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Numerical Assessment of Vortex Generators for Enhancing Thermal Performance in Corrugated Tubes

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ABSTRACT

The effectiveness of triangular baffles in enhancing heat transfer within corrugated tubes is examined numerically in this study. Two key parameters influencing performance are examined: baffle placement (staggered and aligned) and their angles of attack (0°, 15°, 30°, and 45°). Heat transfer, friction, as well as performance metrics are comprehensively examined and compared for both configurations. The finite element method (FEM) implemented in CFD software COMSOL Multiphysics 6.1 is employed for simulations across a range of Reynolds numbers (100-400). Results reveal significant heat transfer improvements due to the proposed baffle configurations. Notably, aligned baffles with a 30° angle of attack achieve a 43.6% increase the heat transfer when compared to the baffle-free scenario. Staggered baffles with a 15° angle of attack demonstrate a superior 55.3% improvement compared to the baseline. A comprehensive evaluation of performance criteria identifies staggered baffles with a 30° angle of attack as the optimal configuration for maximizing heat transfer within corrugated tubes.

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1. INTRODUCTION

Heat exchangers (HEs) are essential across a broad range of technical applications, spanning from the pharmaceutical and chemical industries to dairy processing and renewable energy as a solar parabolic, among others. Their primary purpose is to enhance heat transfer and ensure a uniform temperature distribution in continuous processes. Consequently, the optimization of HE performance holds immense significance for numerous industries, promising substantial gains in energy efficiency, material utilization, and cost reduction (Eiamsa-Ard, 2010; Ghasemi & Ranjbar, 2016a, 2017; Maradiya et al., 2018; Sakhri et al., 2021a, b; Rebhi et al., 2022; Ghasemi, 2023).

In the literature, two fundamental approaches for enhancing heat transfer are well-documented: active and passive methods (Sheikholeslami et al., 2015). Active methods entail the infusion of external energy to drive the heat exchange process, such as the application of a magnetic field (Dahmani et al., 2022), inducing surface vibrations (Mohammed et al., 2021), and utilizing mechanical aids, particularly with viscous or complex fluids (Benhanifia et al., 2022). In contrast, passive methods rely exclusively on stationary inserts without the need for additional energy input to enhance system efficiency. Examples of passive methods include the incorporation of flexible baffles (Dal Jeong et al., 2022), swirl flow devices, and coiled tubes (Babu et al., 2022). All of these approaches adhere to a shared fundamental principle; the creation of vortex generators (VGs), leading to the generation of secondary flow structures, the suppression of boundary layer growth, and the induction of fluid recirculation. These effects, in turn, bolster the interaction between the central and wall regions, thus facilitating enhanced thermal transfer within the channel (Ali et al., 2015). Rahimi

In the area of thermal engineering, nanofluids are also proving to be particularly useful heat exchange fluids, taking advantage of nanoparticles to improve thermal conductivity (Kolsi et al., 2014; Ghasemi & Ranjbar, 2016b; Ghasemi et al., 2017; Rahimi et al., 2017; Ghachem et al., 2021). Additionally, incorporating materials capable of undergoing phase transitions represents

Nomenclature

a	amplitude of wavy channel	Nu_m	average Nusselt number
Cp	specific heat	Nu_x	local Nusselt number
D	tube diameter	**Greek symbols**	
D_h	hydraulic diameter	β	angle of attack
g	gravity acceleration	μ	dynamic viscosity
H	heat transfer coefficient	ρ	density
K_f	thermal conductivity	**Subscripts**	
P	static pressure	in	inlet
Pr	Prandtl number	out	outlet
q	heat flux	b	bulk
Re	Reynolds number	w	wall
T	temperature	**Abbreviated symbols**	
U	average velocity of fluid	HE	Heat Exchanger
u, v, w	x, y, z velocity components	TS	Triangles Staggered
x, y, z	coordinates	TA	Triangles Aligned
f	friction factor	PEC	Performance Evolution Criteria
Δp	pressure drop in flow direction		

a strategic approach to energy conservation, optimizing the efficient utilization of stored thermal energy (Ghasemi & Ranjbar, 2024). The combined use of nanofluids and these phase-change materials in HEs offers great potential for optimizing energy efficiency and improving overall system performance (Moghaddam & Ganji, 2021).

