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Optimization of Helically Coiled Micro-Channel Designs for Improved Thermal–Hydraulic Performance in Laminar Flow Applications

Mst. Heera Khatun,

Dr. Jitendra Singh Rajput

Ph.D. Research Scholar, Assistant professor

School of Applied Science, Department of Mathematics

NIILM University, Kaithal, Haryana, India

heerakhatun@gmail.com, jitendra@niilmuniversity.ac.in

Abstract: Helically coiled micro-channels have garnered considerable interest in contemporary thermal management systems owing to their enhanced heat transfer properties relative to traditional straight micro-channels. This improvement is mostly due to curvature-induced secondary flow phenomena, known as Dean vortices, which facilitate transverse fluid motion and augment mixing even in laminar flow conditions. Consequently, the thermal boundary layer is perpetually disrupted, resulting in elevated convective heat transfer rates. This work concentrates on optimizing helically coiled micro-channel shapes to enhance thermal-hydraulic performance while keeping pressure drop within permissible ranges. The critical geometric and flow parameters, such as coil diameter, helix pitch, curvature ratio, channel hydraulic diameter, and Reynolds number, are methodically analyzed to assess their collective impact on heat transfer enhancement and flow resistance. Significant attention is directed towards comprehending the trade-off between enhanced thermal performance and the corresponding increase in pumping power demands. The analysis indicates that the judicious selection of geometric parameters can substantially improve heat transmission while minimizing hydraulic penalties. The results offer valuable design insights for the creation of optimized helically coiled micro-channel systems and underscore their appropriateness for applications including compact heat exchangers, micro-electronic cooling devices, and other energy-efficient thermal systems functioning in laminar flow conditions.

Keywords: Helically coiled micro-channel; Laminar flow; Heat transfer enhancement; Pressure drop; Dean number; Thermal optimization

1. Introduction

Modern engineering systems are focusing more and more on being small and energy-efficient. This has led to a huge rise in study into advanced thermal management techniques. Applications like micro-electronic devices, biomedical tools, compact heat exchangers, and micro-reactors create large amounts of heat in small spaces. This makes getting rid of the heat effectively a very important design task. Micro-channel-based heat transfer systems look like a good option because they have a lot of surface area compared to their volume. This means they can move heat more quickly than regular macro-scale channels. Even though they have some benefits, straight microchannels that work in laminar flow conditions often have low heat transfer rates. At the micro-scale, flow usually stays laminar in a lot of different operating situations. This keeps the fluids from mixing and creates stable thermal boundary layers. This limit makes heat transfer less effective, especially in situations where turbulence is not wanted or is not possible because it causes more pressure drop, unstable flow, or high energy use. So, making it easier for heat to move through laminar micro-channel flows is still a big research task. To get around these problems, many geometric changes to straight micro-channels have been suggested, such as wavy channels, rib-roughened surfaces, and curvy flow paths. In these arrangements, helically coiled micro-channels have gotten a lot of attention because they can improve heat transfer without using turbulent flow. Because the helical geometry is curved, it creates centrifugal forces that act on the fluid that is moving, creating secondary flow structures in the channel cross-section. These secondary flows, which are often called Dean vortices, help the fluid move across and mix better, which breaks up the thermal boundary layer and makes convective heat transfer better even at low Reynolds numbers.

