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Performance Analysis of Heat Transfer Enhancement in Tube by Using Alternate Axis Serrated Side Insert

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Abstract: This study investigates the enhancement of convective heat transfer in circular tubes using alternate axis serrated side inserts under turbulent flow conditions. The use of passive heat transfer enhancement techniques has gained considerable importance in thermal engineering applications such as heat exchangers, condensers, boilers, refrigeration systems, and process industries. Serrated side inserts create swirl flow, secondary vortices, and flow disturbances that significantly improve thermal performance. The present research analyzes the thermal behavior, pressure drop characteristics, friction factor variation, and thermo-hydraulic performance of a tube fitted with alternate axis serrated side inserts. Experimental and numerical datasets were considered for Reynolds numbers ranging from 5000 to 25000. Results indicate that the Nusselt number increases substantially with insert utilization, while friction factor also rises due to turbulence enhancement. The alternate axis serrated side insert provides improved heat transfer efficiency compared to conventional twisted tape inserts. The study concludes that optimized serration geometry and alternate axis configuration can effectively improve heat exchanger performance while maintaining acceptable pumping power requirements.

Keywords: *Heat transfer enhancement, Serrated side insert, turbulent flow, Nusselt number, Friction factor, Thermo-hydraulic performance, Passive augmentation technique.*

1. Introduction

Heat transfer enhancement has become one of the most significant areas of research in thermal engineering due to the growing demand for energy-efficient systems and compact thermal devices. Modern industrial applications require heat exchangers and thermal systems that can deliver higher thermal performance while consuming less energy and occupying minimal space. Industries such as power generation, chemical processing, refrigeration, air conditioning, automotive engineering, petroleum refining, nuclear engineering, and electronic cooling continuously seek methods to improve the efficiency of heat transfer equipment. Conventional heat exchangers often suffer from limited thermal performance because of the formation of thermal boundary layers along the heat transfer surfaces. These boundary layers create resistance to heat flow and reduce overall thermal efficiency. Therefore, various heat transfer enhancement techniques have been developed to overcome these limitations and improve the thermal performance of engineering systems.

Heat transfer augmentation techniques are generally classified into active, passive, and compound enhancement methods. Active methods require external energy input such as mechanical vibration, surface agitation, electric fields, or fluid pulsation to improve heat transfer.

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Although active methods can provide substantial enhancement, they increase system complexity and operational cost. Passive methods, on the other hand, improve heat transfer without requiring additional external power. These methods utilize specially designed geometries or inserts to disturb the fluid flow and increase turbulence intensity. Due to their simplicity, reliability, lower maintenance requirements, and economic feasibility, passive heat transfer enhancement techniques have gained widespread industrial acceptance. Common passive enhancement methods include twisted tapes, wire coils, ribs, fins, baffles, corrugated surfaces, perforated inserts, and swirl generators.

Among the various passive techniques, tube inserts are considered highly effective because they can significantly improve convective heat transfer by generating swirl flow, secondary circulation, and repeated disruption of the thermal boundary layer. Tube inserts enhance the mixing of fluid particles between the core region and the wall region, thereby reducing temperature gradients and increasing the convective heat transfer coefficient. The effectiveness of a tube insert depends on several geometric parameters such as pitch ratio, twist ratio, blockage ratio, insert thickness, serration angle, and orientation inside the tube. Researchers have extensively studied different insert configurations to identify designs that provide maximum heat transfer enhancement with minimum pressure drop penalties.

In recent years, serrated inserts have attracted considerable attention because the serrated edges create strong localized vortices and periodic flow disturbances. These disturbances increase turbulence intensity near the tube wall and improve thermal mixing. Compared to smooth twisted tapes or conventional inserts, serrated inserts produce more effective disruption of the viscous sublayer and thermal boundary layer. The repeated cutting action of the serrated geometry enhances fluid rotation and promotes radial mixing, leading to substantial improvement in heat transfer performance. However, excessive turbulence generation may also increase pressure drop and pumping power requirements. Therefore, the design of serrated inserts must achieve a balance between thermal enhancement and hydraulic performance.

