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Review paper on Heat Transfer in Helical Coil Heat Exchangers

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Abstract - Helical coil heat exchangers are widely used because of their compact design and superior heat transfer performance compared with straight tube heat exchangers. The enhanced thermal performance is mainly due to the formation of Dean vortices, which improve fluid mixing and increase the heat transfer coefficient. This review summarizes the effects of key parameters such as Reynolds number, Dean number, coil geometry, and fluid properties on heat transfer and pressure drop. It also discusses recent advances in Computational Fluid Dynamics (CFD), nanofluids, and optimization techniques for improving HCHE performance. Finally, the review identifies current research gaps, including the need for standardized predictive models, long-term experimental studies, and sustainable design approaches for industrial applications.

Keywords: Dean vortices, Heat transfer enhancement, Pressure drop, Computational Fluid Dynamics (CFD), Nanofluids, Optimization, Thermal performance.

INTRODUCTION

Helical coil heat exchangers (HCHEs) have gained significant attention in thermal engineering because of their superior heat transfer characteristics, compact structure, and wide range of industrial applications. Unlike straight tube heat exchangers, the curvature of a helical coil induces centrifugal forces that generate secondary flow patterns known as Dean vortices. These secondary flows improve fluid mixing, reduce thermal boundary layer thickness, and consequently enhance the overall heat transfer coefficient. Owing to these advantages, helical coil heat exchangers are extensively used in chemical processing, power generation, refrigeration, food processing, pharmaceutical industries, and renewable energy systems.

Over the past several decades, researchers have investigated the influence of coil geometry, flow conditions, and fluid properties on heat transfer and pressure drop characteristics. Experimental studies, theoretical analyses, and Computational Fluid Dynamics (CFD) simulations have contributed substantially to understanding the thermal and hydraulic performance of helical coil heat exchangers.

EARLY STUDIES ON CURVED TUBE FLOW

The pioneering work on fluid flow through curved pipes was conducted by **Dean (1927)**, who introduced the concept of secondary flow generated due to centrifugal forces acting on the fluid moving through curved tubes. He developed the Dean number, a dimensionless parameter that combines the effects of Reynolds number and curvature ratio. Dean demonstrated that curved tubes exhibit significantly different flow characteristics compared with straight tubes due to the formation of two counter-rotating vortices inside the cross-section.

Subsequently, **Seban and McLaughlin (1963)** experimentally investigated heat transfer in curved tubes under laminar and turbulent flow conditions. Their research confirmed that helical coils provide higher heat transfer coefficients than straight tubes under identical operating conditions.

HEAT TRANSFER CHARACTERISTICS

Mori and Nakayama (1967) performed one of the earliest detailed investigations into forced convection in curved pipes. Their experimental results showed that secondary flow intensity increases with Reynolds number and curvature ratio, resulting in enhanced convective heat transfer. They also proposed empirical correlations for predicting the Nusselt number in curved tubes.

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Xin and Ebadian (1997) examined the influence of coil geometry on heat transfer performance. Their study demonstrated that decreasing the coil diameter strengthens centrifugal effects and significantly increases the heat transfer coefficient. However, they also reported that pressure drop increases with decreasing coil diameter, highlighting the need for design optimization.

Several subsequent investigations have confirmed that the Nusselt number increases with Reynolds number due to improved turbulence and mixing inside the helical coil. Most empirical correlations indicate that the heat transfer coefficient follows a power-law relationship involving Reynolds number, Prandtl number, and Dean number.

INFLUENCE OF GEOMETRICAL PARAMETERS

The geometry of a helical coil plays a crucial role in determining thermal performance.

Researchers have reported that the following parameters strongly influence heat transfer:

- Tube diameter
- Coil diameter
- Coil pitch
- Curvature ratio
- Number of turns
- Coil length

A smaller coil diameter generally enhances secondary flow because of increased centrifugal force, resulting in higher heat transfer rates. Similarly, smaller tube diameters improve convective heat transfer but also increase frictional pressure losses.

The effect of coil pitch has been investigated by several researchers. Smaller pitches produce stronger interaction between adjacent turns, whereas larger pitches reduce the intensity of secondary flow. Consequently, an optimum pitch exists for maximizing thermal performance while minimizing pressure loss.