Previous studies, including experiments and simulations, have explored VGs' effect on enhancing thermal transfer. Notably, Silva et al. (2021) carried out research focusing on the enhancement of thermal transfer through the deployment of VGs on a flat plate situated within a smooth tube. This research spanned a spectrum of Re ranging from 300 to 900. The assessment of heat transfer performance was accomplished through the utilization of a CFD tool in conjunction with the Genetic Algorithm (GA). The results demonstrated a significant rise in the Nu, with a peak enhancement of 60% relative to the baseline smooth tube, observed at a Re of 900.

Deshmukh et al. (2016) experimented with curved delta wing VG inserts to enhance heat transfer in tubes under laminar flow. The findings of this investigation demonstrated that the thermal transfer augmentation attained through the use of VG inserts ranged from 4 to 15 times greater than that of a tube with no VGs. Mehta et al. (2022) studied varying wavy wall amplitudes to enhance heat transfer under laminar flow. Their study compared three distinct types of wavy channels: those with uniform amplitude, amplitude increasing linearly, and amplitude decreasing linearly. The outcomes highlighted that the channel with an amplitude that increased in a linear fashion displayed the highest average Nu number.

Zheng et al. (2017) embarked on an exploration of heat transfer enhancement through the application of conical strip VGs. Their goal was to identify the optimal combination that enhanced heat transfer to the maximum extent while keeping pressure drop to a minimum. The findings demonstrated an increase in both heat transport as well as friction with higher Re numbers and strip filling ratios, while a reduction in pitch further enhanced the system's performance. Chtourou et al. (2021) analyzed a plate HE with small channels and Y and C-shaped baffles computationally. Their results revealed that both Y-shaped and C-shaped ribs significantly improved thermal-hydraulic efficiency compared to a smooth duct. In a separate study, Carpio & Valencia (2021) numerically analyzed heat transfer efficiency in a flat-tube louvered fin compact HE under laminar flow conditions, assessing five different configurations of VG arrays. Among these configurations, G5, featuring 39 alternating louvered VGs), demonstrated superior thermal performance across all Re numbers compared to the other cases. Furthermore, the literature contains additional studies focused on determining the optimal louvered VGs for compact HEs handling compressible fluids (Haque & Rahman, 2020; Deshmukh et al., 2022; Wang et al., 2022; Saini et al., 2023).

Turbulent flow has frequently been harnessed to enhance heat transfer through the strategic implementation of VGs. In a related vein, Saysroy & Eiamsa-Ard (2017) performed a computational analysis aimed at assessing the performance of tubes outfitted with twisted tape inserts. This investigation encompassed an exploration of various parameters, including tape's twist ratio as well as the quantity of channel twisted tapes. The findings uncovered an impressive thermal performance factor, reaching a maximum of 7.28. Furthermore, Aridi et al. (2022) conducted an inquiry into the efficacy of enhancing heat transfer within a concentric tube HE through the utilization of trapezoidal baffles. This research scrutinized four distinct baffle placements within the channel, ultimately revealing that Case 1 achieved the most substantial thermal enhancement, with a factor of 210%. Menni et al. (2020a) delved into the realm of turbulent oil flow and its forced-convection attributes within rectangular-shaped channels furnished with staggered baffles. They explored two different baffle configurations within the duct, and the findings prominently indicated that Case B was the most efficient at improving heat transfer, particularly at elevated Re regimes.

In a related exploration, Lei et al. (2017) suggested the application of delta-winglet VGs affixed to a flat plate situated inside a smooth tube. Their investigation encompassed an array of factors, including the values of attack and separation length. The results demonstrated that elevating the inclination angle and reducing the spacing of the delta-winglet led to a discernible enhancement in the Nu. Other recent studies conducted by Menni & Azzi (2018); Menni et al. (2019a, b, c, d); Menni et al. (2020b); and Maouedj et al. (2021) have reported various VG designs aimed at enhancing the performance of HEs operating under turbulent flows.

