flow and radiative heat transfer of nanofluids in porous media, influenced by variable surface heat flux and chemical reactions, constitutes a complex and critical domain within thermal-fluid sciences, especially pertinent to energy, biomedical, and industrial applications. Nanofluids are designed colloidal suspensions of nanoparticles in base fluids that have improved thermal conductivity and heat transfer properties. When subjected to a magnetic field, the flow behavior of such fluids changes due to the Lorentz force, influencing both velocity and temperature profiles. The presence of porous media introduces additional resistance to the flow, modeled through Darcy's or Brinkman's equations, affecting the fluid dynamics and heat transport.

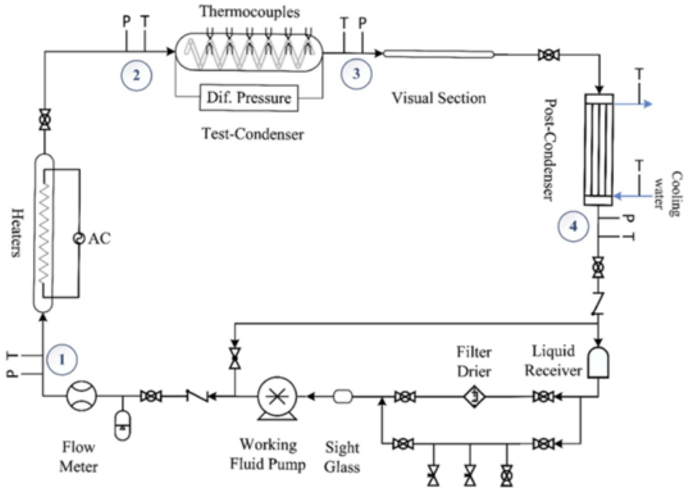

Fig. 2. Flow diagram of the refrigerant test loop.

Devanahalli G. Prabhanjan [5] et. al. Turbulent thermal flow in a multi tube-in-tube helically coiled heat exchanger becomes a problem of current interest on account of enhanced heat transfer performance and compact design. These exchangers consist, among others, of several inner convoluted tubes helically folded up in a larger outer tube, effecting efficient thermal interaction between fluids having opposite or parallel flow directions. Secondary flows are induced by the coils curvature which, has the effect of increasing turbulence and therefore improving the heat transfer at relatively low Reynolds numbers. The effect is further amplified in turbulent flow regime and hence the overall heat transfer coefficient is higher. The thermal performance is modeled by solving the governing equations of fluid flow and heat transfer, which are usually solved in the form of computational fluid dynamics (CFD) simulations or empirical correlations using experimental data.

R. Andrzejczyk et. al. [6] This study investigates the possibilities of passive heat transfer augmentation through the use of baffles to augment the energy efficiency of a shell and coil heat exchanger. The study examines the incorporation of strategically placed baffles in the shell side of the exchanger to interrupt fluid flow, improve mixing, and facilitate increased thermal interaction between the working fluid and the helical coil surface. Baffles induce secondary flows and turbulence, which reduce the thermal boundary layer and enhance the total heat transfer coefficient without requiring extra energy input. The experimental study utilised a modular shell-and-coil heat exchanger apparatus engineered to replicate actual operating circumstances. The module featured an integrated electric heater to ensure accurate temperature regulation during testing.

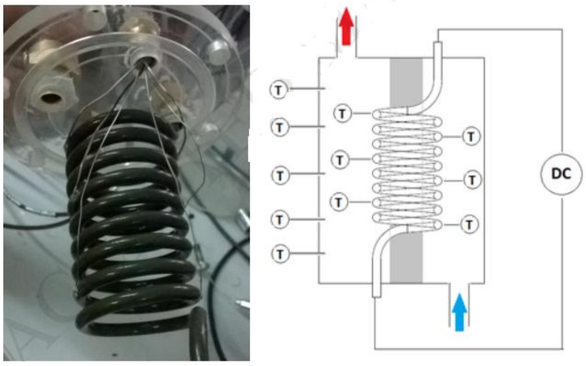

Fig. 3 Experimental testing module: at the left construction of the helical coil experimental module; at the right temperature sensor distribution

Hossein M. et. al. [7] Experimental investigations on heat transfer enhancement in shell coil heat exchangers with variable baffle geometry have gained significant attention due to their potential to improve thermal performance and energy efficiency. Shell coil heat exchangers are widely used in chemical, food processing, and HVAC industries due to their compact structure and high heat transfer area. The geometry and arrangement of baffles within the shell side play a crucial role in directing the flow and enhancing turbulence, which in turn improves convective heat transfer. Traditional segmental baffles often create dead zones and high pressure drops, limiting performance. By varying the geometry—such as using helical, inclined, or perforated baffles—the fluid flow can be better guided, reducing stagnation regions and enhancing thermal efficiency without significantly increasing pressure loss.

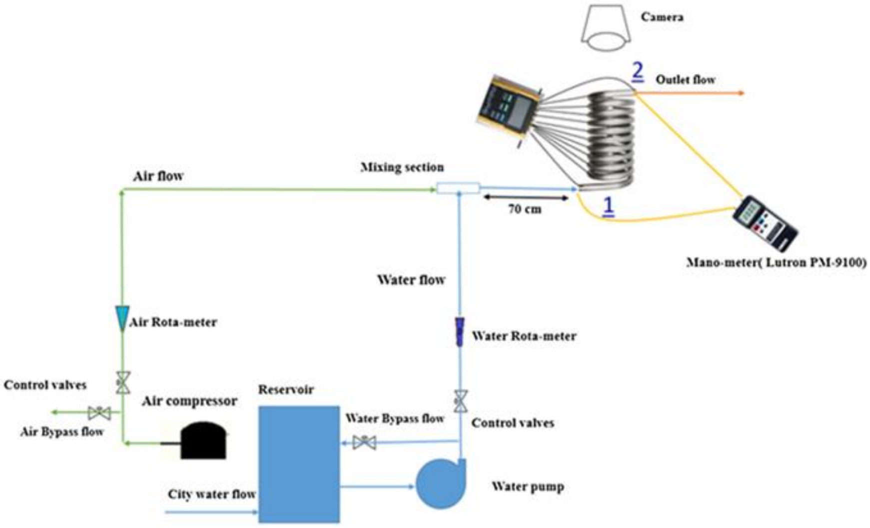

Fig. 4. Schematic view of the setup.

Ashkan Alimoradi [8] Experimental and numerical study on the heat transfer and flow properties of a helical coil heat exchanger has been conducted to show that it offers better performance when compared to straight tube type design, for certain flow conditions, on account of the secondary flow generated by the helical coil geometry. Due to compactness and superior thermal performance, helical coil heat exchangers are widely employed in power plants, chemical processing and refrigeration systems. These secondary flows are created by the centrifugal forces that are induced by the curvature of the coil which improve mixing of the fluid and the heat transfer coefficient. Generally for experimental studies, inlet and outlet temperatures, flow rates and pressure drops are measured in different operating conditions, such as different coil diameters and flow orientations, or fluid properties. Further to these, numerical simulations using computational fluid dynamics (CFD) are conducted for the purpose of visualizing and analyzing temperature and velocity fields within the coils.