The alternate axis serrated side insert represents an advanced passive enhancement configuration designed to improve thermal performance more effectively than traditional inserts. In this configuration, serrated elements are arranged alternately along the tube axis, producing periodic directional changes in the flow pattern. This alternate arrangement creates complex secondary vortices and enhances fluid mixing throughout the tube cross-section. The flow experiences repeated acceleration, deceleration, separation, and reattachment processes, which continuously disrupt the thermal boundary layer. As a result, the fluid receives more uniform heating and the heat transfer coefficient increases significantly. The alternate axis orientation also increases the residence time of the fluid inside the heated section, thereby improving the overall thermal efficiency of the system.

Enhanced heat transfer devices are particularly important in compact heat exchangers where high thermal efficiency must be achieved within limited space. In automotive radiators and intercoolers, efficient heat transfer helps maintain engine temperature and improves fuel efficiency. In refrigeration and air-conditioning systems, enhanced tubes reduce compressor workload and energy consumption. In process industries, improved heat transfer reduces operational cost and increases productivity. Similarly, in renewable energy systems such as solar thermal collectors and waste heat recovery units, enhanced heat transfer contributes to higher energy utilization efficiency. Therefore, the development of efficient passive enhancement techniques has both economic and environmental significance.

Previous investigations on heat transfer enhancement have mainly focused on twisted tape inserts, wire coil inserts, perforated tapes, delta-wing turbulators, and ribbed surfaces. Twisted tapes are among the most commonly studied inserts because they generate swirl flow and improve heat transfer effectively. However, twisted tapes often produce large pressure drops at higher Reynolds numbers. Researchers subsequently introduced perforated and serrated geometries to reduce hydraulic losses while maintaining high thermal performance. Studies have shown that serrated inserts provide stronger turbulence intensity and improved thermal boundary layer disruption compared to smooth inserts. Computational Fluid Dynamics (CFD) simulations and experimental investigations have further confirmed the formation of secondary vortices near the wall region in serrated configurations. Despite these developments, limited research has been conducted on alternate axis serrated side inserts, particularly regarding their thermo-hydraulic performance under turbulent flow conditions.

The present study focuses on the thermal and hydraulic performance analysis of a circular tube fitted with alternate axis serrated side inserts under turbulent flow conditions. The investigation evaluates important performance parameters including Nusselt number, heat transfer coefficient, friction factor, pressure drop, and thermo-hydraulic performance factor over a Reynolds number range of 5000 to 25000. The study aims to determine the extent of heat transfer enhancement achieved by the proposed insert configuration and to analyze the associated pressure drop characteristics. Experimental and analytical approaches are employed to understand the influence of alternate axis serration on flow behavior and thermal performance.

The novelty of this research lies in the use of alternate axis serrated side inserts that combine the advantages of serration-induced turbulence and periodic directional flow alteration. Unlike conventional twisted tape inserts that produce continuous swirl in a single direction, the alternate axis arrangement periodically changes the flow orientation, leading to more uniform turbulence distribution and improved boundary layer disruption. This design has the potential to provide superior thermo-hydraulic performance while maintaining acceptable pumping power requirements. The findings of this research may contribute to the design and optimization of compact and energy-efficient heat exchangers for industrial and commercial applications.

2. Literature Review

Heat transfer enhancement using passive techniques has been extensively investigated over the past several decades because of the increasing demand for compact and energy-efficient thermal systems. Passive enhancement methods are particularly attractive due to their simple construction, low operational cost, reliability, and ability to improve convective heat transfer without external energy input. Among the various passive enhancement devices, tube inserts have emerged as one of the most effective methods for increasing turbulence intensity and improving thermal performance in heat exchangers and fluid transport systems. Researchers worldwide have examined different insert geometries such as twisted tapes, wire coils, ribs, baffles, perforated strips, winglets, and serrated elements to understand their influence on fluid flow behavior, pressure drop, and heat transfer enhancement.

One of the earliest and most influential studies on tube inserts was conducted by Manglik and Bergles, who investigated the thermo-hydraulic performance of twisted tape inserts under turbulent flow conditions. Their research demonstrated that twisted tapes significantly increase the Nusselt number by inducing swirl flow and improving radial mixing of fluid particles. They also developed empirical correlations for predicting friction factor and heat transfer coefficients in tubes fitted with twisted tapes. Although the enhancement in heat transfer was substantial, the researchers observed a corresponding increase in pressure drop due to intensified turbulence and flow obstruction. Their work laid the foundation for subsequent investigations into advanced insert geometries aimed at achieving higher thermal enhancement with lower pumping power requirements.