Previous research articles have extensively explored enhancing thermal performance and hydraulic patterns in sinusoidal ducts, covering critical aspects such as channel configuration, flow dynamics, fluid properties, and the influence of magnetic fields (Budiman et al., 2016; Valiallah Mousavi et al., 2016; Ferrer et al., 2017; Dormohammadi et al., 2018; Jayadevan et al., 2019). However, there remains a significant research gap, particularly concerning investigating heat transfer enhancements in sinusoidal channels with inserted baffles (VGs) under laminar flow conditions. Further investigations are imperative to advance our understanding in this area, especially given the demonstrated superior mixing effectiveness (Bennour et al., 2023). Therefore, this study aims to thoroughly explore how the angle of attack and the placement of baffles impact heat transfer properties within a sinusoidal tube, utilizing numerical simulations as our investigative method. This research endeavors to provide fresh insights into this crucial yet underexplored aspect of thermal science.

2. MATHEMATICAL MODELING

2.1 Examined Geometrical Configuration

Figure 1 presents the geometric arrangement of a corrugated tube with triangular baffles inserted. In this depiction, the '2-TA' designation corresponds to a channel configuration with aligned baffles (see Fig. 2a), while the '2-TS' designation designates a configuration with staggered baffles (see Fig. 2b). The strategic placement of these baffles occurs within the divergent section of the channel. Notably, in the staggered case, each element is oriented at a 90° angle in comparison to its adjacent element.

Comprehensive measurements of our configuration are meticulously outlined in Table 1 for reference.

The x-coordinate signifies the main flow direction. The y-coordinate corresponds to one of the lateral directions, perpendicular to the main flow path. The z-coordinate represents the other lateral direction, also perpendicular to the main flow path.

Table 1 Geometric parameters of the HE

Diameter of the pipe	D	0.02 m
Channel's length	L	0.35 m
Amplitude of the wave	a	0.003 m
Baffle thickness	t	0.001 m
Attack angle	β	0 – 45°

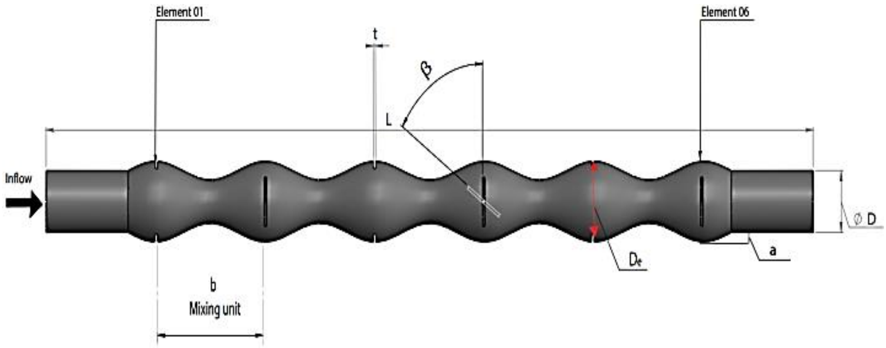
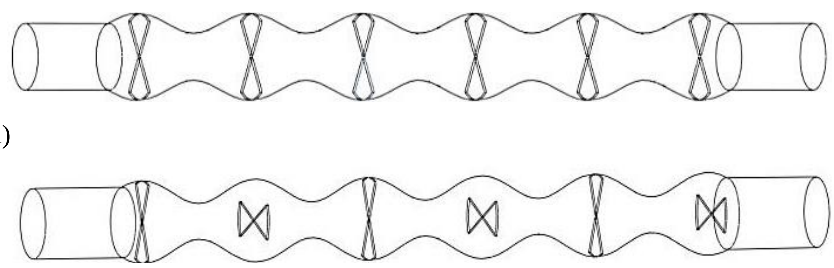


Fig. 1 Illustration depicting the physical model



(a)

(b)

Fig. 2 Both triangular baffle configurations under investigation: (a) 2-TA and (b) 2-TS

2.2 Mathematical Formulation

This study operates on several foundational assumptions. These assumptions encompass the constancy of fluid properties, the omission of gravitational and radiative influences on heat transfer, as well as the stipulation that the investigated problem adheres to laminar flow, remains in a steady state, follows Newtonian behavior, and maintains incompressibility.