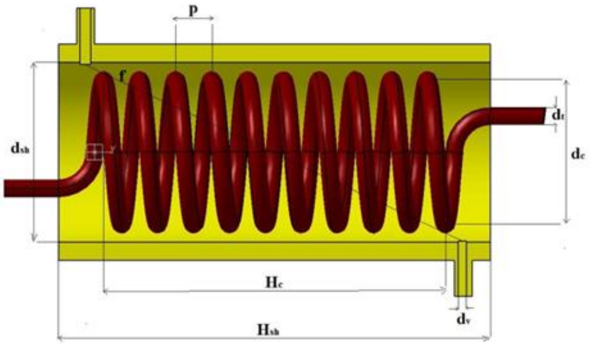

Fig. 5. Typical heat exchanger and its geometrical parameters

Sheeba A. et. al. [9] investigated A natural convection heat transfer from a helically coiled heat exchanger is experimentally investigated to evaluate thermal performance with no forced fluid motion by means of buoyancy driven flow. Helically coiled heat exchangers are characterized with compact structure and potential for the augmentation of heat transfer through the curvature induced secondary flow when operating under natural convection conditions. In such studies, the coil surface is usually immersed in a fluid medium, and the coil surface is heated above the surrounding fluid while studying the heat transfer process.Experimental setups measure variables like surface temperature, heat input, and ambient conditions to calculate key parameters such as the Nusselt number and heat transfer coefficient. Factors like coil diameter, pitch, number of turns, and orientation (vertical or horizontal) significantly influence the natural convection flow patterns and thermal performance.

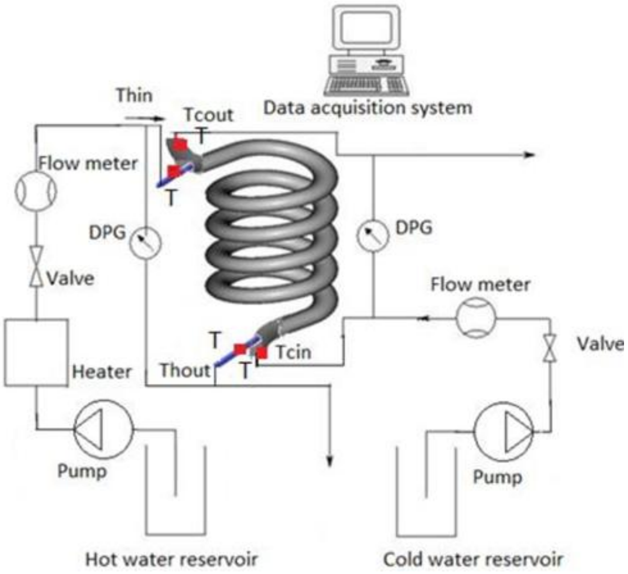

Fig. 6 Experimental setup

Chang-Nian C. et al. [10] investigated the Heat transfer deterioration in helically coiled heat exchangers operating within trans-critical CO2 Rankine cycles is a critical concern due to the unique thermophysical behavior of CO2 near its critical point. In trans-critical conditions, CO2 undergoes rapid property variations, particularly in specific heat and density, which can significantly impact heat exchanger performance. Helically coiled heat exchangers, while generally effective due to their compact structure and enhanced secondary flow, may experience heat transfer deterioration when CO2 flows at or near the pseudo-critical region.

Ehsan Izadpanah et.al. [11] investigated the A computational analysis of heat transfer and pressure drop in a helically coiled tube with spherical corrugation examines the synergistic effects of curvature-induced secondary flow and surface-induced turbulence on thermal efficiency. Helically coiled tubes inherently improve heat transfer due to centrifugal forces that facilitate fluid mixing, while the incorporation of spherical corrugations on the inner surface further disrupts the boundary layer, augmenting turbulence and consequently the heat transfer rate. Computational fluid dynamics (CFD) simulations are utilised to model fluid flow and temperature distribution across different Reynolds numbers, corrugation dimensions, and coil configurations. Critical performance metrics, including the Nusselt number, friction factor, and thermal performance factor, are computed to evaluate improvements and compromises.

Xinxin L. et. al. [12] studied Heat transfer distribution in a helical coil flow boiling system is a complex phenomenon influenced by the interplay of centrifugal forces, phase change dynamics, and coil geometry. In such systems, fluid enters the helical coil under subcooled or saturated conditions and undergoes boiling as it absorbs heat, leading to a two-phase flow regime. The coil's curvature induces secondary flow patterns that enhance fluid mixing and delay dry-out, promoting more uniform heat transfer along the tube length. However, the heat transfer distribution is not uniform due to variations in local flow rates, vapor quality, and wall heat flux. Studies show that the outer side of the coil often experiences higher heat transfer rates because of the centrifugal force pushing the liquid towards the outer wall, enhancing liquid film thickness and nucleate boiling.

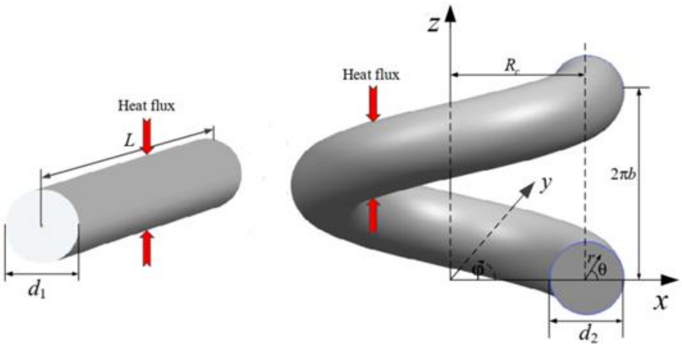

Fig.7. Calculating geometries adopted in the simulation.

Zhang C. [13] investigated In such configurations, the helical geometry introduces centrifugal forces, which enhance turbulence and mixing between the two phases, thereby improving heat transfer performance. The experiment investigates the system under non-boiling conditions, ensuring that the thermal behavior is driven purely by convection and phase interaction rather than latent heat. To judge the thermal efficiency as well as irreversibility, the parameters are measured which include heat transfer coefficient, pressure drop, and entropy generation rates. It is shown that the presence of air in vertical two-phase systems has a significant effect on flow distribution and heat transfer caused by slug or churn flow patterns. Entropy analysis also helps in locating regions where energy is being degraded; a crucial aspect for thermodynamic performance optimization. It is demonstrated that the interaction of phase, coil geometry, and flow rate have a major effect on thermal and entropic performance. The results of this experimental investigation give useful information for design of efficient heat exchangers in industries such as HVAC system, cooling tower, and chemical process industries where flow is in two phase condition.

B.K. Hardik and S.V. Prabhu [14] The focus of the presented is on evaluating the thermodynamic performance of helically coiled tube heat exchangers from an exergy point of view. However, exergy analysis allows to gain a more in depth understanding of the system's energy use by defining exergy losses caused by heat transfer and fluid flow irreversibility's. However, unlike conventional energy analysis, exergy efficiency is able to measure how effectively available energy is being used hence a better performance indicator. In this investigation the helically coiled tube geometry of a shell geometry is examined for various operating conditions such as flow rate changes, inlet temperatures changes and fluid properties changes. Therefore, the curvature of the helical cooper coil improves heat transfer through mixing and turbulence, however, it can lead to increased pressure drop which is an important contribution to the exergy destruction. Exergy efficiency is shown to increase with Reynolds number, as well as with optimized temperature gradients, but too great pressure loss, as well as poor thermal matching, can drastically reduce it.

