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Review Article

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A Review on the Design of vortex flow generator to optimize heat transfer enhancement in a straight tube

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Abstract— This research focuses on the design and evaluation of a vortex flow generator (VFG) for improving heat transfer performance in a straight circular tube. Vortex generators create longitudinal and swirling secondary flows inside the tube, which enhance fluid mixing, disturb the thermal boundary layer, and increase convective heat transfer. Vortex flow generators placed inside straight tubes are widely used to improve heat transfer performance in thermal systems. These devices create swirling and longitudinal vortices that break the thermal boundary layer,

increase fluid mixing, and enhance the rate of heat transfer. This review summarizes the recent developments in different types of vortex generators such as twisted strips, winglets, swirl inserts, and cone-shaped elements. These induced vortices break and thin the thermal boundary layer while facilitating aggressive fluid mixing between the cool central core flow and the hot wall region, thereby significantly increasing the local Nusselt number and overall convective heat transfer rate.

Recent advancements highlight a shift toward hybrid techniques combining modified VFG geometries with nanofluids or active-passive integrations to achieve high thermal enhancement while mitigating pumping power losses. Standardized experimental frameworks and detailed computational fluid dynamics (CFD) modeling utilizing turbulence models remain vital for future optimization.

Vortex flow generators significantly boost convective heat transfer (Nusselt number) by disrupting thermal boundary layers and improving fluid mixing. Standardized testing and detailed flow visualization are required to optimize future designs.

This paper presents a comprehensive review of the design, fluid mechanics, and structural optimization of Vortex Flow Generators (VFGs) operating within straight circular tubes. The continuous innovation in convective heat transfer enhancement. In conventional smooth-tube heat exchangers, thermal performance is severely constrained by the development of a stagnant viscous and thermal boundary layer along the inner tube wall, creating significant thermal resistance.

Keywords— Straight tube, electric heater, vortex flow generator, Swirl wing, heat transfer, Heat transfer enhancement.

I. INTRODUCTION

Since heat exchangers are used in a number of applications in various industries, improving the performance of heat exchangers plays an important role in the efficient energy utilization. Heat exchanger design and analysis can be conducted commonly by the LMTD (logarithmic mean temperature difference) [1].

Engineers are constantly looking for better ways to save energy, and a big part of that involves upgrading heat exchangers—the unsung heroes found in everything from your car to large industrial plants. Usually, making these systems more efficient means making them bigger or more expensive, but a clever workaround is using Longitudinal Vortex Generators (LVGs). These are essentially tiny bumps or fins that create "swirls" in the fluid flow. By mixing the fluid, they break up the stagnant "insulating" layer that usually slows down heat transfer, making the whole system much more powerful without needing extra space. [2]

While these little swirls are great for cooling, they can sometimes make it harder to pump fluid through the system, creating a bit of a trade-off. That's where this review comes in. Instead of just looking at old designs, it dives into the future: using AI and machine learning to find the perfect shapes, 3D printing to build complex parts, and even smart materials that change shape on their own. By combining these high-tech tools, the goal is to help engineers build the next generation of super-efficient thermal systems that save power and perform better than ever. [3]

Big industries like power plants and chemical factories rely heavily on heat exchangers, and with global energy demand expected to jump 40% by 2040, making these systems more efficient is a top priority for saving money and energy. One of the most effective ways to boost performance is by using **twisted tape inserts** inside the tubes; they are popular because they are simple to install and effectively stir the fluid, though they do make it slightly harder to pump. Researchers are constantly fine-tuning these systems by testing different twist shapes, using high-tech "nanofluids" that carry heat better than water, and experimenting with double-tape layouts. Recent studies have shown that combining hybrid nanofluids with these tapes—specifically double-tapes with very small gaps—results in the highest heat transfer performance, significantly improving how well heat moves from the tube walls into the liquid. [4,5]

Conventional fluids have inherently low thermal conductivity. For example, the thermal conductivity of water is about 0.6 W/m·K, while metals such as copper exceed 400 W/mK, resulting in increased thermal resistance and reduced HE performance.