Guided by these assumptions and operating within a three-dimensional Cartesian coordinate system, we employ the following equations:

Continuity equation:

$$\nabla.\vec{u} = 0 \tag{1}$$

The equations that govern momentum and energy in the context of laminar flow can be summarized as follows:

$$\rho(\vec{u}.\nabla)\vec{u} = -\nabla p + \mu\nabla^2\vec{u} \tag{2}$$

$$\rho Cp\nabla.(\vec{u}T) = k_f\nabla.(\nabla T) \tag{3}$$

The velocity at the inlet section was adjusted by varying the Re number:

$$u = \frac{\mu Re}{\rho D_h} \tag{4}$$

Which diameter hydraulic is defined by (Soltani-Tehrani et al., 2018):

$$D_h = \frac{(D_{max}+D_{min})}{2} = D \tag{5}$$

Where D_{max} is diameter of divergence zone and D_{min} is diameter of convergence zone.

Water is the selected fluid within the tube, and it exhibits the following properties (Tian et al., 2020):

$$\rho = 998.2\ kg.m^{-3} \tag{6a}$$

$$k_f = 0.62\ W.m^{-1}.k^{-1} \tag{6b}$$

$$\mu = 0.00103\ Pa.s \tag{6c}$$

$$Cp = 4182\ J.kg^{-1}.K^{-1} \tag{6d}$$

The boundary conditions applied to the tube encompass a uniform distribution of velocity and a constant inlet temperature of 300 K. The solid wall of the channel sustains a constant, uniformly applied heat flux density (q), under the assumption of a no-slip condition. The outlet section is subjected to a zero-pressure boundary condition.

For evaluating the energy consumption and thermal performance of fluid flows, consider the subsequent parameters: average friction factors (f), local Nusselt numbers (Nu_x), and average Nusselt numbers (Nu_m) as outlined below:

$$f = 2\frac{(P_{in}-P_{out})}{\rho U^2}\frac{D_h}{L} \tag{7}$$

$$Nu_x = \frac{qD_h}{k_f(T(x)_w - T(x)_b)} \tag{8}$$

$$Nu_m = \frac{1}{x}\int_0^x Nu_x dx \tag{9}$$

The wall temperature at each position, denoted as $T(x)_w$, and the fluid's average temperature at each station, denoted as $T(x)_b$, can be defined as follows:

$$T(x)_w = \frac{1}{L_w}\int_0^{L_w} T dl \tag{10}$$

$$T(x)_b = \frac{\iint uTdA}{UA} \tag{11}$$

The performance evaluation criterion (PEC) is defined as follows (Arjmandi et al., 2020):

$$PEC = \frac{\left(\frac{Nu}{Nu_S}\right)}{\left(\frac{f}{f_S}\right)^{1/3}} \tag{12}$$

The subscript $'s'$ stands for the empty pipe with the same hydraulic diameter and length (L) as the configuration studied.

3. Numerical Modeling

3.1 Numerical Methods

The continuity and momentum equations were solved using segregated solvers, which entail dividing the system into smaller subsystems. The Generalized Minimal Residual (GMRES) iterative method solver was utilized for solving nonsymmetric linear systems. Smoothing techniques and preconditioners were applied to enhance the convergence and effectiveness of the solution for large systems of linear equations.

Convergence was considered achieved when the solution error estimates for the parameters dropped below 10^{-6}. The computations were carried out on a computer with 16.0 GB of RAM and a 1.30GHz i7 CPU.

3.2 Grid Insufficiency

To ensure the development of a grid-independent solution, an investigation was conducted involving four distinct mesh sizes to pinpoint the ideal number of grid elements. This research employs a non-structured grid that is constructed using a tetrahedral mesh.

The criteria employed in assessing grid independence encompass the PEC and the temperature at the midpoint of the design, with particular focus on a *Re* of 400.

Based on the findings presented in Table 2 and Fig. 3, the mesh configuration associated with Case 3 was selected for the ensuing computational analysis.

3.3 Numerical Validation

To validate the approach proposed in this paper, the local Nusselt numbers were compared with the findings reported by Wang & Chen (2002), who conducted an

Table 2 Elucidating pertinent parameters in the grid independence assessment

	Mesh1	Mesh2	Mesh3	Mesh4
Elements	253144	493909	1369828	2065497
PEC	1.0653	1.0831	1.1286	1.1376
Time [s]	1298	3151	5574	7318