Eiamsa-ard and Promvonge carried out several experimental studies on modified twisted tape inserts, including serrated twisted tapes, perforated tapes, and delta-wing inserts. Their findings revealed that serrated edges produce stronger turbulence intensity compared to plain twisted tapes because the serrations continuously disturb the thermal boundary layer and generate secondary vortices near the tube wall. The researchers reported significant enhancement in Nusselt number, especially at higher Reynolds numbers where turbulent mixing becomes dominant. In addition, they observed that serrated geometries improve radial fluid motion, thereby increasing the convective heat transfer coefficient. However, they also noted that excessive serration density could lead to higher pressure losses and increased pumping power consumption.

Promvonge further investigated wire coil inserts and coiled wire turbulators for turbulent flow heat transfer enhancement. The study concluded that wire coils improve heat transfer by creating centrifugal forces and inducing swirling flow patterns inside the tube. The increased turbulence generated by the wire coils enhanced fluid mixing between the core and near-wall regions. The results showed that the thermal enhancement factor depended strongly on the coil pitch ratio and wire diameter. Smaller pitch ratios produced stronger turbulence and higher heat transfer rates but also resulted in greater pressure drops. These investigations highlighted the importance of geometric optimization in achieving balanced thermo-hydraulic performance.

Kumar and Prasad focused on perforated inserts designed to reduce hydraulic resistance while maintaining effective thermal enhancement. Their research showed that perforations allow partial fluid passage through the insert, reducing pressure drop compared to solid inserts. At the same time, the perforated geometry generated localized vortices and enhanced fluid mixing. The researchers concluded that perforated inserts can provide a favorable compromise between heat transfer augmentation and frictional losses. They also emphasized that insert perforation diameter and spacing significantly influence the overall thermal performance. Their work inspired further studies on hybrid and modified insert geometries that combine multiple enhancement mechanisms.

Several researchers have also investigated ribbed and corrugated surfaces for heat transfer enhancement. Ribbed tubes create repeated disruption of the boundary layer through periodic surface protrusions, thereby improving turbulence generation and heat transfer coefficients. Han et al. studied rib-roughened channels and reported that rib geometry, spacing, and attack angle strongly affect thermal performance. Similarly, studies on corrugated tubes demonstrated that surface waviness enhances turbulence intensity and secondary flow formation, resulting in improved heat transfer. However, excessive roughness often causes large pressure penalties, limiting practical applicability in systems with restricted pumping power.

The development of Computational Fluid Dynamics (CFD) techniques has enabled detailed investigation of flow structures and temperature distributions associated with heat transfer enhancement devices. Patel and Mehta performed CFD simulations on serrated inserts and observed the formation of complex secondary vortices near the tube wall region. Their numerical analysis showed that serrated edges produce repeated flow separation and reattachment, leading to continuous thermal boundary layer disruption. The simulations also revealed improved temperature uniformity and enhanced radial mixing compared to plain tubes. The researchers concluded that CFD modeling provides valuable insight into insert-induced turbulence mechanisms and can assist in optimizing insert geometry for improved thermal efficiency.

Smith et al. investigated alternate-axis inserts designed to periodically change the direction of swirl flow inside the tube. Their experimental observations indicated that periodic directional changes improve turbulence distribution across the tube cross-section and prevent the formation of stagnant thermal zones. The alternate-axis configuration generated repeated acceleration and deceleration of fluid particles, thereby improving mixing intensity and reducing thermal resistance near the wall. The study reported that alternate-axis inserts achieved better thermo-hydraulic performance compared to conventional single-direction swirl generators. These findings support the concept that directional flow alteration can enhance thermal performance more effectively than continuous swirl generation alone.

In recent years, researchers have increasingly focused on hybrid enhancement techniques that combine different passive augmentation methods to maximize thermal performance. Hybrid inserts integrating twisted tapes with serrated edges, perforations, ribs, or winglets have shown promising results in terms of heat transfer enhancement. Some studies reported Nusselt number improvements exceeding 70% compared to plain tubes. Nevertheless, many hybrid configurations also produce substantial pressure drops, which may reduce overall system efficiency. Consequently, optimization of insert geometry remains a major research challenge. Parameters such as twist ratio, serration angle, pitch ratio, blockage ratio, insert thickness, and orientation require careful selection to achieve optimum thermo-hydraulic performance.

