

Enhancement Study of Air-Side Heat Transfer in HVAC&R Heat Exchangers Using Winglet Vortex Generators

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Abstract - Compact fin-and-tube heat exchangers are extensively used in air-conditioning, refrigeration, petrochemical processing, and electronic cooling applications due to their high surface area density and compact design. However, their overall performance is significantly limited by high air-side thermal resistance caused by the low heat transfer coefficient of air. In this study, a detailed computational fluid dynamics (CFD) analysis is conducted to enhance the thermo-fluid performance of a fin-and-tube heat exchanger using passive vortex generator techniques. Specifically, plane rectangular winglet pairs and wavy rectangular winglet pairs arranged in a common-flow-up configuration with inline tube arrangement are investigated. Three-dimensional steady-state simulations are performed using ANSYS Fluent for laminar flow conditions over a Reynolds number range of 400–1500. The numerical model is validated against established experimental and empirical correlations, showing deviations within 10%. Parametric studies on plane winglets reveal that four winglet pairs, an optimal stream-wise spacing of 4.268 mm, and an attack angle of 15° provide the best performance, achieving approximately 21–22% enhancement compared to a smooth channel. Further analysis of wavy rectangular winglets indicates that a wave number of 6, wave height of 0.9 mm, and winglet length of 30 mm yield optimal results. A combined configuration of plane and wavy winglets demonstrates superior performance, with the P2W3 arrangement producing an overall enhancement of approximately 21%. Additionally, empirical correlations for Nusselt number, friction factor, and enhancement factor are developed, showing good agreement with CFD results within 5%.

The findings confirm that properly configured vortex generators significantly improve heat transfer performance while maintaining acceptable pressure drop, making them a viable solution for enhancing compact heat exchanger efficiency.

Key Words: Fin-and-tube heat exchanger, Computational Fluid Dynamics (CFD), Vortex generators, Rectangular winglet pairs, Wavy winglets, Heat transfer enhancement, Thermo-fluid performance, Nusselt number, Friction factor, Enhancement factor, Passive augmentation techniques.

1.INTRODUCTION

Heat exchangers play a crucial role in thermal engineering systems by enabling heat transfer between fluids or between a fluid and a solid surface. Among various types, compact fin-and-tube heat exchangers are widely used in applications such as air-conditioning, refrigeration, automotive cooling, petrochemical processing, and electronic equipment cooling due to their high surface area density and compact structure. However, the performance of these heat exchangers is significantly limited by the high air-side thermal resistance, which arises from the inherently low heat transfer coefficient of air.

To overcome this limitation, various heat transfer enhancement techniques have been developed. These techniques are generally classified into active, passive, and compound methods. Active techniques require external energy input, whereas passive techniques rely on geometric modifications to enhance heat transfer without additional power consumption.

Due to their simplicity, reliability, and cost-effectiveness, passive enhancement techniques are widely preferred in compact heat exchangers.

Among passive methods, the use of vortex generators (VGs) has gained considerable attention. Vortex generators are surface-mounted devices that induce secondary flow structures, such as longitudinal vortices, which enhance fluid mixing and reduce the thickness of the thermal boundary layer.

This results in improved heat transfer performance. Winglet-type vortex generators, in particular, are commonly used due to their effectiveness in generating strong vortical structures with relatively low pressure penalties.

Despite their advantages, vortex generators also introduce additional flow resistance, leading to increased pressure drop. Therefore, an optimal design must achieve a balance between heat transfer enhancement and pressure loss. The performance of vortex generators depends on several parameters, including their geometry, number, placement, and angle of attack, as well as the flow conditions.

In this context, the present study focuses on the thermo-fluid performance enhancement of a fin-and-tube heat exchanger using plane and wavy rectangular winglet pairs. A detailed computational fluid dynamics (CFD) analysis is carried out to investigate the effects of key geometric and flow parameters on heat transfer and pressure drop characteristics.

The study also aims to identify optimal configurations and develop predictive correlations for performance parameters such as Nusselt number, friction factor, and overall enhancement factor.