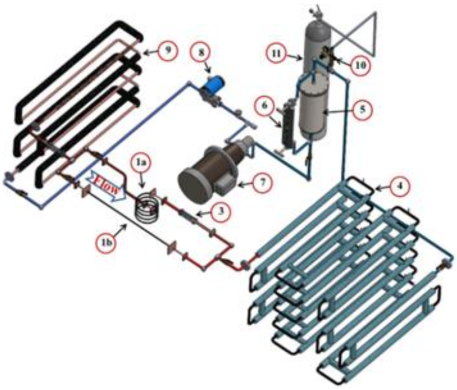

Fig 8. Isometric veiw of experimental set-up

2.2 Heat transfer from a helical coil with air bubbles injection:

Korhan Ö. et. al. [15] Experimental and numerical investigations normally map heat transfer coefficients along the coil from local wall temperatures, pressure drop and vapor distribution. Heat transfer can be locally deteriorated by the existence of flow instabilities such as intermittent dry-out or vapor slugging. This knowledge is key for the design of efficient boiling systems applicable to systems such as nuclear reactors, refrigeration cycles, and compact heat exchangers where the thermal management and the system stability are important.

Fig. 9. A schematic illustration of the experimental set-up.

Saleh K. and Abdolrahman D. [16] Results usually demonstrate that spherical corrugations result in a considerably higher Nusselt number than smooth coils and therefore also enhance convective heat transfer. The improvement, however, is accompanied by a concurrently increasing pressure drop because of an increasing flow resistance. Usually, for example, optimization studies are conducted aiming to determine configurations that maximize heat transfer with a minimum pressure loss. This research is very important for compact heat exchanger applications, particularly in the energy, HVAC sectors and in chemical processing systems due its significance of large thermal efficiency and small footprint. These numerical insights aid in the development of more efficient and energy efficient heat exchanger designs.

Fig. 10 Schematic diagram of setup

Saleh K. [17] Thus the effect of specific experimental parameters including coil diameter, mass flux, pressure, and inlet temperature on the extent of deterioration are investigated experimentally and numerically. Under low mass flow or inappropriate operating conditions, performance is also further aggravated by maldistribution of heat flux and local dry out. It is necessary to understand these phenomena to improve the design and operation of trans-critical CO2 heat exchangers. Mitigation strategies to be effective include changing flow orientation, use of enhanced surfaces, or addition of multi-pass configurations to stabilize thermal performance. Information such as this is critical in order to ensure the safe deployment of supercritical CO2 into compact, high efficiency power and refrigeration systems.

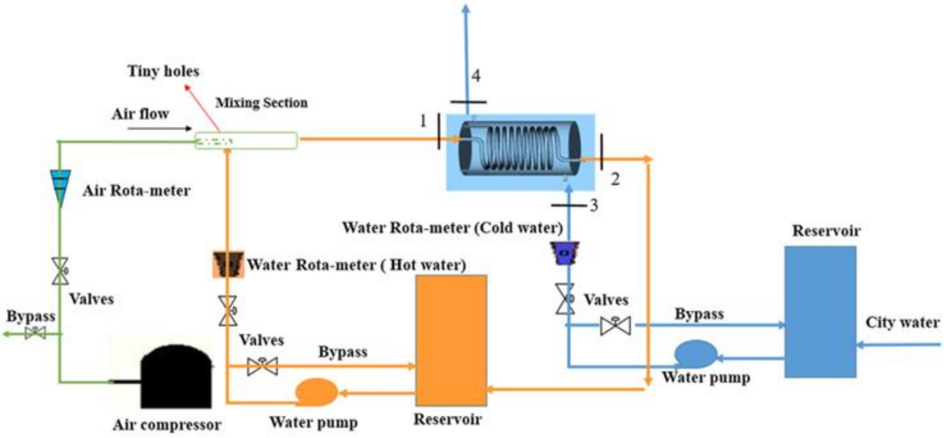

Fig. 11. Schematic diagram of the experimental setup.

Hamed S.et al. [18] The effect of air bubble injection to the thermal performance of a vertical shell and coiled tube heat exchanger was studied in this work. These mixing intensity and heat transfer characteristics change meaningfully by the introduction of air bubbles into the shell side of the fluid flow and may provide the potential to increase efficiency of the exchanger. In order to analyze the effect of these parameters on the performance of exchanger, experiments were performed at different air flow rates and water inlet temperatures. The effectiveness analysis of the heat exchanger was evaluated using the Number of Transfer Units (NTU) method and a detailed exergy analysis was carried out in terms of irreversibilities and quality of energy transfer. Results show that the convective heat transfer coefficient due to air bubble injection improves the NTU values and lower the exergy destruction. The paper also determines optimal operating conditions in such sense that the energy efficiency and thermal performance are maximized. These results are useful in augmenting heat transfer in compact exchangers and thereby, for the industrial applications that demand high thermal efficiency in small spaces.

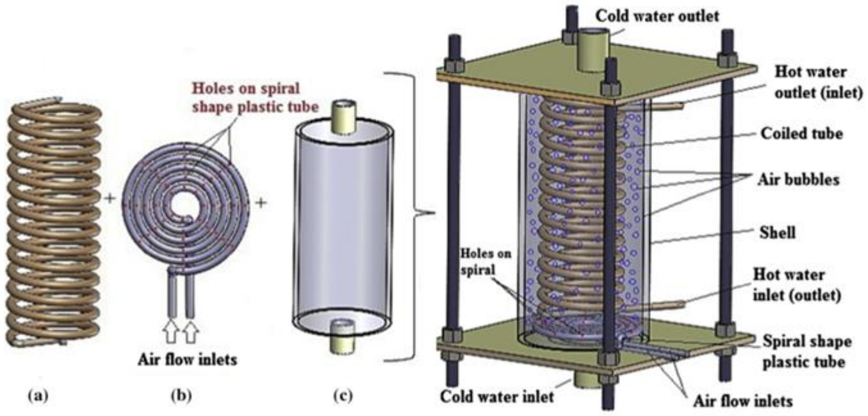

Fig. 12. A general view of test section, its component and air bubble injection method.

Amin M. et al. [19] The aim of this study is to investigate the utilization of air bubble injection technique to enhance heat transfer and minimize the pressure drop characteristics in a vertically placed shell and coiled tube heat exchanger. Aerated flow in the shell side in the form of bubbles introduction into the flow enhances turbulence, breaks thermal boundary and enhances the fluid mixing, all of them contribute to an increase of heat transfer rates. The thermal performance of the vented cavity was compared to conventional channels and tested under various injection rates and inlet temperatures as well as flow rates to analyze these effects on the thermal performance and hydrodynamic behavior. The key performance indicators, namely, the overall heat transfer coefficient, Nusselt number and pressure drop across the shell side are evaluated. The study was performed using a performance evaluation criterion (PEC) to balance thermal enhancement versus pressure loss. The results show that, moderate air injection enhances heat transfer considerably under tolerable increase in pressure drop, whereas additional air injection does not provide proportional returns. Optimal air injection conditions maximizing heat exchanger performance without excessive pumping power requirements are identified in the study, which allows for valuable design insights in the development of compact and energy efficient thermal systems.