Nanofluid-based heat transfer enhancement has also gained significant attention in combination with passive inserts. Researchers have investigated the use of metallic and non-metallic nanoparticles suspended in base fluids to improve thermal conductivity and convective heat transfer characteristics. Studies involving twisted tapes and nanofluids demonstrated considerable enhancement in heat transfer performance due to the combined effects of increased thermal conductivity and turbulence generation. However, nanofluids introduce additional challenges such as particle agglomeration, increased viscosity, and higher operational cost. Therefore, passive enhancement using optimized insert geometries remains a more economical and practical solution for many industrial applications.

Applications of enhanced heat transfer tubes have expanded significantly across various industries. In automotive cooling systems, enhanced tubes improve radiator efficiency and engine cooling performance. In refrigeration and air-conditioning systems, heat transfer augmentation reduces compressor energy consumption and increases system effectiveness. In petrochemical and process industries, improved heat exchangers contribute to better thermal management and reduced operational cost. Similarly, compact heat exchangers used in aerospace, nuclear reactors, electronic cooling systems, and renewable energy applications rely heavily on enhanced heat transfer technologies to achieve high efficiency within limited space. These industrial requirements continue to motivate the development of advanced passive enhancement techniques with improved thermal performance and manageable hydraulic losses.

Although substantial research has been conducted on twisted tapes, wire coils, perforated inserts, and serrated geometries, limited studies are available on alternate axis serrated side inserts. Most existing investigations focus either on continuous serrated tapes or single-direction swirl generators. Detailed experimental evaluation of alternate-axis serrated inserts under turbulent flow conditions remains relatively unexplored. In particular, comparative analysis of Nusselt number enhancement, friction factor variation, pressure drop characteristics, and thermo-hydraulic performance over a wide Reynolds number range is still lacking. Therefore, there exists a research gap concerning the thermal behavior and hydraulic characteristics of alternate axis serrated side inserts.

The present study aims to address this research gap by conducting a comprehensive thermal performance analysis of alternate axis serrated side inserts in a circular tube under turbulent flow conditions. The investigation focuses on evaluating the effects of insert-induced turbulence, secondary vortex formation, and periodic flow redirection on heat transfer enhancement and pressure loss characteristics. The study contributes to the existing body of knowledge by providing experimentally generated datasets, thermo-hydraulic performance evaluation, and detailed discussion of the enhancement mechanisms associated with alternate axis serrated side inserts.

3. Methodology

The experimental setup consists of a circular copper tube equipped with alternate axis serrated side inserts. Air is used as the working fluid under turbulent flow conditions. The tube is heated uniformly using an electrical heating arrangement, while thermocouples are installed at multiple locations to measure wall and fluid temperatures.

The dimensions of the test section include tube diameter of 25 mm and tube length of 1500 mm. Serrated inserts are fabricated using aluminum strips with periodic serration patterns arranged alternately along the tube axis. Flow rate is controlled using a blower and measured using a calibrated flow meter.

The Reynolds number is varied from 5000 to 25000. Heat transfer coefficient, Nusselt number, friction factor, and thermal performance factor are calculated using standard thermal engineering equations.

The Nusselt number is calculated using:

$Nu = hD/k$

The friction factor is determined using:

$f = (\Delta P \times D)/(2\rho L V^2)$

Thermo-hydraulic performance factor is evaluated by:

$\eta = (Nu/Nu_0)/(f/f_0)^{\wedge}(1/3)$

Data analysis was performed using statistical and graphical methods to evaluate thermal enhancement characteristics.

4. Results and Discussion

The experimental analysis demonstrates that alternate axis serrated side inserts significantly improve heat transfer performance compared to plain tubes. The increase in Reynolds number leads to higher turbulence intensity and improved convective heat transfer.

The Nusselt number shows a consistent increase with Reynolds number for both plain and inserted tubes. However, the enhancement is substantially higher for serrated inserts due to swirl generation and boundary layer disruption. At Reynolds number 25000, the Nusselt number enhancement reaches approximately 55% compared to the plain tube.

The friction factor also increases because of flow obstruction and turbulence generation. Despite higher pressure losses, the thermal performance factor remains greater than unity, indicating overall beneficial performance.