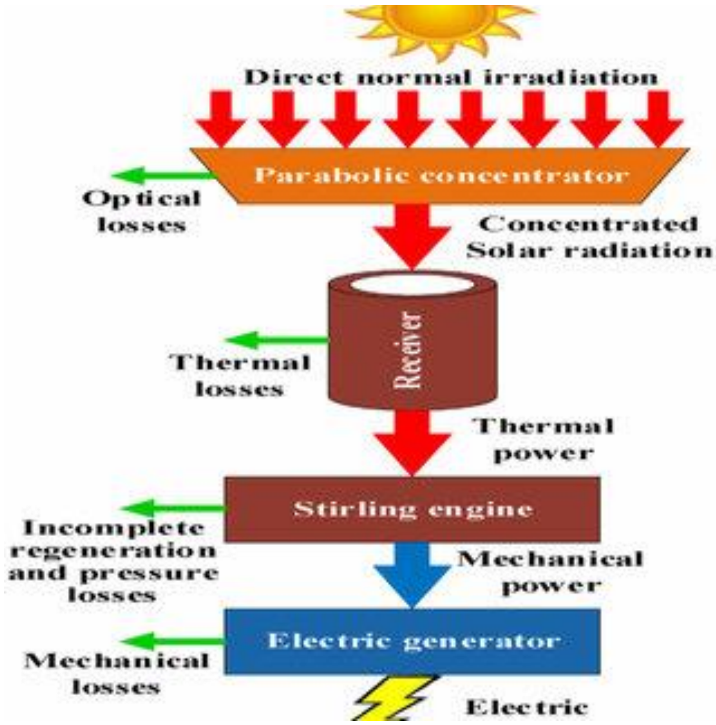

Fig. 1 Numerical study on thermal-hydraulic performance and exergy analysis

However, the benefits of better heat movement in microchannels that are helically wound come with higher hydraulic resistance. Centrifugal forces make secondary flows stronger, but they also cause more frictional losses and pressure drops than in straight micro-channels. In real-world thermal systems, too much pressure drop can mean that more pumping power is needed, which could cancel out the benefits of better heat movement. So, for helically coiled micro-channel designs to work well, there needs to be a careful balance between improving heat performance and improving hydraulic performance. In this situation, it is very important to improve the shape of the microchannels that are helically wound. A lot of the design factors that matter, like the coil diameter, helix pitch, curvature ratio, and channel hydraulic diameter, affect how strong the secondary flows are and how the heat and fluids behave as a result. A thorough study of these factors is needed to find setups that improve heat transfer significantly while still allowing for acceptable pressure drop levels. This study was inspired by this need and aims to help create better helically coiled micro-channel designs that can be used in laminar flow uses that need to be small, reliable, and energy-efficient.

Table 1: Key Geometric Parameters of Helically Coiled Micro-Channels

Geometric Parameter	Description	Influence on Thermal Performance	Influence on Hydraulic Performance
Coil Diameter	Diameter of the helical coil	Smaller diameters enhance secondary flows and heat transfer	Smaller diameters increase pressure drop
Helix Pitch	Axial distance between successive coil turns	Optimal pitch improves heat transfer by enhancing flow disturbance	Very small pitch increases flow resistance
Curvature Ratio	Ratio of channel hydraulic diameter to coil diameter	Higher curvature ratio strengthens Dean vortices	Higher curvature increases friction losses
Hydraulic Diameter	Effective diameter of the micro-channel	Smaller diameter increases heat transfer coefficient	Smaller diameter causes higher pressure drop
Channel Length	Total length of the coiled channel	Longer channels increase heat transfer area	Longer channels result in higher pressure loss

Background

Improving heat transfer in systems with laminar flow has been a problem in thermal engineering for a long time, especially as micro-scale technologies have gotten better. Traditional ideas and relationships about heat transfer were mostly made for large-scale systems, where turbulent flow is most important for improving convective performance. On the other hand, when the size of the system gets smaller, to the micro-scale, low Reynolds numbers make flow regimes mostly laminar. This makes it much harder to use traditional methods that boost turbulence. Early research on micro-channel heat exchangers showed that decreasing the size of the channels improves the ratio of surface area to volume, but this does not always improve heat transfer performance in the same way. Creating stable boundary layers of velocity and temperature in straight micro-channels often lowers the efficiency of convection, especially in situations where the heat flow stays the same. Because of these problems, experts looked into other channel configurations that might be able to change the flow without turning it into turbulence. Curved and coiling channels looked like a good way to solve this problem. The Dean number, which shows how curvature affects fluid flow, was the first thing that was used to formally explain the idea of secondary flow in curved ducts. Later, experiments and computer simulations proved that curvature-induced rotational forces create transverse vortices in the channel cross-section. These are often called Dean vortices. By constantly moving hot fluid from the wall area to the channel center and replacing it with cooler fluid, these vortices improve fluid mixing and heat transfer. As micro-fabrication methods got better, it became possible to use helical coil geometries on the micro-scale. Because they are helical, coiled micro-channels are small and good at managing heat, so they can be used in modern thermal management uses. Studies have shown that these kinds of arrangements can get much higher Nusselt numbers than straight microchannels with the same flow conditions. However, these thermal benefits are often followed by a higher pressure drop because curvature effects add to the flow resistance.