D. Panahi [20] This experimental study has been employed for investigating the impact of air bubble injection in a vertical shell and coiled tube heat exchanger in terms of Nusselt number and the effectiveness evaluation. Combining this air injection into the water flow on shell side makes higher turbulence and boundary layer disruption in order to enhance convective heat transfer. The experiments were carried out for different air injection rates, fluid flow conditions and inlet temperatures. Based on measured temperature and flow data, it was calculated the Nusselt number that represents convective heat transfer enhancement and the thermal effectiveness, which indicates the performance of the exchanger. The results indicate that an increase in the shell side Nusselt number with air injection is considerable and the enhancement is attributed to the increased mixing and heat transfer rates. Under optimal air flow conditions, effectiveness also greatly improved. However, above some air injection threshold, additional heat transfer was achieved at the cost of higher flow resistance and instability. The fundamental insights provided by the study pertain to passive means by which heat transfer can be enhanced and are applicable to the design of energy efficient, compact heat exchangers.

Samira P. et. al. [21] In this study, an experimental investigation of thermal and energetic performance of an air bubble injected double–tube heat exchanger has been presented. Turbulence and thermal mixing are increased by introducing air bubbles to increase heat transfer and evaluating energy losses associated with such air bubbles. To quantify the influence of air injection rate, fluid flow rate and inlet temperature on heat exchanger performance, experiments were conducted with air injection rates, fluid flow rates, and inlet temperatures varied. Thermal metrics of the same such as the heat transfer coefficient and the Nusselt number as well as the exergy-based parameters (exergy destruction, etc.) were analyzed. It is shown that air bubble injection substantially improves thermal performance by increasing the Nusselt number and overall heat transfer. Simultaneously, exergy analysis shows a decrease of irreversibility's and an enhancement of second-law efficiency in comparison with optimal conditions of bubble injection. However, too much bubble injection will require pressure penalties and diminishing returns. It is concluded that passive control of bubble injection is a viable approach for enhancing compact double tube heat exchanger thermal and exergetic performance.

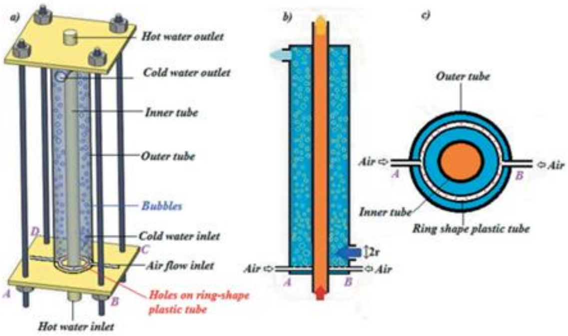

Fig 13. Test section and injection technique: (a) total view, (b) front view, and (c) top view.

Emad M.S. El-Said, M.M. Abou Al-Saad [22] The effect of air injection on the thermal performance of a horizontal shell and multi tube heat exchanger equipped with segmental baffle is investigated in this experimental study. The thermal boundary layer is disrupted by the introduction of air bubbles to achieve enhancement in the heat transfer characteristics of the shell side flow. The overall heat transfer coefficient, Nusselt number and pressure drop were evaluated at different air flow rate, water inlet temperature, and flow velocity. Directions are imparted to the fluid through the baffles which run across the tubes, the effect of the baffles with bubble induced agitation strongly enhances thermal mixing. It is found that moderate air injections significantly improve the heat transfer performance with a minor increment of pressure drop. However, when air rates are too high, flow is maldistributed and efficiency is reduced. The thermal effectiveness of a heat exchanger is found optimal conditions that are offered by the heat exchanger itself. This work presents practical guidance for high performance and energy efficient heat exchangers in industrial thermal systems.

Mohammad M. et. al. [23] This thesis offers experimental investigation of thermal and exergetic performance of double pipe heat exchanger, injected with air bubbles into the annular side. Air bubbles are introduced into the air core to enhance turbulence, fluid mixing and destabilize the thermal boundary layer to enhance heat transfer efficiency. The first law and second law performance indicators were assessed under different air injection rates, flow velocities, and temperature conditions. These have been investigated and key thermal parameters such as the overall heat transfer coefficient, Nusselt number as well as exergy related parameters including exergy destruction, exergy efficiency and irreversibility distribution evaluated. These show that controlled air injection can significantly increase heat transfer rates as well as decrease exergy losses especially for moderately injected cases. However, flow instabilities and increased pressure drop limit the returns of growing air flow rates. It is concluded that air bubble injection is an effective passive technique to increase heat exchanger performance when optimized and may provide useful design guidelines for the thermal system design.

Sajida L. Ghashim and Ayser M. Flayh [25] The effect of air bubble injection into a helical coil heat exchanger employed in a cold thermal energy storage (CTES) system is experimentally investigated for the purpose of enhancing local heat transfer. To enhance the heat transfer during the charging (cooling) process, air bubbles are introduced into the shell side fluid in order to enhance the turbulence and disrupt the boundary layers. With varying air injection rates, flow velocities, and inlet temperatures, the thermal behavior of the heat exchanger was studied with the experiments. The efficiency of system, by analyzing performance metrics like the heat transfer coefficient, Nusselt number and temperature gradients was studied. It is found that bubble injection leads to a significant enhancement in convective heat transfer, which is caused mainly by increasing fluid mixing and surface renewal rates at moderate operating conditions. Better thermal response and quicker refrigeration of the storage medium is the result of helical coil geometry with bubble induced agitation. The potential to improve CTES system charging efficiency is illustrated by this technique, and leads to more efficient use of low temperature energy sources in energy storage applications.

Ahmad Z. et al. [23] Experimental investigation that the heat transfer performance in the region of the lower heat exchanger tube can be enhanced through injection of air bubbles into the annular region of a horizontal double pipe heat exchanger. The additional turbulence and disturbance to the thermal boundary layer due to the injection of air bubbles causes improvement on convective heat transfer between the hot and cold fluids. An increase in the Nusselt number and overall heat transfer coefficient was observed as a result of the study, especially at moderate air flow rates. Moreover, a relatively small increase in pressure drop improved the thermal performance, suggesting a good energy input versus performance gain compromise. At air injection rates beyond an optimal, the induced turbulence was ineffective in increasing mixing because of the onset of flow instability, increased pressure loss, and possibly bubble coalescence. Thus, it is important to have good control of bubble injection parameters for optimal performance. Basically, air bubble injection is a passive and simple technique to enhance the double pipe heat exchangers efficiency. The findings of these results are very useful for compact, energy efficient thermal systems design, where both industrial and renewable energy applications serve.

H. Sadighi Dizaji and S. Jafarmadar [24] Experimental results indicate that the thermal performance of a vertical shell and helical coiled tube heat exchanger is very sensitive to the size of air bubbles that are injected. Due to a higher surface area to volume ratio for the smaller bubbles, they are regarded as being more effective in the enhancement of heat transfer by allowing the better interaction of the bubble with the fluid and a more uniform distribution of turbulence caused by the bubbles. The flow residence time is increased and the thermal contact is improved as these bubbles store longer in the flow. Conversely, taller bubbles normally rise fast through the shell side fluid producing flow separation and local mixing with reduced effectiveness for sustaining fairly consistent heat transfer enhancement. All bubble sizes enhanced convective heat transfer above that of non bubbled condition, but optimum thermal performance is obtained with small to medium sized constant injection rate bubbles. Excessive large size of the bubbles introduced flow instability, marginally higher pressure drop with no corresponding gain in heat transfer. By controlling the bubble size in a shell and coiled tube heat exchanger, the thermal performance can be improved to its maximum, while hydraulic penalty is still very minor compared to vertical shell and coiled tube heat exchanger used in compact and energy sensitive applications.