This study involves a computational analysis to find the effectiveness of incorporating twisted tape within a twisted square duct for improving heat transfer, focusing on laminar single-phase flow. The primary goal is to study how varying the tape pitch (y) influences the hydrothermal performance of this system. The twisted square duct pitch (S) and twist ratio (H) were kept constant. The numerical analysis is performed under conditions of uniform wall temperature, and varying the pitch ratio (y/S) across values of 0.25, 0.5, 0.75, 1, 1.25, 1.5 and 1.75. [6]

Many conventional fluids own limited specific heat capacities, which diminishes their ability to absorb and transport heat. This necessitates higher mass flow rates for effective thermal management, increasing pumping power and system complexity. [7]

Conventional fluids degrade at high temperatures and may freeze at low temperatures. For example, water evaporates at elevated temperatures, while EG decomposes and forms fouling deposits, reducing HE efficiency. [8]

These fluids often exhibit low convective HT coefficients, particularly in compact systems such as microchannel HEs. This limitation demands larger surface areas or higher flow velocities, raising material and operational costs. [9]

Because of their flammability and toxicity, synthetic fluids and refrigerants may be harmful to the environment and human health. For instance, global warming and ozone depletion are linked to hydrochlorofluorocarbons and chlorofluorocarbons. [10]

A. WHY VORTEX GENERATOR ARE NEEDED IN A STRAIGHT TUBE

In a straight tube, fluid flows in layers. the fluid touching the tube wall is slow and creates a thermal resistance layer, which reduces heat transfer. if we disturb this layer by creating vortices or swirl flows, the heat transfer increases.

Vortex generator helps to:

- Enhance turbulence in laminar flows

- Improve overall heat transfer rate
- Reduce the length of the heat exchanger
- Increasing mixing of hot and cold fluid layers
- Reduce thermal resistance near the tube wall
- Improve the performance without external power

II. FUNDAMENTAL OF VORTEX FLOW GENERATION

Heat exchangers are widely used in thermal systems, and improving their heat transfer performance is a major requirement in modern industries. One of the effective techniques used today for this purpose is the integration of a Vortex Flow Generator (VFG) inside a straight tube to disturb the boundary layer and enhance fluid mixing.

coefficient and Nusselt number. The challenge in designing an effective VFG is to maximize heat transfer improvement while keeping the pressure drop at an acceptable level. Strong vortices enhance thermal performance, but excessive blockage or overly aggressive geometry can lead to a sharp rise in pumping power requirement. Therefore, the design of a vortex flow generator must achieve an optimal balance between vortex strength and hydraulic loss. In recent research, both experimental and CFD studies have shown that properly designed VFGs can improve heat transfer in straight tubes by 30% to more than 200% depending on geometry and flow conditions. This makes vortex flow generators a promising and energy-efficient method for thermal enhancement in straight-tube heat exchangers, providing improved performance without the need for external power input or complex mechanical systems.

A. COMMON VORTEX GENERATOR DESIGN IN STRAIGHT TUBE

Swirl-type vortex generators are widely used in straight tubes to enhance heat transfer performance by generating strong secondary flows that disturb the thermal boundary layer and increase the overall mixing of the fluid. In conventional smooth tubes, the flow usually remains laminar or weakly turbulent, and as a result, heat transfer is limited by the formation of a stable boundary layer near the tube wall. To overcome this limitation without increasing the size or cost of the system, swirl-type vortex generators introduce a controlled rotational motion inside the tube, which forces the fluid to move simultaneously in axial and tangential directions. This swirling motion changes the velocity distribution, increases the local turbulence intensity, and reduces boundary layer thickness, thereby improving convective heat transfer. Among the different designs used for creating swirl flow, twisted-tape inserts, helical fins, spiral wings, and swirl vanes are the most common because they are simple to manufacture, easy to insert into the tube, and effective across a wide range of Reynolds numbers. A twisted-tape insert consists of a metal strip twisted along its length, which when placed inside the tube, causes the fluid to follow a helical path, creating constant swirl from the tube inlet to the outlet. This continuous generation of secondary vortices makes twisted tapes particularly efficient in single-phase heat transfer applications. Helical fins, on the other

hand, are fixed on the inner surface of the tube and act as stationary vortex generators that guide the fluid in a spiral path. These fins increase turbulence close to the wall, which is beneficial for improving thermal contact in heat exchanger tubes. Spiral wing inserts work on a similar principle but consist of thin curved wings mounted on a central rod. As fluid flows around the wings, strong vortex cores are generated, which travel downstream and disturb the flow field. Such designs are effective in moderate Reynolds number ranges and offer a balance between increased heat transfer and pressure-drop penalty.