More and more research shows that the thermal and hydraulic performance of microchannels that are helically wrapped depends on geometric factors like coil diameter, pitch, curvature ratio, and channel cross-sectional measurements. Even though many studies have looked at different factors separately, we still don't fully understand how they all work together in laminar flow. Also, a lot of the designs that are already out there focus on improving heat movement without taking hydraulic penalties into account enough, which can make them hard to use in real life. As a result, it is clear that systematic optimization studies are needed to find the best mix between improving heat transfer and limiting pressure drop. Setting up an ideal design framework is necessary to create helically coiled micro-channel systems that are reliable, use little energy, and can be expanded. The current study is based on this basic information. Its goal is to test and improve helically coiled micro-channel designs for better thermal–hydraulic performance in laminar flow situations.

2. Flow Characteristics in Helically Coiled Micro-Channels

The flow behavior in microchannels that are helically coiled is very different from that in straight microchannels because the flow path is curved. When the flow is laminar, fluid motion in straight lines is mostly controlled by axial pressure gradients. This makes the velocity profile pretty uniform. On the other hand, when you curve a helical channel, you add centrifugal forces that have a big effect on the structure of the flow inside, even if the Reynolds number stays in the laminar regime. As fluid moves along a curved path, the centrifugal force pushes the fluid away from the channel center and toward the coil's outer wall. There is an inward return flow near the sides that balances this motion outward. This creates two secondary vortices that spin counterclockwise across the channel cross-section. These vortices are often called Dean vortices. The Dean number describes them. It is the sum of the Reynolds number and the curve ratio. As the curve and speed of the flow go up, these secondary flows get stronger, making them the most important part of helically coiled micro-channel flows. Having secondary vortices in a canal changes both the flow rate and the temperature distribution. Helically coiled channels have better transverse mixing than straight channels, where velocity and temperature differences stay mostly in the close-to-wall areas. Fluid is constantly moving between the core and wall regions because of this mixing. This stops thermal stratification and stops the formation of stable thermal border layers. This makes the local heat transfer coefficients go up, which means that the average Nusselt number is higher than it would be in a straight microchannel with the same laminar flow conditions. One of the best things about helically coiled micro-channels is that they break up the temperature boundary layer. By exposing new fluid to the hot walls over and over again, the secondary flow structures improve the efficiency of convective heat transfer without having to switch to turbulence. Because of this feature, helically coiled micro-channels are great for uses where laminar flow needs to be kept because of design or operation limitations.