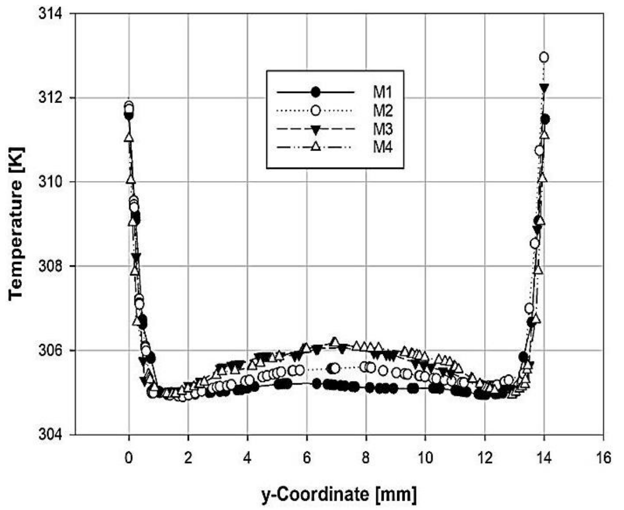


Fig. 3 Temperature distribution with different cases of mesh size, for 2-TS (β=45°) and Re = 400

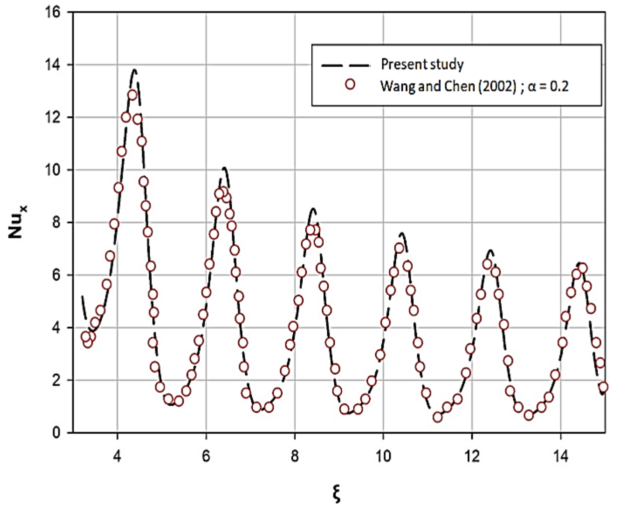


Fig. 4 Temperature comparative analysis of local Nusselt number against Wang and Chen (2002) results, α = 0.2, and Re = 100

investigation on heat transport via forced-convection through a wavy-wall tube using pure water. A specific case was selected from the various amplitude-wavelength ratios of the corrugated channel, represented as α = 0.2 in Fig. 4. Notably, there is a clear and complete agreement between our results and those obtained by Wang & Chen (2002).

Where ξ represents the proportion of the corrugated section's length to the wavelength.

4. FINDINGS AND ANALYSIS

To deepen our understanding of improving heat transfer using triangular baffles inserted in a corrugated tube, we compared the flow characteristics within our configuration under specific conditions (Re = 400), while varying the angles of attack (β = 0° to 45°). In Fig. 5, the velocity magnitude contours obtained after the first element at different angles of attack illustrate that the velocity magnitude changes as the angle of attack is modified, giving rise to the development of a swirling