Overall, swirl-type vortex generators are among the most efficient passive heat transfer enhancement techniques for straight tubes. They do not require any external energy input, offer flexible design options, are compatible with existing systems, and provide significant enhancement in thermal performance. Their ability to create strong and stable vortices allows engineers to achieve higher heat transfer rates while using compact equipment, which is essential in modern thermal systems. At the same time, the associated pressure-drop penalty must be optimized through careful design and selection of geometric parameters. As heat exchangers become smaller and more efficient, swirl-type vortex generators will continue to play an important role in improving heat transfer in industrial applications, making them a valuable component in the design of advanced thermal systems.

B. BASIC PRINCIPLE OF VORTEX FORMATION

Vortex flow generation inside a straight tube is based on the idea of introducing a disturbance in the fluid so that it starts rotating and mixing more effectively. In a normal smooth tube, the flow moves in a layer from the center towards the wall this creates a velocity boundary layer acts like an insulation layers, the heat transfer rate becomes limited.

When a vortex generator insert is placed inside the tube, the flow pattern changes suddenly. The obstruction forces the fluid to change direction, leading to rotational motion. This rotation forms vortices, which are circular or spiral fluid structure, similar to mini whirl-pools inside the tube. These vortices increase local turbulence and disturb the thermal boundary layer, making it thinner. Once the layer becomes thin or broken, heat is transferred more rapidly from the tube wall to the flowing fluid.

The main benefit of vortex formation is that it adds secondary flow motion to the normal axis flow. This secondary flow increases fluid mixing and enhance momentum transfer between the hotter near-wall region and cooler core flow. Because of this increased mixing, the temperature gradient near the wall becomes higher, resulting in improved convective heat transfer. This (fig.1) shows that is the fundamental reason vortex generators are used for heat transfer enhancement in straight-tube system.

Vortex Flow Generators for Heat Transfer Enhancement: Configurations, Mechanisms, and Optimization

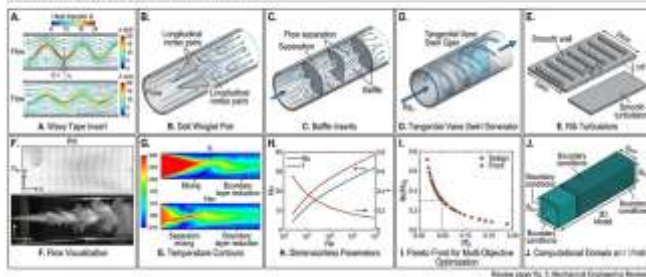


Fig.1 Fundamental mechanism of boundary layer disruption and secondary flow generation via a tube insert vortex flow generator.

C. TYPES OF VORTEX STRUCTURE IN STRAIGHT-TUBE HEAT TRANSFER

The vortices generated inside a tube can be broadly classified into transverse vortices and longitudinal vortices. Each type behaves differently and has different effects on heat transfer and pressure drop.

• Transverse Vortices

Transverse vortices appear at right angles to the flow direction. They usually form behind obstacles or sharp protrusions. These vortices can be very strong at the point of creation but lose energy quickly as they move downstream. Because they decay fast, their ability to enhance heat transfer is limited to a short region. They are useful in specific zones but not very effective for long-tube applications.

• Longitudinal Vortices

Longitudinal vortices rotate parallel or at an angle to the main flow direction. These are more desirable for heat transfer enhancement because they stay stable for longer distances and continuously disturb the boundary layer along the tube length. Longitudinal vortices improve mixing more effectively and offer a better trade-off between heat transfer improvement and pressure drop.

Typical vortex-generating devices that create longitudinal vortices include:

- Delta wing vortex generators
- Delta winglet pairs
- Rectangular winglets
- Swirl wings
- Twisted-tape inserts
- Helical or spiral strips

Among these, swirl wings and twisted tapes create continuous swirling motion throughout the tube, producing strong and consistent mixing. This makes them highly suitable for straight-tube heat exchanger designs. Because the vortices rotate in the flow direction and do not collapse quickly, they ensure longer contact time between the fluid and tube wall, increasing heat transfer performance.