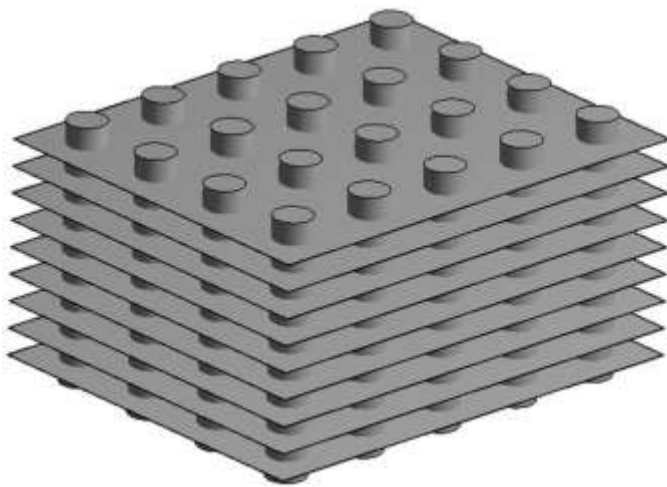


Figure 1: Schematic Diagram of core region of a Fin-and-tube heat exchanger

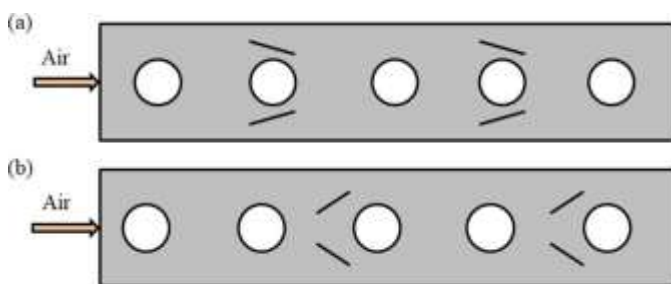


Figure 2: Orientation of winglets around the tubes: (a) "common-flow-up"; (b) common-flow-down

2. LITERATURE REVIEW

Enhancement of heat transfer in compact heat exchangers using vortex generators (VGs) has been widely investigated through experimental and numerical studies. These studies primarily focus on improving thermo-fluid performance by increasing heat transfer while minimizing pressure drop penalties. Based on the available literature, research can be broadly categorized into two groups: (i) channel flows without tubes and (ii) channel flows with tubes.

A. Channel Flows without Tubes

Early studies demonstrated that vortex generators significantly enhance heat transfer by inducing longitudinal vortices, which improve mixing between the core flow and boundary layer. Experimental investigations showed that both delta and rectangular winglets can provide substantial enhancement, with performance depending on parameters such as angle of attack, size, and spacing of the vortex generators.

Comparative studies indicated that winglet-type vortex generators generally perform better than wing-type devices due to lower pressure penalties. It has also been observed that heat transfer enhancement increases with Reynolds number and angle of attack, although higher angles often result in increased pressure drop. Furthermore, the geometry of vortex generators plays a crucial role, with delta winglets typically offering better thermo-hydraulic performance, while rectangular winglets provide higher heat transfer at the cost of increased flow resistance.

Recent numerical studies have explored advanced configurations such as curved, trapezoidal, and perforated vortex generators. These investigations revealed that modified geometries can further improve heat transfer by enhancing vortex strength and flow destabilization. Additionally, the orientation of vortex generators, namely common-flow-up and common-flow-down configurations, has been found to significantly influence the flow structure and thermal performance.

B. Channel Flows with Tubes

In fin-and-tube heat exchangers, the presence of tubes introduces complex flow features such as wake regions and recirculation zones, which reduce heat transfer efficiency. The use of vortex generators in such systems has been shown to effectively suppress these regions and enhance thermal mixing.

Experimental and numerical studies have reported that placing vortex generators near the tube wake region yields maximum heat transfer enhancement. Both inline and staggered tube arrangements have been investigated, with staggered configurations generally providing higher heat transfer but also incurring greater pressure drop. The effectiveness of vortex generators in these systems depends on their placement, number, and orientation.

Several studies have highlighted that downstream placement of winglets results in better performance due to enhanced mixing in the wake region. The angle of attack is another critical parameter, with moderate values typically providing an optimal balance between heat transfer enhancement and pressure loss. Moreover, multi-row winglet configurations have been found to significantly improve heat transfer, although excessive use increases pressure drop.

Advanced studies have also examined different tube geometries, such as circular and oval tubes, and their interaction with vortex generators. Results indicate that optimized combinations of tube geometry and vortex generator

configuration can lead to substantial improvements in thermo-fluid performance.

C. Summary and Research Gap

From the reviewed literature, it is evident that vortex generators are effective in enhancing heat transfer in compact heat exchangers. Key findings include:

- Longitudinal vortices provide better heat transfer enhancement compared to transverse vortices.
- Winglet-type vortex generators offer improved performance with lower pressure penalties.
- Rectangular winglets generally produce higher heat transfer but also higher pressure drop compared to delta winglets.
- The thermo-fluid performance is highly dependent on the geometry, placement, and orientation of vortex generators.
- Staggered tube arrangements enhance heat transfer but increase pressure drop compared to inline arrangements.

Despite extensive research, limited studies have focused on the optimization of span-wise and stream-wise placement of rectangular winglet pairs, as well as the combined use of plane and wavy winglet configurations. Furthermore, the development of reliable empirical correlations for predicting thermo-fluid performance based on geometric parameters remains insufficiently explored.