PRESSURE DROP CHARACTERISTICS

Although helical coils provide enhanced heat transfer, they also introduce additional hydraulic resistance. Pressure drop increases because of friction and centrifugal effects associated with curved flow.

Studies consistently report that pressure loss increases with:

- Reynolds number
- Curvature ratio
- Flow velocity
- Surface roughness

The increased pumping power required for high-pressure losses remains one of the major limitations of helical coil heat exchangers. Therefore, researchers emphasize balancing heat transfer enhancement with acceptable pressure drop.

EXPERIMENTAL INVESTIGATIONS

Numerous experimental studies have been conducted to evaluate the thermal performance of helical coil heat exchangers using different working fluids and geometries.

Experimental investigations generally involve measurements of:

- Inlet and outlet temperatures
- Flow rate

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- Pressure drop
- Heat transfer coefficient
- Overall heat transfer coefficient
- Effectiveness

Most experiments conclude that helical coil heat exchangers outperform conventional straight tube exchangers due to enhanced fluid mixing generated by Dean vortices.

CFD STUDIES

Advancements in computational resources have made Computational Fluid Dynamics (CFD) an indispensable tool for analyzing flow and heat transfer in helical coils.

CFD enables researchers to visualize:

- Velocity distribution
- Temperature contours
- Pressure variation
- Secondary vortices
- Turbulence intensity

ANSYS Fluent, COMSOL Multiphysics, and OpenFOAM are among the most commonly used simulation platforms.

Several studies have shown good agreement between CFD predictions and experimental measurements, validating numerical models for engineering design.

HEAT TRANSFER ENHANCEMENT TECHNIQUES

Recent research has focused on improving thermal performance using passive enhancement techniques.

Common approaches include:

- Twisted tape inserts
- Wire coil inserts
- Corrugated tubes
- Helical fins
- Ribbed surfaces

These modifications disturb the thermal boundary layer, increasing turbulence and improving heat transfer.

In addition, researchers have investigated active enhancement techniques such as pulsating flow and mechanical vibration. Although these methods provide higher heat transfer rates, they often require additional energy input.

NANOFLUIDS IN HELICAL COIL HEAT EXCHANGERS

Nanofluids have emerged as promising working fluids because of their improved thermal conductivity.

Researchers have investigated nanoparticles such as:

- Aluminum oxide (Al_2O_3)
- Copper oxide (CuO)

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- Titanium dioxide (TiO_2)
- Silicon dioxide (SiO_2)
- Graphene

Experimental studies generally report improvements in heat transfer coefficient ranging from 10% to 40%, depending on nanoparticle concentration and operating conditions.

However, increased viscosity of nanofluids may lead to higher pressure drop and pumping power. Therefore, optimization of nanoparticle concentration remains an active research area.

OPTIMIZATION STUDIES

Modern research increasingly applies optimization algorithms to improve the design of helical coil heat exchangers.

Frequently used optimization methods include:

- Genetic Algorithm (GA)
- Particle Swarm Optimization (PSO)
- Response Surface Methodology (RSM)
- Artificial Neural Networks (ANN)
- Machine Learning (ML)

These techniques optimize design variables such as coil diameter, pitch, tube diameter, and flow rate while simultaneously maximizing heat transfer and minimizing pressure drop.

RESEARCH GAPS

Despite extensive research, several challenges remain:

- Limited studies under transient operating conditions.
- Insufficient long-term experimental investigations on fouling.
- Lack of standardized correlations for nanofluids.
- Limited application of hybrid nanofluids in industrial systems.
- Need for experimental validation of advanced CFD models.
- Limited studies integrating economic, thermal, and environmental analyses.

Future research should focus on sustainable heat exchanger designs with improved energy efficiency and reduced operating costs.

CONCLUSION

It has been shown in literature that helical coil heat exchangers have better thermal performance than straight tube heat exchangers because of the formation of Dean vortices. The heat transfer is mainly affected by Reynolds number, Dean number, coil geometry and fluid properties. Both experimental and numerical studies consistently show the enhanced heat transfer with the penalty of higher pressure drop. Recent progress in nanofluid, CFD, artificial intelligence and optimisation techniques provide promising opportunities for the improvement of heat exchangers' performance. Nonetheless, further research is required to establish generalised predictive models and optimise designs for industrial applications.

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