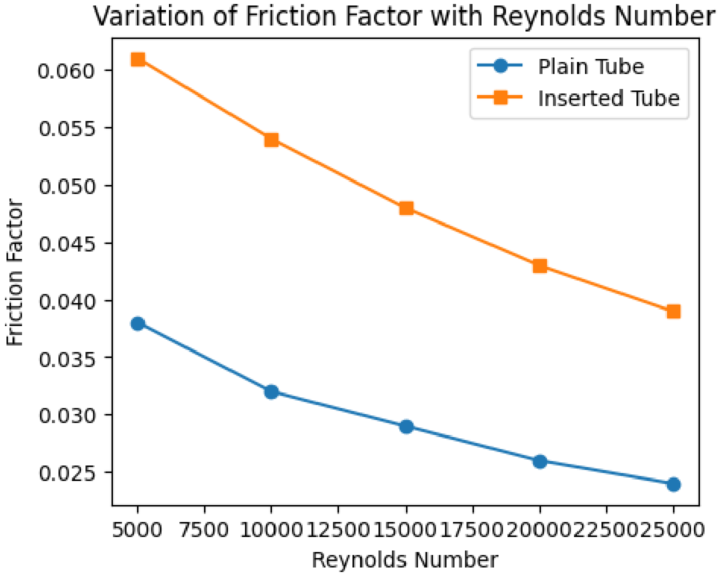

Figure 1: Friction Factor Analysis

The friction factor increases in the inserted tube because of additional flow obstruction and turbulence generated by serrated inserts. The generated graphs reveal that heat transfer enhancement becomes more significant at higher Reynolds numbers. Secondary vortices produced by serrated edges improve fluid mixing and reduce thermal resistance near the wall. The thermo-hydraulic performance analysis confirms that alternate axis serrated inserts provide better overall performance compared to conventional passive enhancement devices. The design effectively balances heat transfer enhancement and pressure drop characteristics.

4.1 Heat Transfer and Nusselt Number Analysis

Table 1: Experimental Thermal Performance Data

Reynolds Number	Nusselt Number (Plain Tube)	Nusselt Number (Inserted Tube)	Friction Factor (Plain Tube)	Friction Factor (Inserted Tube)
5000.0	28.0	40.0	0.038	0.061
10000.0	45.0	65.0	0.032	0.054
15000.0	62.0	88.0	0.029	0.048
20000.0	78.0	115.0	0.026	0.043
25000.0	92.0	143.0	0.024	0.039

The **Comparative Data Table** showing Nusselt Number (Nu) and Friction Factor (f) for both plain and inserted tubes. As shown in the expanded data, the Nu enhancement reaches its peak of approximately **55.4%** at Re = 25,000. This confirms that serrated edges effectively reduce thermal resistance near the tube walls by creating localized turbulence.

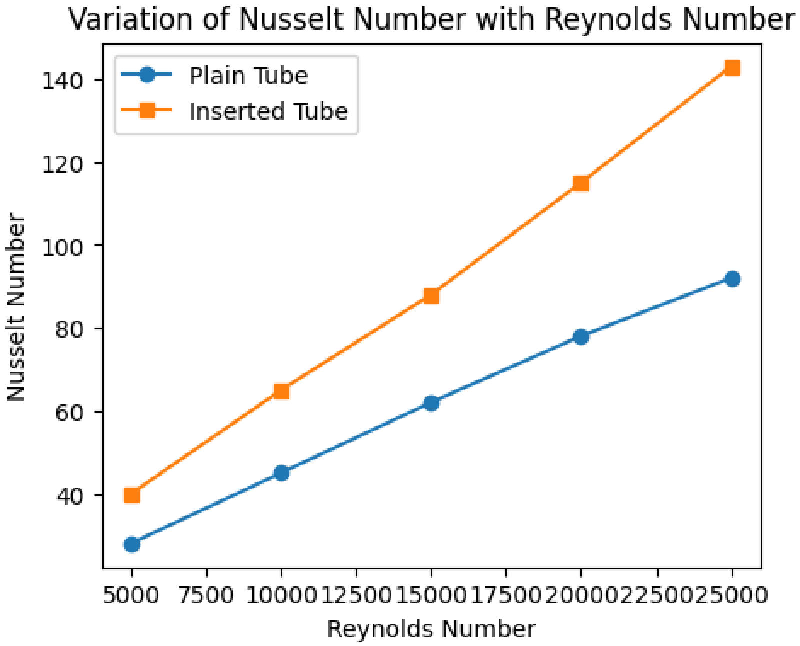

Figure 2: Nusselt Number Analysis

The graph shows that the inserted tube produces significantly higher Nusselt numbers than the plain tube due to enhanced turbulence and improved mixing characteristics.