Importance of Helical Coil Geometry in Heat Transfer

The heat transfer performance can be effectively enhanced due to the compactness of helical coil geometry and its nature of developing secondary flow patterns. Helical coils are not straight tubes, and hence, the curvature of the coil causes centrifugal forces to be created in the flow as the fluid moves around the coil resulting in the creation of secondary flows within the coils, or Dean vortices. The reason for this is the influence of these vortices which continuously disturb the thermal boundary layer, thus promoting enhanced mixing and creating additional convective heat transfer. Helical coils also have a greater surface area per unit volume and are hence efficient in transferring the heat in small spaces, making them perfect for compact thermal systems. The more uniform temperature distribution and elimination of hot and cold spots inside heat exchanger is possible because of the continuous curvature. Additionally, helical coil configurations have superior thermal responsiveness and pressure drop characteristics and therefore are advantageous in applications where phase change or variable heat loads are present. The advantages of helical coil heat exchangers offer suitable applications for power generation, chemical process, refrigeration and renewable power systems to achieve high rates of heat transfer and compact designs.. [25-26].

3.1 Enhanced Fluid Mixing

Critical phenomena for enhanced fluid mixing are of great importance in thermal and chemical engineering processes to enhance the efficiency of heat and mass transfer in a host of applications. Enhanced mixing promotes uniform temperature and concentration distributions and, thus, decreases thermal and concentration boundary layers, which are most often the cause of limiting mass and heat transfer rates. These can be achieved through some passive or active methods such as introducing the turbulence promoter or air bubble injection or use of helical geometries or mechanical agitation. In particular, a secondary flow or vortex, which is caused by curved flow path, such as helical coil, or by introducing air bubbles in liquid medium produces a continuous disturbance to the flow field and increases the rate of fluid particle interaction. In addition, it increases the rate with which energy and matter are exchanged between different flow regions. In addition, improved mixing enhances the control of reaction kinetics during chemical processes, achievable temperature control during heat exchangers, and reduced thermal stratification of storage systems. In addition, improved mixing also leads to downsizing equipment and reducing operating costs as well as improving overall process efficiency. This makes understanding and using improved fluid mixing mechanisms critical to the optimisation of performance in such industrial systems which involve fluid flow and heat transfer.

3.1 Increased Surface Area

One of the basic principles of augmentation of heat and mass transfer processes is the increased surface area mainly in thermal systems like heat exchangers, reactors and evaporators. A larger surface area results in increased interface between the fluid and the heat transfer surface, thus valve the rate of energy exchange. In the case of heat exchangers, fins (extended surfaces), corrugated tubes, helical coils and the like are used as geometrical changes to maximize the surface area that can be fitted into a restricted volume. These configurations increase the contact area through which more efficient heat conduction and convection can occur between fluids at different temperature. In this case, it is particularly useful due to limited space in a compact heat exchanger design and the requirement of high thermal performance. Furthermore, higher surface area is very effective in enhancing surface dependent phase change processes such as condensation or boiling. In chemical processes a larger surface area means better mass transfer i.e., more reactant in contact with catalytic or reactive zones, thus the reaction rate. But it’s important to balance enlargement of surface area with that of associated pressure drops and likely increased flow resistance to performance of the system. Overall, increasing surface area offers one of most effective ways, if not the most effective, and it is most widely adopted method for improving the energy efficiency and thermal performance in engineering systems.

3.2 Flow Acceleration and Secondary Circulation

Due to the special capability to create flow acceleration and secondary circulation in the fluid, the helical shape of the coil becomes important in enhancing the heat transfer performance. When fluid goes through the curved path of the helical coil, centrifugal forces force it to its outer wall as it moves along the tube. Thus the formation of secondary flow patterns, so called Dean vortices, is being established, which circulate perpendicular to the main flow direction. They continuously disturb the thermal boundary layer, resulting in much better mixing of fluid layers and a corresponding substantial increase of convective heat transfer rates. Moreover, the helical configuration generates piecewise acceleration and deceleration of the flow because of the alteration of the flow direction and geometry, which enhances shear force and turbulence. The helical coils are effective in the low Reynolds number regimes where the turbulent heat transfer scenario described above can also be observed even when the flow is laminar. In addition, due to the compact nature of the helical coil, a larger heat transfer surface area can be accommodated in a small volume, helping to save potentially useful space while still providing sufficient thermal performance. Overall, this helical shape of coil is the key to efficient thermal exchange through the pay load of geometric advantage and better fluid dynamics for compact high performance heat exchanger applications.

3.3 Reduced Fouling and Sedimentation

Advanced heat exchanger geometries, particularly those using helical coil designs, offer significant benefits of reduced fouling and sedimentation. In conventional straight-tube heat exchangers, flow of the fluid can be uniform with little tendency towards mixing, producing stagnant zones in which suspended particles eventually settle and deposits similarly accumulate with time. However, helical coils due to curvature provide continuously acting centrifugal forces and secondary flows that give rise to agitation in the normal direction to the flow within the entire cross section. The dynamic flow patterns formed promote the minimizing of the existence of low-velocity regions and dead zones and thus reduces the chance of particles depositing and biofouling. Furthermore, the greater shear stress on the internal surfaces caused by enhanced turbulence assists in mechanically dislodging particles before their attachment, keeping heat transfer surfaces cleaner for longer duration of operation. Besides the reduction of the heat transfer efficiency the frequency of maintenance shutdowns is also reduced and the operation life of the equipment is extended. In addition, a lower fouling can result in more stable pressure drop and a more stable thermal performance, a requirement in application with long term or continuous use. Given its inherent self cleaning features; the self cleaning helical coil designs provide a passive yet very effective fouling and sedimentation mitigation strategy which makes them suitable for challenging industrial and process application.

4. APPLICATIONS OF HELICAL COILS IN HEAT TRANSFER SYSTEMS

Helices have been widely used as compact structure, high performance heat transfer devices for various flow conditions. Helical coil heat exchangers are preferred in industrial applications like chemical processing; petroleum refining; memory and heat recovery systems because they can amplify heat transfer even under laminar regime. It induces secondary flows that enhance mixing and reduce boundary layer resistance, and this provides for a very significant increase in the convective heat transfer coefficient. The properties are conducive, in particular, for fluids of high viscosity or for processes where pressure drops have to be kept to a minimum without having to sacrifice thermal efficiency.

Helical coils are valuable in solar thermal collector, geothermal and nuclear reactor energy and power generation systems. Due to their high temperature and pressure capabilities plus their space conserving design, these materials are good for use in compact thermal systems. Helical coils are used in cold and thermal energy storage applications in order to support fast charging and discharging cycles, providing high surface area and efficient mixing of the fluid. They also exhibit their responsive thermal behavior, which due to them being able to respond to dynamic load conditions makes for good energy transfer and contributes to system stability and energy utilization.

Helical coils are used in heat exchangers, specifically in evaporators, condensers, and liquid heating or cooling systems in HVAC or food processing where care to thermal control and hygiene is necessary. The geometry of the coil alleviates natural turbulence minimizing fouling and sedimentation allowing operation for longer periods with little maintenance. For many reasons, the use of helical coils can be advantageous in food and beverage processing where product quality and safety are key issues, as they provide efficient heat exchange with uniform temperature distribution. The pipes are a flexible solution for a variety of thermal management requirements in many industries due to their adaptability and ease of installation into complex piping layouts.