D. Objectives of the Present Study

Based on the identified research gaps, the objectives of the present work are as follows:

1. To investigate the effect of plane rectangular winglet parameters, including number, placement, and angle of attack, on thermo-fluid performance.
2. To analyze the influence of wavy rectangular winglet configurations, such as wave number, height, and length.
3. To study the combined effect of plane and wavy winglet arrangements.
4. To evaluate the overall performance in terms of heat transfer and pressure drop characteristics.
5. To develop predictive correlations for Nusselt number, friction factor, and enhancement factor based on CFD analysis.

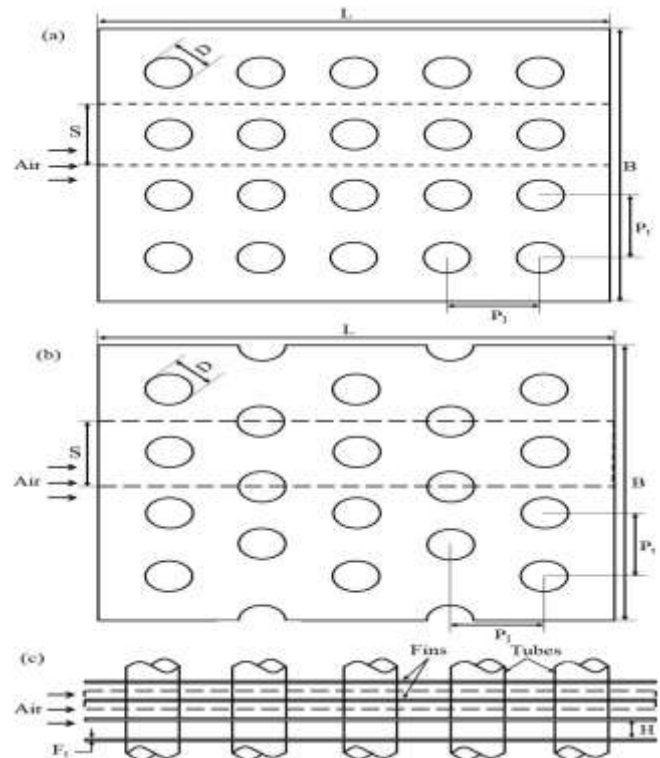


Figure 3: (a) & (b) Top view fin-and-tube heat exchanger with inline and staggered tubes respectively, (c) side view of fin-and-tube heat exchanger (inline and staggered)

3. MATHEMATICAL FORMULATION AND NUMERICAL METHODOLOGY

A. Physical Model

A three-dimensional model of a compact fin-and-tube heat exchanger with inline tube arrangement is considered in the present study. Due to the periodic nature of the geometry, a representative computational domain is selected to reduce computational cost. The working fluid is air, and all solid surfaces (fins and tubes) are assumed to be made of aluminum.

The inlet air temperature is maintained at 310.6 K, while the tube wall temperature is assumed constant at 291.77 K, owing to the high thermal conductivity of the tube material and the high heat transfer coefficient of the internal fluid. The flow is assumed to be steady, laminar, and incompressible within the Reynolds number range of 400–1500.

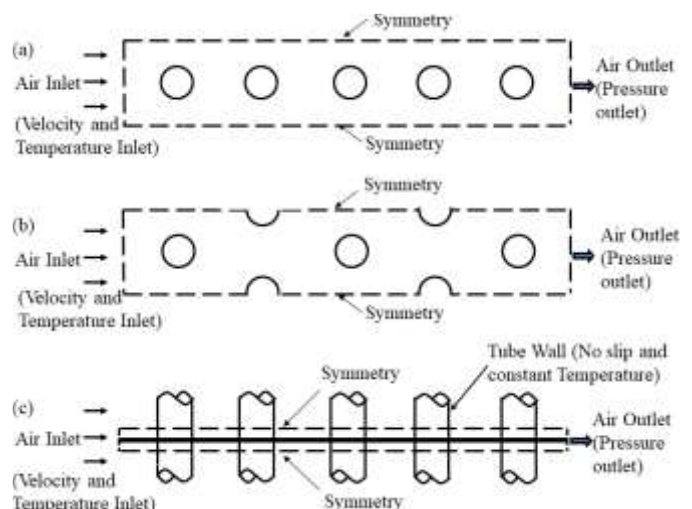


Figure 4: Applied boundary conditions (a) top view of the computational domain for inline arranged tubes, (b) top view of the computational domain for staggered arranged tubes, and (c) side view of the computational domain

B. Governing Equations

The thermo-fluid behavior is governed by the three-dimensional steady-state conservation equations of mass, momentum, and energy.

1. Continuity Equation: $\nabla \cdot (\rho \mathbf{u}) = 0$
2. Momentum Equation: $\rho(\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u}$
3. Energy Equation: $\rho c_p (\mathbf{u} \cdot \nabla T) = k \nabla^2 T$

For the solid regions (fins and winglets), the heat conduction equation is solved: $\nabla^2 T = 0$

Air density is treated as a function of temperature using the ideal gas relation, while other thermo-physical properties are assumed constant within the operating temperature range.