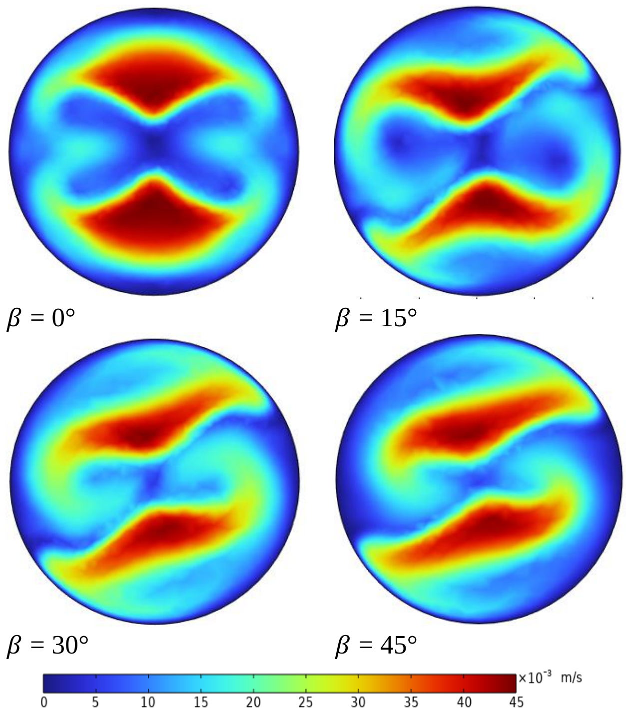


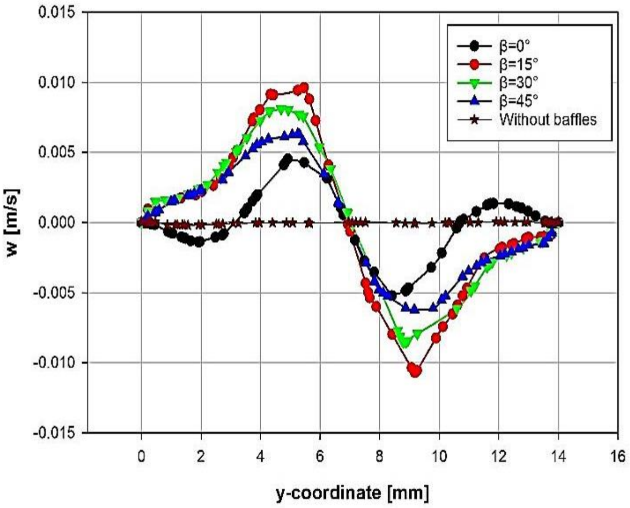
Fig. 5 Velocity magnitude contours downstream of the initial element at varying angles of attack, Re = 400

motion. Notably, the highest tangential velocities are primarily concentrated near the channel wall, especially when the angle of attack is set to 30° and 45°. This swirling motion significantly alters the flow pattern and influences the behavior of the boundary layer. The incorporation of baffles aims to induce secondary flows within the transverse planes. A comprehensive understanding of these secondary flows can be achieved by plotting the profiles of tangential velocity at the midpoint of the HE.

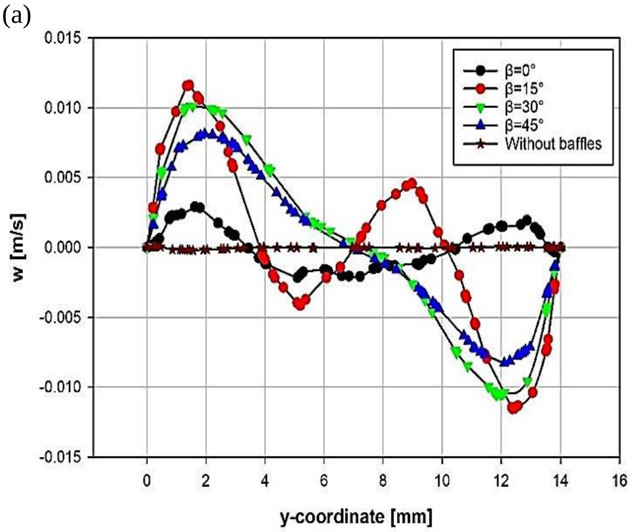
To demonstrate the impact of the position and angle of the baffles on the secondary flow and its effectiveness in enhancing heat transfer, tangential velocity profiles were plotted within the convergence zone between the second and third elements. This position was chosen to clearly illustrate the influence of staggered and aligned baffles.

Figure 6(a) displays a symmetrical profile for tangential velocity, with a zero value at the core and higher values between the center and the channel wall. In particular, the highest velocity is observed when β is fixed at 15°. This observation highlights the impact of angular orientation on tangential velocity distribution inside the core and channel, providing valuable information on the fluid dynamics related to the specified configurations.

In Fig. 6(b), variations in secondary flows are evident, influenced by changes in baffle arrangement. Tangential velocity profiles for cases with aligned baffles at β = 0° and 15° notably differ from those with staggered baffles, impacting friction factor and heat transfer. The intensified flow deviation upon colliding with blades contributes to increased friction, as observed. Additionally, the symmetric pair of counter-rotating



(a)



(b)

Fig. 6. Tangential velocity profiles under various angles of attack: (a) staggered configuration, (b) aligned configuration, Re = 400