5. FUNDAMENTALS OF HEAT TRANSFER IN HELICAL COILS

The fundamentals of heat transfer in helical coils are same with that of straight tubes, conventional heat transfer by conduction, convection or radiation, while the coiled form adds its complexity and advantages. As fluid flows in the curved path, the curvature of the coil brings in centrifugal force acting on it, leading to a pressure difference across the cross section. This leads to development of secondary flow patterns, Dean vortices. Even under low Reynolds number flow conditions (laminar flow), the effects of these vortices are to continuously disturb the thermal boundary layer near the tube wall and in consequence to enhance convective heat transfer. Such helical coils have an increased turbulence and therefore give greater Nusselt number than straight tubes, making them more efficient under heat transfer.

One more important fact is that helical coils enhance the compact design, i.e. it allows to have a larger surface area within a limited volume. Systems under space restrictions benefit from this greatly. The helical configuration also allows for better fluid distribution, significantly reducing the occurrence of flow maldistribution or dead zones can be found in shell and tube heat exchangers. As a result, flow direction continuously changes, and as a result the fluid interacts more frequently with the walls of the tube throughout the coil length, achieving more uniform temperature profile and more efficient heat exchange throughout the length of the coil.

Furthermore, helical coils offer enhanced thermal performance with reasonable pressure drops. The increased friction factor due to the curvature of the coil is, however, slightly overpowered by the additional heat transfer. Helical coils are thus fit for application where high thermal efficiency is needed but at the same time energy savings are desired. By utilizing these fundamentals, helical coils can be adapted for a number of uses from industrial heating and cooling systems to compact heat exchangers used in renewable energy systems through better performance and reliability that results from the inherent thermal advantages.

a. Importance of helical coil geometry in thermal applications

It is found that the helical coil geometry has an important role in improving the thermal performance of heat exchange systems. The centrifugal forces induced by flow inside curved helical coils differ from straight tubes due to the curvature of the coils. The relative l/mh shape also arises through these forces and leads to secondary flow patterns - Dean vortices - that enhance fluid mixing throughout the cross-section of the tube. This higher heat transfer coefficient is due to the continual disturbance of the thermal boundary layer. The fact that this heat transfer mechanism does not depend on the evolution of a turbulent boundary layer, especially in the interest of small heat transfer enhancement factors, makes helical coils especially effective in applications that require compact and efficient thermal performance, even under laminar flow conditions..[32]

An advantage of helical coil geometry is that they provide a significantly higher surface area in a compact volume. Due to the coiled configuration, a great amount of tube run can be fitted into a small area, and hence the heat transfer area is more. Especially it is useful in situations where the amount of space is limited, for example, in aerospace, naval and portable energy systems. Furthermore, the tighter configuration enables greater use of space both shell side and tube side arrangements, and thus, allows for better thermal design and integration into existing systems.[33]

The helical design of the box also helps in uniform temperature distribution and effective fluid flow in the box. When the fluid flows through the coil, the flow direction is changing and reduces the occurrence of such hot or cold spots. Product requires precise thermal control, such as chemical reactors, food processing systems and pharmaceuticals, this feature is valuable. Additionally, the increased turbulence reduces the likelihood of fouling and sediment deposition and together lead to maintaining long term performance with less maintenance needs.[34]

Within the thermal application utilizing phase change including condensation and boiling, helical coil have positive heat transfer rates because of their dynamic fluid behavior and high surface area. Their operation under highly pressurised and temperature conditions with good thermal response makes them very suitable for use in energy storage, process heating, and waste heat recovery systems. Overall, the special geometry of helical coils has resulted in a higher thermal efficiency and higher operational reliability, which is why this kind of heat transfer devices is applied in a variety of heat transfer applications.[35]

b. Fluid dynamics in helical coils

Fluid dynamics in helical coils differ significantly from those in straight tubes due to the curvature of the coil, which introduces centrifugal forces acting on the flowing fluid. As the fluid navigates through the curved path, it is subjected to a radial pressure gradient that generates secondary flows—specifically, a pair of counter-rotating vortices known as Dean vortices. These vortices circulate perpendicular to the main flow direction, enhancing mixing across the tube's cross-section. The result is a disruption of the velocity and thermal boundary layers, promoting more uniform fluid temperature and velocity profiles. This leads to an increase in the convective heat transfer coefficient, even in flows that would otherwise be laminar in a straight tube.[38]

The Dean number, a dimensionless parameter that combines the Reynolds number and the coil curvature, characterizes the intensity of these secondary flows. A higher Dean number indicates stronger secondary circulation and greater mixing. [39]This enhanced mixing is advantageous in applications requiring efficient thermal exchange, as it improves heat transfer without the need for external energy input. The constant development and reorganization of the flow structure within the coil also prevent the formation of stagnant zones, which are often responsible for fouling and reduced performance in heat exchangers.[40]

Additionally, fluid acceleration and deceleration due to the curvature and pitch of the helical coil influence pressure drop and shear stress within the tube. While the friction factor may be slightly higher than that in straight tubes, the benefits of improved heat transfer often outweigh the energy penalty.[41] The continuous reorientation of the flow direction also promotes better particle suspension and reduced sedimentation. These characteristics make helical coils particularly suitable for multiphase flows, non-Newtonian fluids, and applications where enhanced fluid dynamics are essential to maintaining high thermal efficiency and system reliability.[42]

5. AIR BUBBLES' IMPACT ON HEAT TRANSFER

The injection of air bubbles into a liquid flow is a passive heat transfer enhancement technique that significantly improves thermal performance in various heat exchanger configurations. When air bubbles are introduced into the shell-side or fluid domain, they interact with the liquid flow, promoting greater mixing and disturbance of the thermal boundary layer. This leads to an increase in the convective heat transfer coefficient, particularly in vertical or horizontal configurations where natural buoyancy and flow direction complement the movement of the bubbles.[43]

One of the primary mechanisms behind this enhancement is the agitation caused by rising bubbles. As the bubbles move upward, they create localized turbulence and induce secondary flows within the liquid. These effects disrupt the otherwise smooth thermal gradients near the heated or cooled surfaces, resulting in more effective energy exchange. Smaller air bubbles tend to remain suspended longer and mix more uniformly, while larger bubbles may rise rapidly but create stronger flow disturbances in shorter intervals.[44]

The size, frequency, and distribution of the air bubbles are critical in determining their impact. Optimized bubble injection ensures improved heat transfer without significantly increasing the pressure drop or causing flow instability. However, excessive bubble injection or improper distribution can lead to coalescence, channeling, and uneven flow, which may reduce thermal efficiency or lead to operational challenges.[45]

In systems like helical coil or double pipe heat exchangers, air bubble injection is especially effective due to the enhanced contact between the fluid and the coil surface. [46]The geometry supports prolonged bubble-fluid interaction and better mixing, further boosting heat transfer. These systems benefit from improved performance without the need for major structural changes or active mechanical components.[47]

In general, it is found that incorporating air bubbles into liquid flows is a simple and inexpensive means of increasing liquid heat transfer. Notable energy gains in the thermal efficiency are obtained, especially in compact or low flow systems, and within applications as energy recovery, chemical process and cooling technologies. Moreover, due to proper control of injection parameters of optimal performance able to keep stability of system.[48]

6. CONCLUSION AND FUTURE SCOPE

The findings of the experimental and analytical work demonstrate that the method of air bubble injection is effective for increasing heat transfer for helical coil heat exchangers. The secondary flow generation resulting from the unique geometry of helical coils already enhances convective heat transfer in coils and, together with air bubble injection, the effect is increased significantly. Localized turbulence and disruption of the thermal boundary layer due to air bubbles of the coil induces mixing of fluids as well as increases in the rate of heat exchange between the coil and the surrounding fluid. It was found critical for maximum enhancement to be achieved without causing adverse effects such as flow instability or excessive pressure drop, that optimal bubble size and injection rate were used.