C. Boundary Conditions

Appropriate boundary conditions are applied to simulate the physical system accurately:

- **Inlet:** Uniform velocity and temperature are specified at the inlet boundary.
- **Outlet:** Zero-gradient boundary condition is applied for all variables.
- **Walls (fins, tubes, and winglets):** No-slip boundary condition is imposed. The tube wall is maintained at constant temperature, while fins and winglets are treated as conducting surfaces.
- **Symmetry Boundaries:** Symmetry conditions are applied on the lateral and transverse boundaries to represent periodic flow behavior.

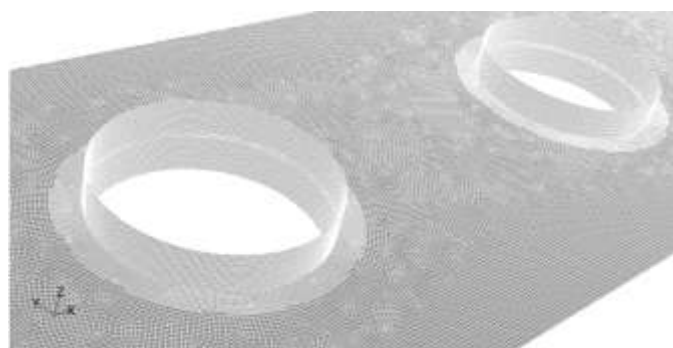


Figure 5: Three-dimensional view of generated mesh over the fin and tube surface

Mesh Level	Inline			Staggered		
	Number of Cells	Nu	f	Number of Cells	Nu	f
I	7,24,564	3.95	0.033	6,37,294	5.73	0.051

II	10,13,264	4.37	0.037	9,83,544	6.11	0.055
III	13,54,184	4.72	0.04	12,72,398	6.36	0.062
IV	15,48,366	4.79	0.045	15,43,178	6.45	0.069
V	17,89,494	4.81	0.049	17,73,240	6.49	0.073
VI	19,27,784	4.83	0.051	19,32,544	6.5	0.074

Table 1: Variation in Nusselt number and friction factor with the change in grid size for the baseline model

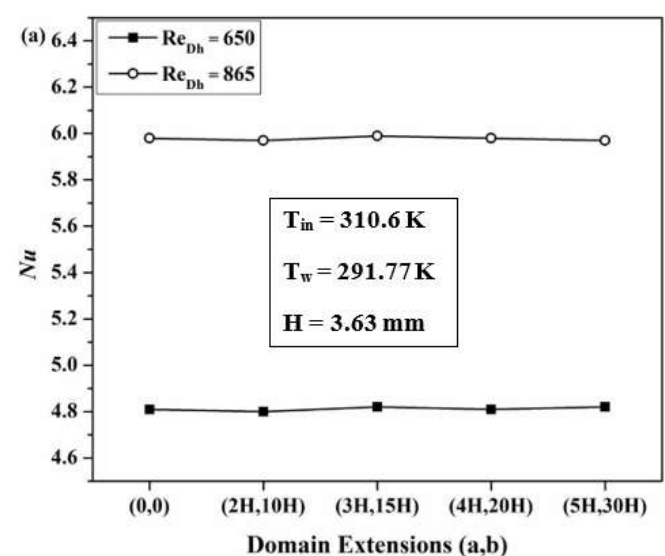
D. Numerical Methodology

The numerical simulations are performed using a finite volume-based CFD solver. The governing equations are discretized using a second-order accurate scheme for improved solution accuracy. Pressure-velocity coupling is achieved using the SIMPLE algorithm.

A structured/unstructured mesh is generated over the computational domain, with finer grid resolution near solid surfaces to capture boundary layer effects accurately. Grid independence studies are conducted to ensure that the numerical results are not sensitive to mesh size.

E. Model Validation

The numerical model is validated against available experimental data and established empirical correlations from the literature. Key performance parameters such as Nusselt number and friction factor are compared with benchmark results. The maximum deviation between the present numerical results and reference data is found to be within 10%, confirming the reliability and accuracy of the computational approach.



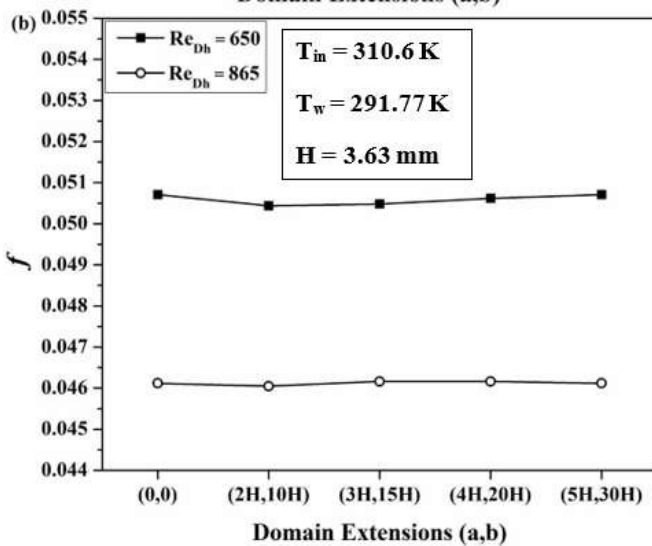


Figure 6: Effect of Domain extensions on (a) Nusselt number, and (b) friction factor