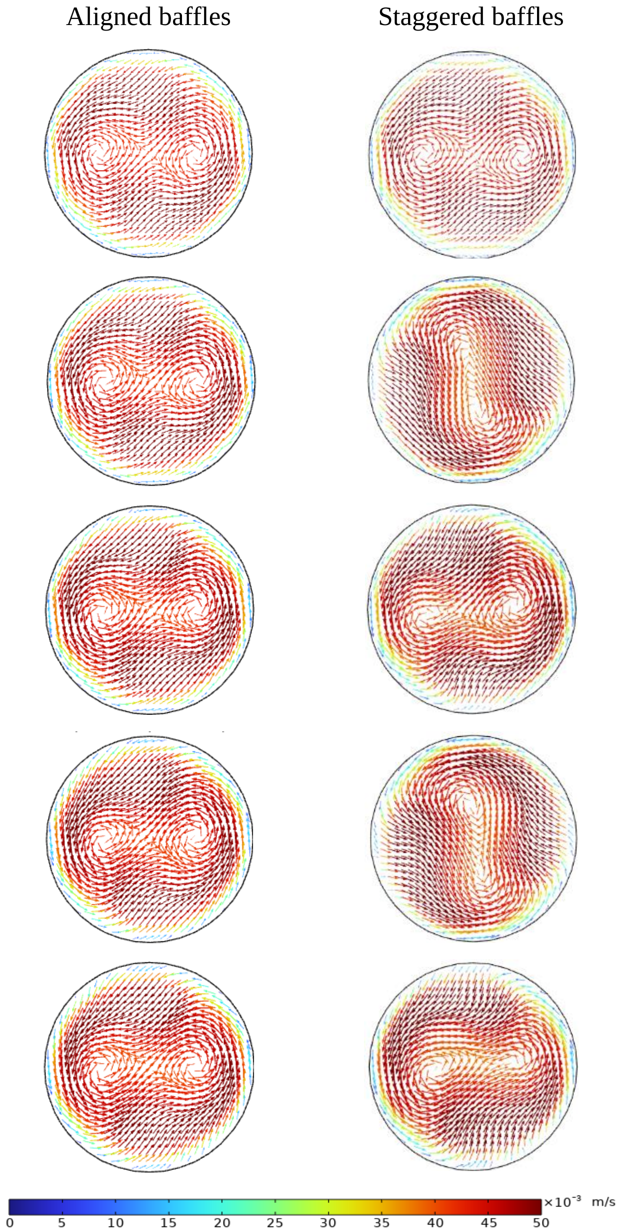


Fig. 7 V-field visualization in diverse convergence zones of the heat exchanger at β = 15° and Re = 400

flows, depicted in Fig. 7, further accentuates the variance, influencing both friction factor and heat transfer characteristics. This effect is intricately linked to the strategic placement and arrangement of baffles in the system.

For a more comprehensive understanding of the impact of baffles and their placement on temperature distribution, Fig. 8 provides temperature contours for three different heat exchanger arrangements at a Re number of 400. These contours are presented on various slices along the X direction. It is evident that, in both staggered and aligned arrangements, heat transfer is significantly more effective, especially behind the elements. This enhancement results from the generation of longitudinal recirculation by the VGs, which promote better mixing between hot and cold fluids and inhibit the development of thermal boundary layers. In contrast, the corrugated tube without baffles exhibits a minor mixing effect, signifying a relatively lower influence on heat transfer compared to the arrangements featuring baffles.

To assess the influence of corrugated tubes with baffle inserts on local heat transfer rates, Fig. 9 depicts the progression of the local Nusselt number (Nu_x) at Re = 400 for three distinct HE configurations. It is evident that the effects of amplitude are more pronounced in the configuration without baffles, particularly within the convergence zone where the Nu_x value reaches its peak. This occurs due to the alteration in the flow passage's diameter, resulting in an elevation in fluid speed, consistent with the principle of mass conservation. The elevated velocities within this zone contribute to an enhanced convective heat transfer process.