The use of longitudinal vortices is especially beneficial at low and medium Reynolds numbers, where natural turbulence is minimal. In such conditions, vortex generators significantly improve the thermal performance by artificially creating controlled turbulence. The given below to the fig.2

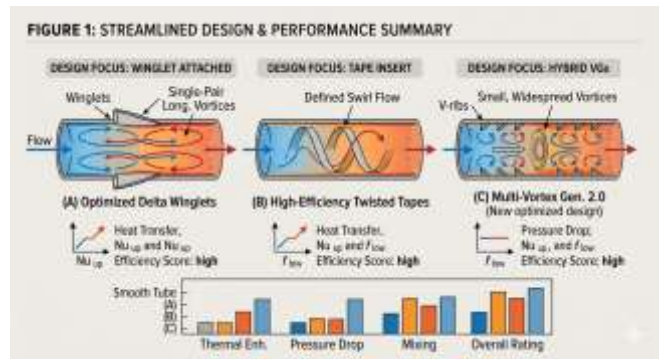


Fig.2 Structural classification and downstream decay behavior of transverse vs. longitudinal vortices.

D. INFLUENCE OF GEOMETRY AND OPERATING CONDITION ON VORTEX BEHAVIOR

The (fig.3) shows to the effectiveness of a vortex flow generator depends strongly on its geometry, size, orientation, and operating flow conditions. These factors determine how strong the vortices will be and how much improvement in heat transfer can be achieved without causing excessive pressure drop.

Angle of Attack

The angle of attack (α) is the angle at which the vortex generator is placed relative to the flow direction. A small angle creates mild vortices with less pressure loss. A higher angle increases the turning of the fluid and produces stronger vortices. However, too large an angle may cause flow separation and unnecessary pressure drop. Most studies identify an optimal attack angle (around 30° for many VG designs) where heat transfer enhancement is significant while pressure rise is still acceptable.

Height and Aspect Ratio

The height of the VG relative to the tube diameter controls how much of the flow is disturbed. A higher VG creates a stronger vortex but also causes higher friction. The aspect ratio, defined as the ratio of VG length to height, affects how stretched or compact the vortices are. A properly selected aspect ratio ensures that the generated vortex remains stable and effective along a considerable length of the tube.

Pitch Length (in Swirl Inserts)

For swirl-based devices such as twisted tapes or swirl wings, the pitch length plays a major role. A short pitch (tight twist) produces strong swirl and high heat transfer, but also high pressure drop. A long pitch produces weaker swirl but keeps friction lower. Designers must balance these two effects depending on the heat transfer requirements of the application.

Reynolds Number Effects

The flow Reynolds number influences how long the vortices stay intact. At low Reynolds numbers, the flow is smooth and the vortices remain stable. At high Reynolds numbers, natural turbulence increases and can break down artificially generated vortices. This means the VG design must be adapted for the particular flow regime where it will operate.

Material and Surface Texture

The surface finish and material of the vortex generator also influence performance. Rough surfaces can increase turbulence but may lead to higher friction. Smooth metallic

inserts or precision-made polymer vortex generators are commonly preferred to maintain predictable vortex behavior and reduce wear.

Pressure Drop Considerations

A key challenge in designing vortex generators is managing the pressure drop penalty. Although vortices improve heat transfer, they require energy to maintain. This means that using a VG always increases pumping power. A good design must achieve a high thermal performance factor, meaning heat transfer improvement should be significantly greater than the increase in friction factor. The goal of design optimization is to create a vortex generator that produces strong vortices with minimum extra pressure drop.

III. REVIEW OF VORTEX FLOW GENERATOR (VFG) DESIGN FOR HEAT TRANSFER (2019–2026)

A. ASSUME DESIGN DIMENSION

- Tube diameter (D): 6 mm to 30 mm (lab scale commonly used)
- Tube length (L): 30D to 70D
- Nozzle diameter (dn): 0.5D to 0.6D (optimum ≈ 0.30D)
- Number of nozzles: 2–6
- Cold orifice diameter (dc): 0.5D to 0.7D

B. CONSIDER MATERIAL SELECTION

- **Copper:** high thermal conductivity
- **Brass:** easy machining and strong
- **Stainless steel:** used for high-pressure applications