F. Performance Parameters

The thermo-fluid performance of the heat exchanger is evaluated using the following parameters:

- **Nusselt Number (Nu):** Represents convective heat transfer enhancement.
- **Friction Factor (f):** Indicates pressure drop characteristics.
- **Enhancement Factor (η):** Evaluates the overall performance by considering both heat transfer and pressure drop.

The enhancement factor is defined as: $\eta = \frac{(Nu/Nu_0)}{(f/f_0)^{1/3}}$

where Nu_0 and f_0 correspond to the baseline (smooth channel) values.

Parameter	Value Kays and London (1998)
Tube outside diameter	10.2 mm
Stream-wise tube pitch	22 mm
Span-wise tube pitch	25.4
Tube row number	3
Channel height	3.2
Fin thickness	0.33
Wall temperature	300 K
Air inlet temperature	340 K

Table 2: Geometrical configuration of the fin-and-tube heat exchanger used to validate the model and numerical method

Re_{Dh}	Experimental Results		Numerical Results			
	ΔP	Nu	Chu et al. (2009)		Present CFD	
			ΔP	Nu	ΔP	Nu
500	8.11	6.1	11	6	8.45	5.82
1000	27.6	9.2	25.1	8.4	26.68	8.3
1500	51.5	11.3	56	10.5	51.84	10.2

Table 3: Comparison of Present CFD results with the experimental results of Kays and London (1998) and numerical results of Chu et al. (2009)

4. THERMO-FLUID PERFORMANCE OF PLANE RECTANGULAR WINGLET PAIRS

A. Introduction

This section presents a detailed numerical investigation of the thermo-fluid performance of a fin-and-tube heat exchanger enhanced with plane rectangular winglet pairs. The effects of key geometric parameters, including the number of winglet pairs, their placement, and angle of attack, are analyzed to determine optimal configurations for heat transfer enhancement with minimal pressure drop penalty.

B. Effect of Number of Winglet Pairs

The number of rectangular winglet pairs plays a significant role in determining the strength of generated longitudinal vortices and the resulting heat transfer performance. Numerical results indicate that increasing the number of winglet pairs enhances the Nusselt number due to improved fluid mixing and boundary layer disruption.

However, a corresponding increase in friction factor is also observed due to higher flow resistance. Among the configurations studied, the use of **four winglet pairs** provides the best overall thermo-fluid performance, yielding approximately **21–22% enhancement** compared to the smooth baseline case. Beyond this number, the increase in pressure drop outweighs the heat transfer benefits.

C. Effect of Winglet Placement

The placement of winglet pairs relative to the tubes significantly influences the interaction between generated vortices and the wake region behind the tubes.

- **Stream-wise Placement (ΔX):** Variation in stream-wise distance affects the development and persistence of vortices. An optimal placement of $\Delta X = 4.268 \text{ mm}$ is found to maximize heat transfer by effectively energizing the wake region and delaying flow separation.
- **Span-wise Placement (ΔY):** Span-wise positioning controls the lateral distribution of vortices. Proper alignment ensures uniform mixing across the fin surface. It is observed that optimized span-wise

placement improves heat transfer without causing excessive pressure drop.

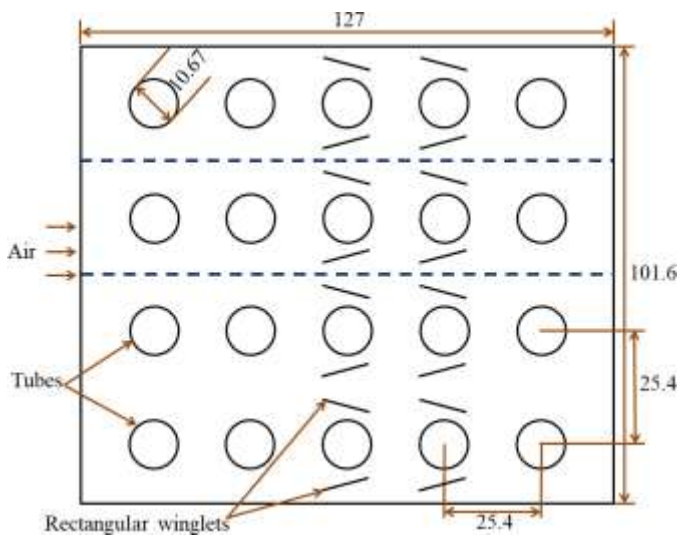


Figure 7: Top view of the fin-and-tube heat exchanger with winglets placed near third and fourth tubes