The additional effect of helical curvature and bubble induced agitation makes this approach especially suitable for compact systems that have constraints both in space and in energy efficiency. Additionally, the method is passive and demands little or no modification of the system, which results into low cost and easy implementation in a present setup. In addition, the technique keeps fluid particles suspended and therefore prevents fouling and sedimentation, enabling improved surface contact and therefore an enhanced operational life along with reduced maintenance.

In the future, more advanced studies can focus on optimizing the bubble size distribution, injection orientation, and flow rates using computational fluid dynamics (CFD) models and real-time flow visualization techniques. Additionally, the integration of this technique in multiphase and non-Newtonian fluid systems can be explored to expand its industrial applicability. Investigations into hybrid methods—combining bubble injection with nanofluids or surface modifications—can further boost performance. With growing demand for energy-efficient and compact heat exchange solutions, air bubble-assisted helical coil heat exchangers hold significant potential for applications in power generation, renewable energy systems, chemical processing, and thermal storage technologies.

REFERENCES

[1] Zhao, D., Qian, X., Gu, X., Jajja, S. A., & Yang, R. (2016). Measurement techniques for thermal conductivity and interfacial thermal conductance of bulk and thin film materials. *Journal of Electronic Packaging*, *138*(4), 040802.

[2] Zhang, C., Zheng, L., Zhang, X., & Chen, G. (2015). MHD flow and radiation heat transfer of nanofluids in porous media with variable surface heat flux and chemical reaction. *Applied Mathematical Modelling*, *39*(1), 165-181.

[3] A. Fouda , S.A. Nada , H.F. Elattar , H.A. Refaey , A. Bin Mahfouz , Thermal Performance Modeling of Turbulent Flow in Multi Tube in Tube Helically Coiled Heat Exchangers, International Journal of Mechanical Sciences (2017), doi: 10.1016/j.ijmecsci.2017.12.015

[4] Sajjad Zakeralhoseini, Behrang Sajadi, Mohammad Ali Akhavan Behabadi, Soorena Azarhazin and Hamidreza Fazelnia , 'Experimental investigation of the heat transfer coefficient and pressure drop of R1234yf during flow condensation in helically coiled tubes' International Journal of Thermal Sciences 157 (2020) 106516

[5] Devanahalli G. Prabhanjan, Timothy J. Rennie and G.S. Vijaya Raghavan, 'Natural convection heat transfer from helical coiled tubes', International Journal of Thermal Sciences 43 (2004) 359–365

[6] Andrzejczyk R, Muszynski T, Gosz M, Experimental investigations on heat transfer enhancement in shell coil heat exchanger with VARIABLE Baffles GEOMETRY, Chemical Engineering and Processing - Process Intensification (2018), https://doi.org/10.1016/j.cep.2018.08.017

[7] Hossein Moradia, Amirhossein Bagheria, Maziar Shafaeea, Saleh Khorasani, 'Experimental investigation on the thermal and entropic behavior of a vertical helical tube with none-boiling upward air-water two-phase flow', Applied Thermal Engineering 157 (2019) 113621

[8] Ashkan Alimoradi, Investigation of exergy efficiency in shell and helically coiled tube heat exchangers, Case Studies in Thermal Engineering, http://dx.doi.org/10.1016/j.csite.2016.12.005

[9] A. Sheeba , C.M. Abhijith , M. Jose Prakash , Experimental and Numerical Investigations on the Heat Transfer and Flow Characteristics of a Helical Coil Heat Exchanger, International Journal of Refrigeration (2018), doi: https://doi.org/10.1016/j.ijrefrig.2018.12.002

[10] Chang-Nian Chen, Ji-Tian Han, Tien-Chien Jen and Li Shao,' Thermo-chemical characteristics of R134a flow boiling in helically coiled tubes at low mass flux and low pressure', Thermochimica Acta 512 (2011) 163–169

[11] Ehsan Izadpanah , Ahmad Zarei , Saeed Akhavan , Marzie Babaie Rabiee , An experimental investigation of natural convection heat transfer from a helically coiled heat exchanger, International Journal of Refrigeration (2018), https:// doi:10.1016/j.ijrefrig.2018.06.008

[12] Liu X, Xu X, Liu C, Bai W, Dang C, Heat transfer deterioration in helically coiled heat exchangers in trans-critical CO2 Rankine cycles, Energy (2018), doi: 10.1016/ j.energy.2017.12.163.

[13] Zhang Cancan, Wang Dingbiao , Xiang Sa, Han Yong, Peng Xu,' Numerical investigation of heat transfer and pressure drop in helically coiled tube with spherical corrugation', International Journal of Heat and Mass Transfer 113 (2017) 332–341

[14] B.K. Hardik, S.V. Prabhu,' Heat transfer distribution in helical coil flow boiling system', International Journal of Heat and Mass Transfer 117 (2018) 710–728

[15] Korhan Ökten, Burak Kurşun, Ali Toksöz, Mehmet Kara,' Analysis of coiled tube waste heat storage tank under water injection,' Journal of Energy Storage 26 (2019) 100979

[16] S. Khorasani, A. Dadvand, Effect of air bubble injection on the performance of a horizontal helical shell and coiled tube heat exchanger: An experimental study, Applied Thermal Engineering (2016), doi: http://dx.doi.org/10.1016/j.applthermaleng.2016.09.101

[17] Saleh Khorasani, Amin Moosavi, Abdolrahman Dadvand and Mehran Hashemian,' A comprehensive second law analysis of coil side air injection in the shell and coiled tube heat exchanger: An experimental study', Applied Thermal Engineering 150 (2019) 80–87

[18] Hamed Sadighi Dizaji, Samad Jafarmadar , Majid Abbasalizadeh and Saleh Khorasani,' Experiments on air

bubbles injection into a vertical shell and coiled tube heat exchanger; exergy and NTU analysis', Energy Conversion and Management 103 (2015) 973–980

[19] A. Moosavi, M. Abbasalizadeh, H.S. Dizaji, Optimization of heat transfer and pressure drop characteristics via air bubble injection inside a shell and coiled tube heat exchanger, Experimental Thermal and Fluid Science (2016), doi: http://dx.doi.org/10.1016/j.expthermflusci.2016.05.011

[20] D. Panahi (2016): Evaluation of Nusselt number and effectiveness for a vertical shell-coiled tube heat exchanger with air bubble injection into shell side, Experimental Heat Transfer, DOI: 10.1080/08916152.2016.1233145

[21] Samira Pourhedayat, Hamed Sadighi Dizaji & Samad Jafarmadar (2018): Thermal-exergetic behavior of a vertical double-tube heat exchanger with bubble injection, Experimental Heat Transfer, DOI: 10.1080/08916152.2018.1540504

[22] E.M.S. El-Said, M.M.A. Al-Saad, Experimental Investigation of Air Injection Effect on the Performance of Horizontal Shell and Multi-Tube Heat Exchanger with Baffles, Applied Thermal Engineering (2018), doi: https://doi.org/10.1016/j.applthermaleng.2018.02.001