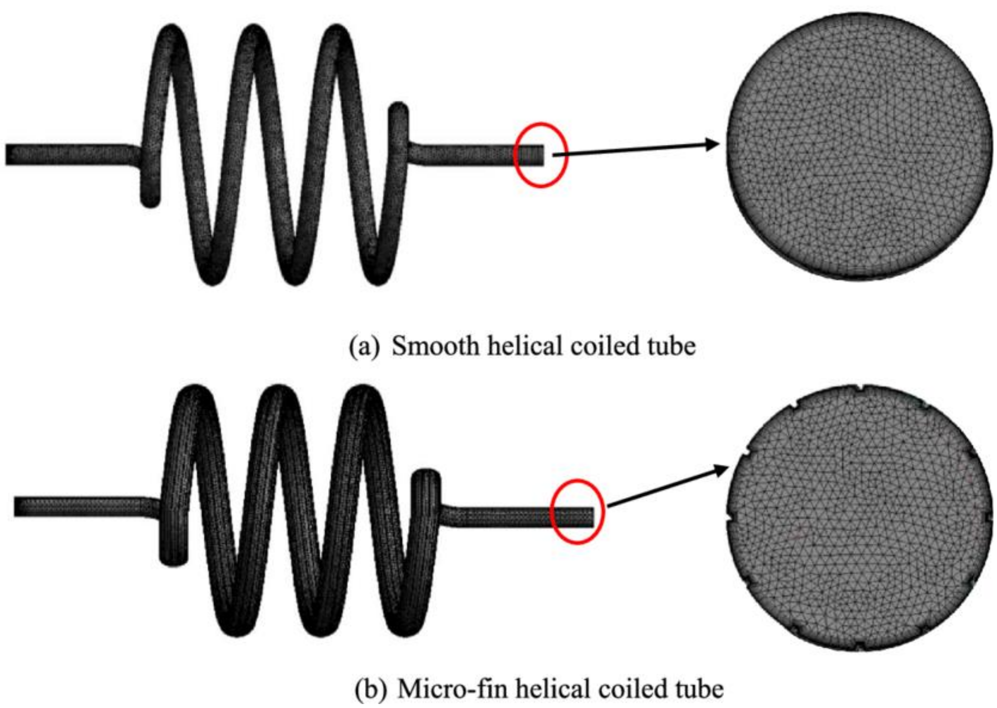

Fig. 2 Meshing of smooth and micro-fin helically coiled tube

But along with better heat movement, there is also more hydraulic resistance. The extra flow curve and secondary motion cause more frictional losses, which makes the pressure drop along the length of the channel bigger. Helically curved microchannels need more pumping power to keep the same flow rate as straight microchannels. Dean vortices are good for heat performance, but they are bad for hydraulic performance and need to be carefully thought out in real-world designs. Overall, the way fluid moves through micro-channels that are helically wound is controlled by a complicated relationship between axial flow, centrifugal forces, and secondary vortices. It's important to understand how these two things interact in order to judge the thermal and hydraulic performance of these kinds of systems. It's also the ground for finding the best channel geometry to balance heat transfer enhancement and pressure drop.

3. Effect of Geometric Parameters on Thermal–Hydraulic Performance

3.1 Influence of Overall Channel Geometry

Helically coiled micro-channels' temperature and hydraulic performance is mainly determined by their geometric shape, since the shape of the channel directly affects how strong and how often secondary flows happen. In normal, straight microchannels, physical factors mostly affect surface area and viscous resistance, which makes laminar flow behavior pretty predictable. In helically coiled micro-channels, on the other hand, the curve adds centrifugal forces that change the internal flow structure in a big way. These forces create complicated secondary flow patterns that help mix and move heat better but also make flow more difficult. So, factors like coil diameter, helix pitch, curvature ratio, and hydraulic diameter work together to find the right mix between increasing heat transfer and lowering pressure. This makes geometry an important part of how well the whole system works.

3.2 Effect of Coil Diameter

In helically coiled micro-channels, the width of the coil has the most significant impact on the strength of the effects caused by curvature. When the diameter of the coil is shrunk, the flow path becomes more curved. This makes the centrifugal forces working on the fluid stronger. These forces help make bigger secondary vortices in the channel cross-section, which improves the mixing of the core fluid with the areas close to the walls. The thermal boundary layer is more successfully broken up by this mixing, which leads to higher local and average heat transfer coefficients. But the bigger curve also causes more wall shear stress and sliding losses, which makes the pressure drop along the channel stand out more. So, smaller coil sizes are better for thermal reasons, but they have big effects on hydraulics that need to be carefully thought through when designing the best solution.

Table 2: Effect of Flow and Geometric Parameters on Thermal–Hydraulic Characteristics

Parameter	Increase in Parameter Leads to	Effect on Heat Transfer	Effect on Pressure Drop
Reynolds Number	Higher flow velocity	Increased convective heat transfer	Increased pressure drop
Dean Number	Stronger secondary flows	Significant heat transfer enhancement	Moderate to high pressure loss
Reduced Coil Diameter	Increased curvature	Improved mixing and higher Nusselt number	Substantial increase in pressure drop
Reduced Hydraulic Diameter	Higher surface-area-to-volume ratio	Enhanced heat transfer coefficient	Sharp increase in pumping power
Optimized Helix Pitch	Balanced flow disturbance	Maximum thermal efficiency	Controlled pressure losses