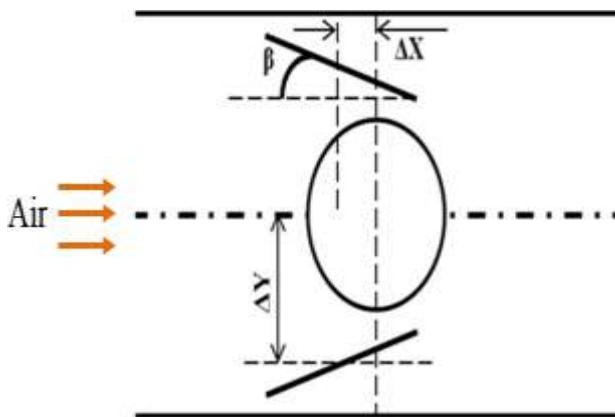


Figure 8: Top view of rectangular winglet orientation around the tube

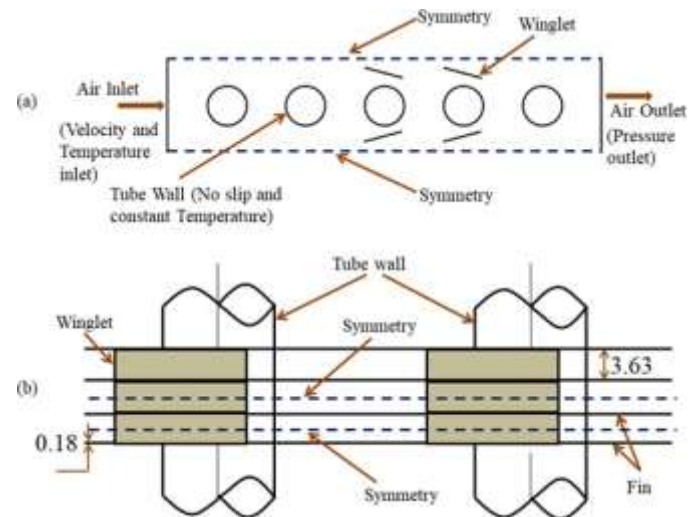


Figure 9: (a) Top view and (b) side view (shown for third and fourth tubes only) of the computational domain with applied boundary conditions

D. Effect of Angle of Attack (β)

The angle of attack of the winglet pairs is a critical parameter influencing vortex strength and flow structure. Increasing the angle of attack enhances vortex intensity, leading to improved heat transfer. However, it also increases form drag and pressure loss.

An optimal angle of attack of $\beta = 15^\circ$ is identified, which provides the best balance between heat transfer enhancement and pressure drop. Lower angles produce weaker vortices, while higher angles result in excessive pressure penalties.

E. Flow and Thermal Characteristics

The presence of rectangular winglet pairs generates strong longitudinal vortices that enhance mixing between the high-temperature core fluid and the cooler boundary layer near the fin surface. This results in:

- Reduction of thermal boundary layer thickness
- Suppression of wake regions behind the tubes
- More uniform temperature distribution across the fin surface

Velocity and temperature contour analysis shows that winglet-supported configurations significantly alter the flow field compared to the smooth channel, leading to improved convective heat transfer.

F. Overall Thermo-Fluid Performance

The combined effect of winglet number, placement, and angle of attack is evaluated using the enhancement factor. Results indicate that:

- Optimal configuration: **four winglet pairs**, $\Delta X = 4.268 \text{ mm}$, and $\beta = 15^\circ$
- Maximum enhancement: approximately **21–22% over baseline**

- Performance improvement is achieved with a moderate increase in pressure drop

These findings confirm that properly designed rectangular winglet pairs can significantly enhance the thermo-fluid performance of fin-and-tube heat exchangers.

G. Summary

The study demonstrates that plane rectangular winglet pairs are effective passive devices for heat transfer enhancement. The thermo-fluid performance is highly sensitive to geometric parameters, and careful optimization is required to achieve the best trade-off between heat transfer and pressure drop.

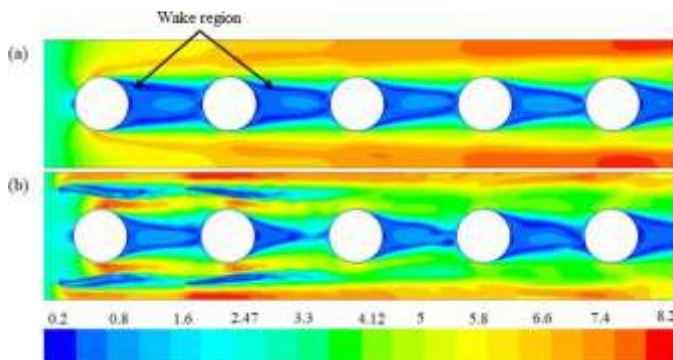


Figure 10: Velocity contours over the fin surface (units: m/s), (a) Smooth channel, and (b) two winglet pairs. ($Re_{Dh} = 650$)