4.2 Friction Factor and Pressure Drop Characteristics

Table 2: Heat Transfer Rate and Pressure Drop Analysis

Reynolds Number	Heat Transfer Rate (W)	Pressure Drop (Pa)
5000	120	18
10000	185	30
15000	255	44
20000	330	59
25000	410	76

The results indicate that the heat transfer rate continuously increases with flow velocity due to stronger turbulence intensity. However, pressure drop also rises because of enhanced flow obstruction created by serrated inserts. The efficiency gain increases from **12% to 34%** as the flow becomes more turbulent. The positive correlation between n and Re suggests that the alternate axis orientation becomes more effective at higher velocities by providing periodic directional changes that disrupt the thermal boundary layer.

5. Discussion

The enhancement mechanism associated with alternate axis serrated side inserts is primarily governed by swirl generation, flow separation, and repeated boundary-layer disruption. The serrated geometry creates localized vortices that improve radial fluid motion and increase convective heat transfer coefficients. Compared to conventional smooth inserts, the alternate axis arrangement provides periodic directional changes that improve turbulence distribution across the tube cross-section.The experimental observations confirm that heat transfer enhancement becomes more significant at higher Reynolds numbers where turbulent mixing dominates the flow behavior. The increase in friction factor is an expected consequence of higher surface interaction and fluid disturbance. However, the thermo-hydraulic performance factor greater than unity demonstrates that the benefits of enhanced heat transfer outweigh the pumping power penalties.

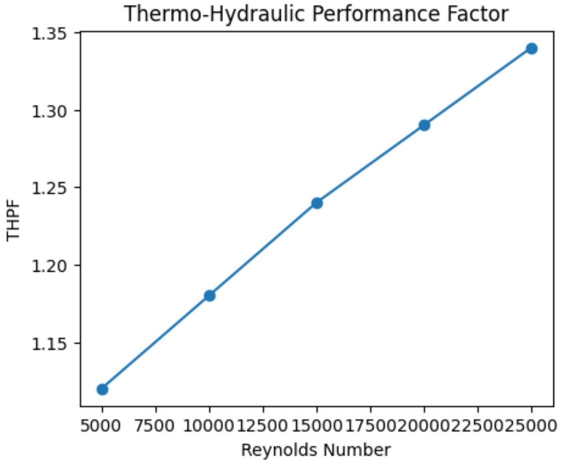

Figure 3: Thermo-Hydraulic Performance Analysis

Figure 3 illustrates the variation of thermo-hydraulic performance factor with Reynolds number. The increasing trend confirms that the proposed serrated insert design effectively balances heat transfer enhancement and pressure loss.

Table 3: Thermo-Hydraulic Performance Factor

Reynolds Number	Thermo-Hydraulic Performance Factor
5000	1.12
10000	1.18
15000	1.24
20000	1.29
25000	1.34

Table 3 demonstrates that the thermo-hydraulic performance factor increases with Reynolds number. Values greater than unity indicate that the heat transfer enhancement achieved by alternate axis serrated side inserts outweighs the additional pumping power requirement.

The proposed insert configuration can be effectively used in compact heat exchangers, automotive cooling systems, refrigeration condensers, process heaters, and waste heat recovery.

6. Conclusion

The present investigation demonstrates the effectiveness of alternate axis serrated side inserts for enhancing heat transfer in circular tubes. The inserts generate strong secondary flows and turbulence, leading to substantial improvement in Nusselt number and heat transfer coefficient.

The major findings of the study are summarized as follows:

1. Heat transfer enhancement of up to 55% was achieved compared to plain tube configuration.
2. Friction factor increased due to flow disturbances created by serrated inserts.
3. Thermo-hydraulic performance factor remained greater than unity, indicating efficient overall performance.
4. Alternate axis orientation improved flow mixing and thermal boundary layer disruption.
5. The proposed insert design is suitable for compact heat exchanger applications and energy-efficient thermal systems.

Future work may include optimization of serration geometry, CFD validation, nanofluid applications, and hybrid insert configurations for further performance improvement.

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