[23] M. Mahdi Heyhat, A. Abdi, A. Jafarzad, Performance Evaluation and Exergy Analysis of a Double Pipe Heat Exchanger under Air Bubble Injection, Applied Thermal Engineering (2018), doi: https://doi.org/10.1016/j.applthermaleng.2018.07.129

[24] Lafta Ghashim, S., Muneer Flayh, A., Experimental Investigation of Heat Transfer Enhancement in Heat Exchanger due to Air Bubbles Injection, Journal of King Saud University - Engineering Sciences (2020), doi: https://doi.org/10.1016/j.jksues.2020.06.006

[25] Zarei, A., Seddighi, S., Elahi, S. et al (2022). Experimental investigation of the heat transfer from the helical coil heat exchanger using bubble injection for cold thermal energy storage system. Applied Thermal Engineering, 200. http://dx.doi.org/10.1016/j.applthermaleng.2021.117559

[26] H. Sadighi Dizaji and S.Jafarmadar,' Heat transfer enhancement due to air bubble injection into a horizontal double pipe heat exchange,' International Journal of Automotive Engineering Vol. 4, Number 4, Dec 2014.

[27] Hasan, S. S., Baqir, A. S., & Mahood, H. B. (2021). The effect of injected air bubble size on the thermal performance of a vertical shell and helical coiled tube heat exchanger. *Energy Engineering*, *118*(6), 1595-1609.

[28] Hulet, C., Clement, P., Tochon, P., Schweich, D., Dromard, N., & Anfray, J. (2009). Literature review on heat transfer in two-and three-phase bubble columns. *International Journal of Chemical Reactor Engineering*, *7*(1).

[29] Suri, A. R. S., Kumar, A., & Maithani, R. (2018). Convective heat transfer enhancement techniques of heat exchanger tubes: a review. *International Journal of Ambient Energy*, *39*(7), 649-670.

[30] Abdullah, M. S., & Hussein, A. M. (2023). Thermal Performance of a Helical Coil Heat Exchanger Utilizing Nanofluids: A Review. *Journal of Heat and Mass Transfer Research*, *10*(1), 121-134.

[31] Abbaspour, M., Mousavi Ajarostaghi, S. S., Hejazi Rad, S. A., & Nimafar, M. (2021). Heat transfer improvement in a tube by inserting perforated helical ring and wire coil as turbulators. *Heat Transfer*, *50*(6), 6164-6188.

[32] Li, H., Wang, Y., Han, Y., Li, W., Yang, L., Guo, J., ... & Jiang, F. (2022). A comprehensive review of heat transfer enhancement and flow characteristics in the concentric pipe heat exchanger. *Powder Technology*, *397*, 117037.

[33] Narrein, K., & Mohammed, H. A. (2014). Heat transfer and fluid flow characteristics in helically coiled tube heat exchanger (HCTHE) using nanofluids: A review. *Journal of Computational and Theoretical Nanoscience*, *11*(4), 911-927.

[34] Kumar, A., & Maithani, R. (2018). Analysis of coiled tube waste heat storage tank under water injection. *International Journal of Ambient Energy*, *39*(7), 649-670.

[35] Ali Sh. Baqir, Hameed B. Mahood and Ahmed R. Kareem, A. (2024, December). Optimisation and Evaluation of NTU and Effectiveness of a Helical Coil Tube Heat Exchanger with Air Injection. In *2024 International Conference on Artificial Intelligence and Quantum Computation-Based Sensor Application (ICAIQSA)* (pp. 1-6). IEEE.

[36] Saleh Khorasani & Abdolrahman Dadvand. (2021). Effect of air bubble injection on the performance of a horizontal helical shell and coiled tube heat exchanger: an experimental study. 11. 375-382. 10.11591/ijece.v11i1.pp375-382.

[37] Saleh Khorasania, Amin Moosavib, Abdolrahman Dadvanda,& Mehran Hashemian (2024). A Critical Investigation into the Impact of Big Data in the Food Supply Chain for Realizing Sustainable Development Goals in Emerging Economies. In *Advanced Technologies for Realizing Sustainable Development Goals: 5G, AI, Big Data, Blockchain, and Industry 4.0 Application* (pp. 204-214). Bentham Science Publishers.

[38] Hamed Sadighi Dizaji, Samad Jafarmadar, Majid Abbasalizadeh & Saleh Khorasani C. (2024). Experiments on air bubbles injection into a vertical shell and coiled tube heat exchanger; exergy and NTU analysis. In *Advanced Technologies for Realizing Sustainable Development Goals: 5G, AI, Big Data, Blockchain, and Industry 4.0 Application* (pp. 270-282). Bentham Science Publishers.

[39] Amin Moosavi, Majid Abbasalizadeh, Hamed Sadighi Dizaji (2014). *Optimization of heat transfer and pressure drop characteristics via air bubble injection inside a shell and coiled tube heat exchanger*. 22. 291-299.

[40] *D*. Panahi. (2024). Evaluation of Nusselt number and effectiveness for a vertical shell-coiled tube heat exchanger with air bubble injection into shell side, Experimental Heat Transfer (pp. 1-8).

[41] Z. Zhao, D. Chen, Y. Zhang, S. Yao, K. Zhang, and Y. Lin,. (2016). Numerical Investigation on Conjugate Heat Transfer to Supercritical CO2 in Membrane Helical Coiled Tube Heat Exchangers, Exp. Heat Transf., vol. 69, pp. 977–995, 2016

[42] Kitagawa, K. Kosuge, K. Uchida, and Y. Hagiwara (2008) , Heat Transfer Enhancement for Laminar Natural Convection Along a Vertical Plate Due to Sub-Millimeter-Bubble Injection, Exp. Fluids, vol. 45, pp. 473–484,

[43] H. Sadighi Dizaji, S. Jafarmadar,(2015) Heat transfer enhancement due to air bubble injection into a horizontal double pipe heat exchanger, Int. J. Autom. Eng. 4 (4), 973–980.

[44] F. Hormozi, B. ZareNezhad, H. R. Allahyar,(2016), An experimental investigation on the effects of surfactants on the thermal performance of hybrid nanofluids in helical coil heat exchangers, Int. Comm. Heat Mass Transf.78, 271–276.

[45] H. B. Mahood, A.N. Campbell, R.B. Thorpe, A.O. Sharif (2015), Heat transfer efficiency and capital cost evaluation of a three-phase direct contact heat exchanger for the utilisation of low-grade energy sources, Energy Conversion and Management 106, 101–109.

[46] P. Vassallo, R. Kumar (2019), Liquid and gas velocity measurements using LDV in air-water duct flow, Experimental Thermal and Fluid Science 19 ,85-92.

[47] Odaymet, H. Louahlia-Gualous (2012), Experimental study of slug flow for condensation in a single square microchannel, Experimental Thermal and Fluid Science 38 ,1–13.

[48] Y. Wang, C. Yan , L. Sun, C. Yan (2014), Characteristics of slug flow in a vertical narrow rectangular channel, Experimental Thermal and Fluid Science 53 ,1–16.

[49] Adil A. Khdhair1, Ziad M. Almakhyoul,' Effect of Air Bubbles on Heat Transfer Using a Helical Coil: A Review', Journal of Information Systems Engineering and Management, 2025, 10(17s)