3.3 Effect of Helix Pitch

Helix pitch, which is the distance along the axis between each turn of the helical coil, has a big effect on how axial flow and secondary flow patterns interact with each other. A smaller pitch makes a coil that is tightly wound, which makes flow problems happen more often and more strongly along the length of the channel. This improved interaction makes secondary vortices stronger and helps heat transfer by constantly shaking up the thermal boundary layer. But if the diameter is too small, the closeness of the coil turns can stop flow from developing, which causes higher flow resistance and too much pressure loss. On the other hand, a very large pitch lessens the effect of curvature, weakens secondary flows, and lowers the effectiveness of heat transfer increase, bringing performance closer to that of micro-channels that are straight. As a result, there is a perfect pitch value where heat transfer is maximized and pressure drop stays within accepted limits.

3.4 Effect of Hydraulic Diameter

The microchannel's hydraulic width has a big effect on both how heat moves through it and how much pressure drops. The ratio of surface area to volume goes up when the hydraulic diameter goes down. This makes the contact between the fluid and the wall stronger and raises the convective heat transfer coefficients. This effect helps a lot in micro-scale systems, which need to get rid of heat quickly but have limited room. On the other hand, smaller hydraulic sizes make viscous effects stronger, which leads to higher wall shear stress and higher flow resistance. So, as the hydraulic width goes down, the pressure drop goes up sharply. Even small changes in channel measurements can have big effects on the amount of pumping power needed. This is why choosing the right hydraulic diameter is so important for balancing thermal and hydraulic performance.

3.5 Combined Influence of Geometric Parameters

Geometric parameters don't have separate effects on thermal and hydraulic performance; instead, these parameters interact in a complex way to decide how the system acts as a whole. For instance, a design that combines a small coil diameter with a small hydraulic diameter might produce strong secondary flows and great heat transfer improvement, but the pressure drop that happens might be too high for real-world use. A modest curvature, on the other hand, along with the right helix pitch and hydraulic diameter, can make both heat transfer and hydraulic efficiency better in a more balanced way. These interactions show how important it is to think about all the important geometric factors at the same time instead of just optimizing one.

3.6 Summary of Geometric Effects

In conclusion, the thermal and hydraulic efficiency of microchannels that are helical coiled is controlled by a trade-off between increasing heat transfer and decreasing pressure. There are geometric factors like coil diameter, helix pitch, and hydraulic diameter that have a direct effect on the strength of secondary flows, the amount of fluid mixing, and the flow resistance. For finding the best channel configurations, it's important to fully understand both the individual and combined effects of these factors. This knowledge sets the stage for the optimization methods we'll talk about next, which aim to improve thermal performance while keeping hydraulic efficiency at a good level in laminar flow situations.

4. Optimization Considerations

4.1 Trade-off Between Heat Transfer Enhancement and Pressure Drop

Helically coiled micro-channels are much better at moving heat because they create secondary flows that are caused by curves. These flows mix the fluid better and weaken the thermal boundary layer along the channel walls. These secondary flow patterns raise the convective heat transfer coefficient even when the flow is smooth, which is not the case with straight microchannels. But adding curvature also raises flow resistance because the fluid has to deal with more centrifugal forces and more complicated flow routes. This makes the wall shear stress and frictional losses larger, which makes the pressure drop along the length of the channel much bigger. So, it's clear that helically coiled micro-channels have heating benefits, but these benefits must be carefully weighed against the hydraulic drawbacks so that too much pumping power isn't needed.

4.2 Need for Combined Performance Evaluation

Simply looking at how well helically coiled micro-channel designs transfer heat can lead to wrong conclusions, since the designs that transfer the most heat may also have pressure drops that are too high. This problem is often fixed by using combined performance evaluation factors in optimization studies. This includes both heat transfer and pressure drop effects in one measure, like the thermal performance factor, performance evaluation criterion, or overall efficiency index. With these factors, it's easier to see if the increase in heat transfer is worth the increase in hydraulic resistance, which makes the comparison of different geometrical configurations more realistic. Therefore, designs that improve heat transfer slightly while reducing pressure losses usually work better overall than designs that only try to increase heat transfer.