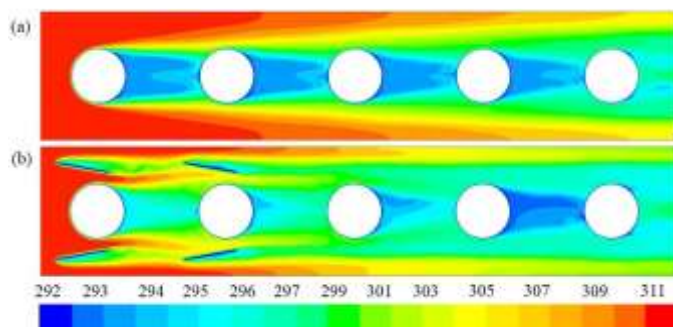


Figure 11: Temperature distribution over the fin surface near the winglets and the tube surface (a) Smooth channel, and (b) Double winglet (unit: K)

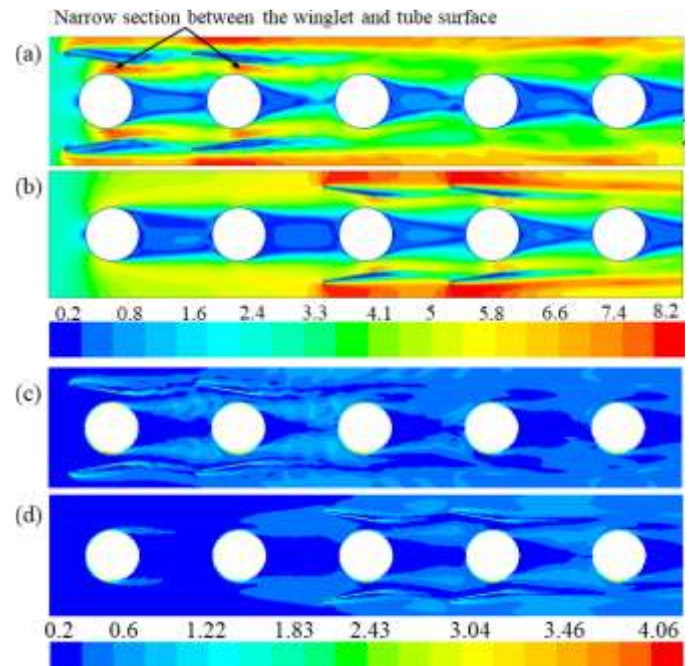


Figure 12: Contours of velocity (unit: m/s) and vorticity magnitude (unit: 10^{-3} s^{-1}) over the fin surface for T12, and T34 at $Re_{Dh} = 650$: (a) velocity contours for T12; (b) velocity contours for T34; (c) vorticity magnitude for T12; (d) vorticity magnitude for T34.

5. THERMO-FLUID PERFORMANCE OF WAVY RECTANGULAR WINGLET PAIRS

A. Introduction

This section investigates the thermo-fluid performance of a fin-and-tube heat exchanger enhanced with **wavy rectangular winglet pairs**. The introduction of waviness in winglet geometry modifies the flow structure, intensifies vortex generation, and improves fluid mixing. A detailed parametric study is carried out to evaluate the effects of wave number, wave height, winglet length, angle of attack, and combined configurations with plane winglets.

B. Effect of Winglet Placement

The placement of wavy winglet pairs relative to the tube rows significantly influences heat transfer performance. Numerical results indicate that positioning the winglets near downstream tube locations enhances thermal mixing in the wake region, leading to improved heat transfer.

Among the configurations studied, placing the winglet pair over the third tube provides better performance compared to upstream placement due to stronger interaction with developed flow structures.

C. Effect of Wave Number (n)

The wave number determines the number of undulations in the winglet geometry, directly affecting vortex generation.

Results show that increasing the wave number initially enhances heat transfer due to stronger and more distributed

vortices. However, beyond an optimal value, excessive waviness leads to increased flow resistance without proportional heat transfer gains.

An optimal wave number of $n = 6$ is identified, which provides the best thermo-fluid performance.

D. Effect of Wave Height (Wh)

Wave height plays a crucial role in determining the strength of induced vortices. Increasing wave height enhances the interaction between the main flow and boundary layer, thereby improving heat transfer.

However, higher wave heights also lead to increased pressure drop. The optimal wave height is found to be $Wh = 0.9 \text{ mm}$, which provides a favorable balance between heat transfer enhancement and flow resistance.

E. Effect of Winglet Length (l)

The length of the wavy winglet affects the extent of flow disturbance and vortex development.

Shorter winglets generate weaker vortices, while excessively long winglets increase pressure drop significantly. An optimal winglet length of $l = 30 \text{ mm}$ is identified, providing maximum heat transfer enhancement with acceptable pressure penalty.