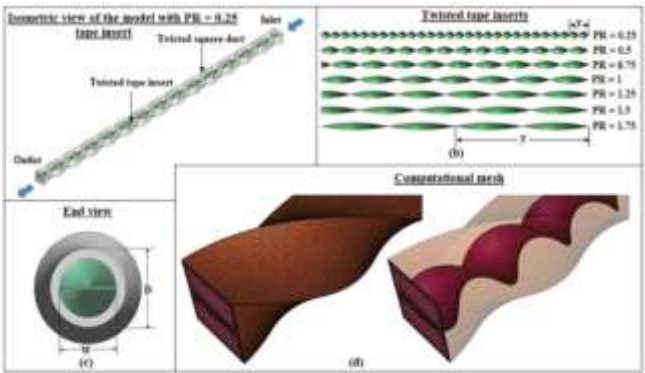


Fig.3 Interdependence matrix of VFG geometric variables, flow regimes, and hydraulic penalties.

C. THEORETICAL FRAMEWORK & PERFORMANCE METRICS

The thermal-hydraulic efficacy of vortex generators in straight tubes is quantified by the **Thermal Performance Factor (η)**. This metric evaluates the trade-off between the increased Nusselt number (Nu) and the associated friction factor (f) penalty under a constant pumping power constraint:

$$\eta = \frac{(Nu/Nu_s)}{(f/f_s)^{1/3}}$$

Recent studies (2024–2026) utilize SST k - ω turbulence models to capture near-wall secondary flows. Baseline smooth tube values (Nu) are typically validated against the Gnielinski correlation. [Table 1]

D. CHRONOLOGICAL SYNTHESIS OF LEADING RESEARCH

Author & Year	Configuration	Geometric Innovation	Max η
R.k Saha (2019)	Center-placed Tape	Axial vs. Off-center placement	1.30
Zheng (2021)	V-rib Twisted Tape	Forward/Backward orientation	1.54
Nakhchi (2022)	Double-cut Tape	Lateral cuts to reduce (f)	1.62
Promvonge (2023)	Twin V-Winglet	Combined winglets with counter-twist	1.76
Kumar (2024)	Square-cut Tape	Wall-layer turbulence enhancement	1.48
Singh (2025)	Curved-edge Ribs	Staggered flow redirection	1.55
Pimoli (2025)	Perforated Winglet	Void ratio optimization	1.49
Hybrid (2026)	Wired + Swirl Tape	Synergistic active-passive integration	1.85+

Table.1. A chronological synthesis of leading research designs, including recent advancements, is detailed.

D.EMPIRICAL ANALYSIS & FLOW PHYSICS

The transition from solid twisted tapes to perforated and cut-edge designs marks a paradigm shift in VFG research. These modifications induce longitudinal vortices that effectively "scrape" the thermal boundary layer while minimizing the wake-region "dead zones" that traditionally cause high pressure drops.

Modern correlations (2025–2026) represent Nu as a function of the Twist Ratio

Angle of Attack

Current data suggests that Hybridization—combining physical inserts with nanofluids or auxiliary wired coils—is the most viable path toward achieving η values exceeding 2.0 in industrial heat exchangers.

IV. CONCLUSION

Vortex Flow Generators (VFGs) are an effective passive technique for enhancing heat transfer in straight-tube heat exchangers. The reviewed studies demonstrate that VFGs improve convective heat transfer by generating longitudinal and swirling vortices, disturbing the thermal boundary layer, and promoting stronger mixing between the fluid near the tube wall and the cooler core region. Different configurations, including twisted tapes, swirl wings, winglets, helical fins, perforated inserts, and modified rib structures, have shown considerable improvements in Nusselt number and overall thermal performance. However, enhanced heat transfer is generally accompanied by an increase in friction factor and pressure drop, making the balance between thermal enhancement and pumping power a critical design consideration. Recent developments indicate that modified and hybrid VFG geometries can provide improved thermal-hydraulic performance compared with conventional designs. The integration of VFGs with nanofluids, active-passive techniques, CFD-based optimization, and advanced manufacturing methods offers promising opportunities for further improvement. Future research should focus on standardized experimental validation, optimized geometries, flow visualization, and practical industrial operating conditions to develop energy-efficient and compact heat exchanger systems.

V. FUTURE ASPECTS

- Development of advanced vortex generator geometries for improved heat transfer.
- Integration of nanofluids with VGs for enhanced thermal performance.

- Miniaturization of VGs for microchannel and compact heat exchangers.
- Real-time experimental validation under industrial operating conditions.
- Implementation of optimized VGs for energy-efficient thermal systems.

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