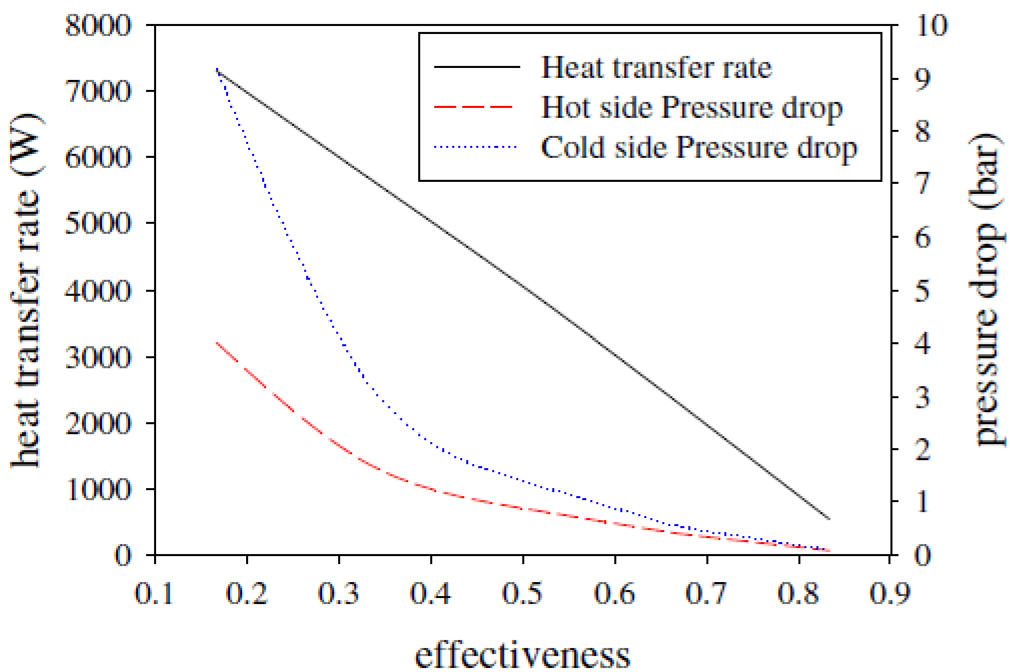

Fig. 3 Relationship of the pressure drop and the heat transfer rate

4.3 Role of Numerical and Experimental Approaches

Numerical models are very important for improving helically coiled micro-channel designs because they show in great detail how flow structure, heat transfer, and pressure distribution all affect each other. Computational fluid dynamics (CFD) tools let you change geometric factors like coil diameter, pitch, curvature ratio, and hydraulic diameter in a planned way. This lets you do full parametric studies in controlled settings. These simulations help find trends and the best sets of parameters without having to do a lot of experiments, which can be expensive and take a lot of time. But number predictions need to be tested in the real world to make sure they are accurate. Flow behavior and thermal performance can be confirmed in the real world by doing experiments that take into account manufacturing tolerances and working conditions. So, using both numerical and experimental methods together makes a strong foundation for accurate optimization.

4.4 Importance of Energy Efficiency in Laminar Flow Systems

Keeping energy efficiency high is especially important in laminar flow situations where turbulence-induced enhancement mechanisms are not present. Consequently, any rise in pressure drop directly leads to higher pumping power needs, which can greatly lower the thermal system's total efficiency. Extremely high energy use for fluid circulation is usually not allowed in situations like electronic cooling and micro-scale heat exchanges. As a result, attempts to improve performance should focus on designs that improve heat transfer significantly while keeping pressure drop within acceptable levels. This balance makes sure that the temperature benefits of helically coiled micro-channels aren't cancelled out by higher system energy costs.