F. Effect of Angle of Attack (β)

Similar to plane winglets, the angle of attack influences vortex intensity and flow behavior. Increasing the angle enhances heat transfer due to stronger vortices but also increases drag.

An optimal angle of attack of $\beta = 15^\circ$ is observed for wavy winglet configurations, ensuring an effective trade-off between heat transfer and pressure drop.

G. Combined Plane and Wavy Winglet Configuration

To further enhance performance, a combined configuration of plane and wavy winglet pairs is analyzed. The interaction between different winglet geometries results in improved vortex structures and enhanced mixing.

Among various combinations, the **P2W3 configuration** (plane winglet at tube 2 and wavy winglet at tube 3) demonstrates the best overall performance, achieving approximately **21% enhancement** over the baseline case.

H. Flow and Thermal Characteristics

The introduction of wavy geometry leads to:

- Stronger and more distributed longitudinal vortices
- Enhanced mixing between core flow and near-wall fluid
- Reduction in thermal boundary layer thickness

- Improved temperature uniformity across the fin surface

Velocity and temperature contour analyses confirm that wavy winglets outperform plane winglets in terms of flow destabilization and thermal mixing.

I. Overall Thermo-Fluid Performance

The performance evaluation based on Nusselt number, friction factor, and enhancement factor indicates that:

- Wavy winglets provide higher heat transfer compared to plane winglets
- Pressure drop increases moderately due to enhanced flow disturbance
- Optimal parameters ($n = 6$, $Wh = 0.9 \text{ mm}$, $l = 30 \text{ mm}$, $\beta = 15^\circ$) yield maximum performance

J. Summary

The study demonstrates that wavy rectangular winglet pairs are highly effective in enhancing thermo-fluid performance of fin-and-tube heat exchangers. Proper optimization of geometric parameters is essential to achieve maximum heat transfer with controlled pressure drop. Furthermore, combining plane and wavy winglets offers additional performance benefits, making it a promising approach for advanced heat exchanger design.

6. CONCLUSIONS AND FUTURE SCOPE

A. Conclusions

A comprehensive computational investigation has been carried out to evaluate the thermo-fluid performance of a fin-and-tube heat exchanger enhanced with plane and wavy rectangular winglet pairs. Based on the numerical analysis, the following key conclusions are drawn:

1. The use of vortex generators significantly enhances heat transfer performance by inducing longitudinal vortices, which improve fluid mixing and reduce thermal boundary layer thickness.
2. For plane rectangular winglet pairs, the thermo-fluid performance is strongly influenced by geometric parameters such as number of winglets, placement, and angle of attack. An optimal configuration of four winglet pairs, stream-wise distance $\Delta X = 4.268 \text{ mm}$, and angle of attack $\beta = 15^\circ$ provides the best performance, achieving approximately 21–22% enhancement over the baseline case.
3. Wavy rectangular winglet pairs further improve heat transfer performance by generating stronger and more distributed vortices. The optimal parameters are identified as wave number $n = 6$, wave height $Wh = 0.9 \text{ mm}$, winglet length $l = 30 \text{ mm}$, and angle of attack $\beta = 15^\circ$.
4. The combined configuration of plane and wavy winglets enhances thermo-fluid performance beyond individual configurations. The **P2W3 arrangement** (plane winglet at tube 2 and wavy winglet at tube 3)

yields the highest overall enhancement of approximately 21%.

5. Although heat transfer enhancement is achieved, an increase in pressure drop is observed for all winglet configurations. However, optimized designs ensure that the improvement in heat transfer outweighs the pressure penalty.
6. The developed empirical correlations for Nusselt number, friction factor, and enhancement factor show good agreement with numerical results, with deviations within acceptable limits.

Overall, the study confirms that optimized vortex generator configurations are an effective and practical approach for enhancing the performance of compact fin-and-tube heat exchangers.

B. Future Scope

Based on the findings of the present work, the following directions are suggested for future research:

1. Experimental Validation: Conduct experimental studies to validate the numerical results and verify the performance of optimized winglet configurations under real operating conditions.
2. Turbulent Flow Analysis: Extend the present study to higher Reynolds numbers and turbulent flow regimes to evaluate performance under practical industrial conditions.
3. Alternative Tube Arrangements: Investigate the performance of vortex generators in staggered tube configurations and compare with inline arrangements.
4. Advanced Winglet Geometries: Explore innovative vortex generator designs such as perforated, curved, split, or hybrid winglets for further enhancement.
5. Nanofluids and Advanced Working Fluids: Study the effect of using nanofluids or other advanced fluids to improve heat transfer performance in combination with vortex generators.
6. Optimization Techniques: Apply optimization algorithms (e.g., genetic algorithms, machine learning approaches) to identify globally optimal configurations considering multiple design parameters.
7. Multi-Objective Analysis: Perform multi-objective optimization considering heat transfer, pressure drop, cost, and energy efficiency simultaneously.

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