Table 3: Comparison Between Straight and Helically Coiled Micro-Channels

Performance Parameter	Straight Micro-Channel	Helically Coiled Micro-Channel
Flow Regime	Predominantly laminar	Laminar with secondary flows
Secondary Flow	Absent	Present (Dean vortices)
Heat Transfer Rate	Relatively low	Significantly enhanced
Pressure Drop	Lower	Higher due to curvature
Pumping Power Requirement	Low	Moderate to high
Suitability for Compact Systems	Limited	Highly suitable
Thermal–Hydraulic Efficiency	Moderate	High when optimized

4.5 Objective of the Optimization Process

The main goal of improving helically coiled micro-channel designs is to find the geometrical arrangements that provide the best mix between improving thermal performance and improving hydraulic efficiency. To do this, the coil diameter, pitch, and channel measurements must be chosen in a way that creates strong secondary flows that help heat transfer without making the flow too difficult. Instead of trying to get the best performance in a single area, the optimization process aims to make the whole system work better and be more useful. For helically coiled micro-channels to work in small, reliable, and energy-efficient heat management systems that work with laminar flow, designs that are well-balanced and optimized are necessary.

5. Applications

- **Electronic Device Cooling**

Micro-channels that are optimized and helically wound are used a lot to cool electronic parts like microprocessors, power electronics, and integrated circuits. These machines make a lot of heat in small areas, so they need to get rid of the heat quickly and reliably. Curvature-induced secondary flows improve heat transfer, which makes cooling work well in smooth flow conditions. This means that less pumping power is needed, and the device is more reliable and lasts longer.

- **Micro-Heat Exchangers**

Micro-heat exchangers work well with helical-coiled micro-channels because they are small and good at transferring heat. The better heat transfer ability makes it possible for heat exchangers to be much smaller and lighter than traditional designs. This makes them very useful in fields like aerospace, automotive, and portable energy systems, where limited room and weight are important design factors.

- **Biomedical and Healthcare Systems**

It is common for precise temperature control to be needed in biomedical settings to protect living samples and medical devices. Lab-on-a-chip devices, biomedical monitors, and drug delivery systems all need to work with laminar flow, so they use microchannels that are wound around a helix. Their ability to improve heat transfer without creating turbulent flow helps keep temperature levels even while reducing shear stress on living materials that are easily damaged.

- **Micro-Reactors and Chemical Processing**

Micro-channels that are wound around each other in a spiral are an important part of micro-reactors that are used for chemical and biological processes. To control reaction rates and keep hot spots from forming, heat must be removed or supplied efficiently. Helically coiled micro-channels have better thermal and hydraulic performance, which makes temperature uniformity and reaction stability better. This makes them perfect for continuous-flow micro-reactor systems.

- **Energy-Efficient Thermal Management Systems**

Helically coiled micro-channels are being used more and more in energy-efficient thermal management because they improve heat transfer in laminar flow situations. Their optimized designs help lower the amount of power needed for pumping while keeping the thermal performance high. This makes them perfect for systems that are limited in room and energy.

6. Conclusion

In laminar flow situations, where straight microchannels often don't work well for convection, helical coiled microchannels show promise as an effective way to improve heat transfer performance. The helical geometry's curve creates secondary flow structures, which are also known as Dean vortices. These vortices make mixing fluids much better and break up thermal boundary layers. Because of this process, higher heat transfer coefficients can be reached without turbulent flow. This makes helically coiled micro-channels ideal for small, energy-efficient thermal systems. Even with these benefits, the better heat transfer in microchannels that are helical-wound comes with a higher hydraulic resistance and pressure drop. Higher frictional losses are caused by the same curve effects that make secondary flows stronger. This means that more power is needed to pump the fluid. So, to make helically coiled micro-channel systems work well, the balance between improving heat performance and improving hydraulic performance must be carefully considered. A big part of getting this balance is making sure that geometric factors like coil diameter, helix pitch, and hydraulic diameter are optimized. The results of this study make it clear that judging temperature performance by itself is not enough for real-world use. A full thermal–hydraulic analysis is needed to find configurations that improve heat transfer in a useful way while still allowing for acceptable pressure drop levels. Helically coiled micro-channels can be much more efficient than straight micro-channels if they are properly optimized. This is especially true in laminar flow situations where energy use and system reliability are very important. Finally, improved helically coiled micro-channel designs have a lot of promise for high-tech thermal management uses, such as electronic cooling, micro-heat exchangers, biomedical systems, and micro-reactors. By taking thermal and hydraulic factors into account during the design process, helically coiled micro-channels can be used as effective, small, and dependable solutions for modern engineering systems that have to work within strict thermal and space limits.

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