This study examines the variation in the angle of attack β, within the range of 0° to 45°, and the placement of baffles affect the performance of the corrugated tube with baffle inserts. In Fig. 10(a), the influence of the β angle on the mean value of Nusselt (Nu_m) is depicted for the scenario with aligned baffles. The Nu_m value

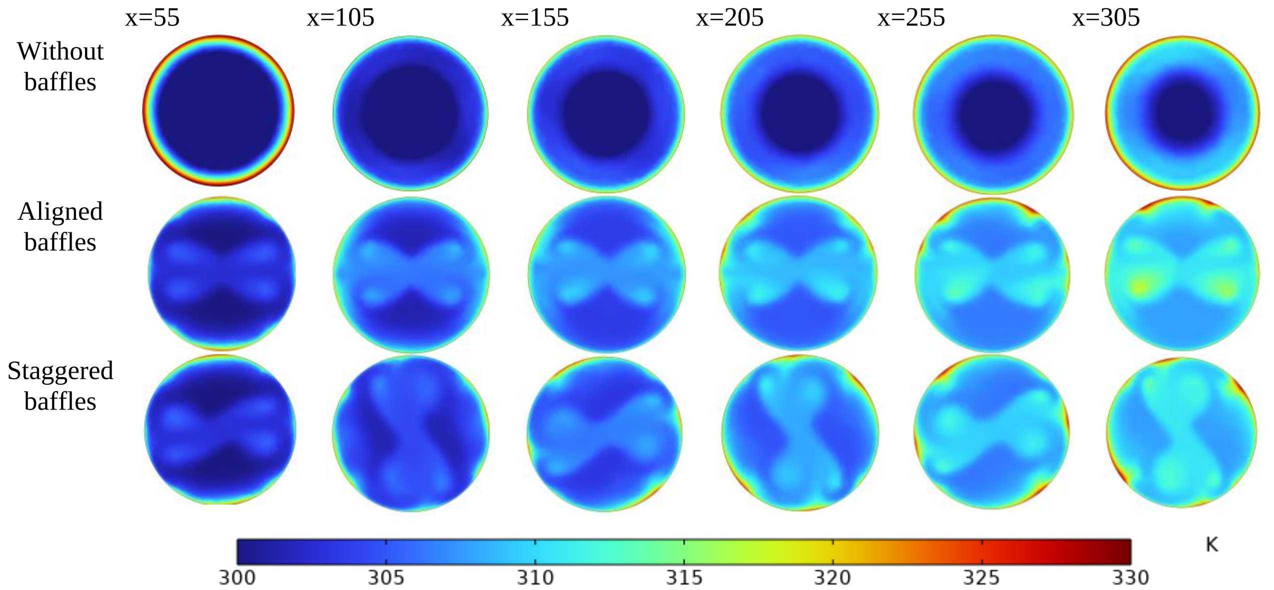


Fig. 8 Temperature contour plots for three distinct heat exchanger configurations across various X-direction slices, Re = 400

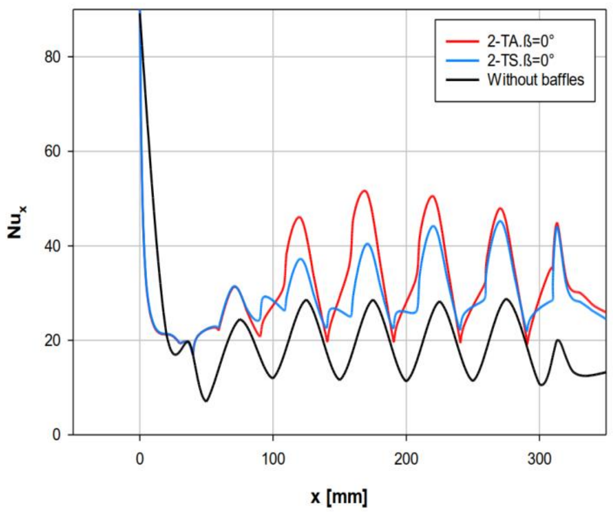


Fig. 9 Local Nusselt numbers in three distinct heat exchanger configurations at Re = 400

consistently rises with the rising Re number across all values of the attack angle. Notably, within the range of investigated Re numbers, a more significant improvement in the Nu_m number is observed compared to the case without baffles, especially when the angle of attack is set at 15°, whereas the improvement is less pronounced when the baffles are set at an angle of 45°. This difference is attributed to the symmetric pair of counter-rotating flows created by the placement and angle of the baffles. This finding implies that heat transfer does not consistently increase with the angle of attack, which aligns with observations from previous research studies (Biswas et al., 2012; Yongsiri et al., 2014; Xu et al., 2017). For instance, Biswas et al. (2012) established a correlation between the β angle and enhanced thermal transfer. They noted that heat transfer consistently improved as the β angle enhanced up to 55°, after which it began to decrease.

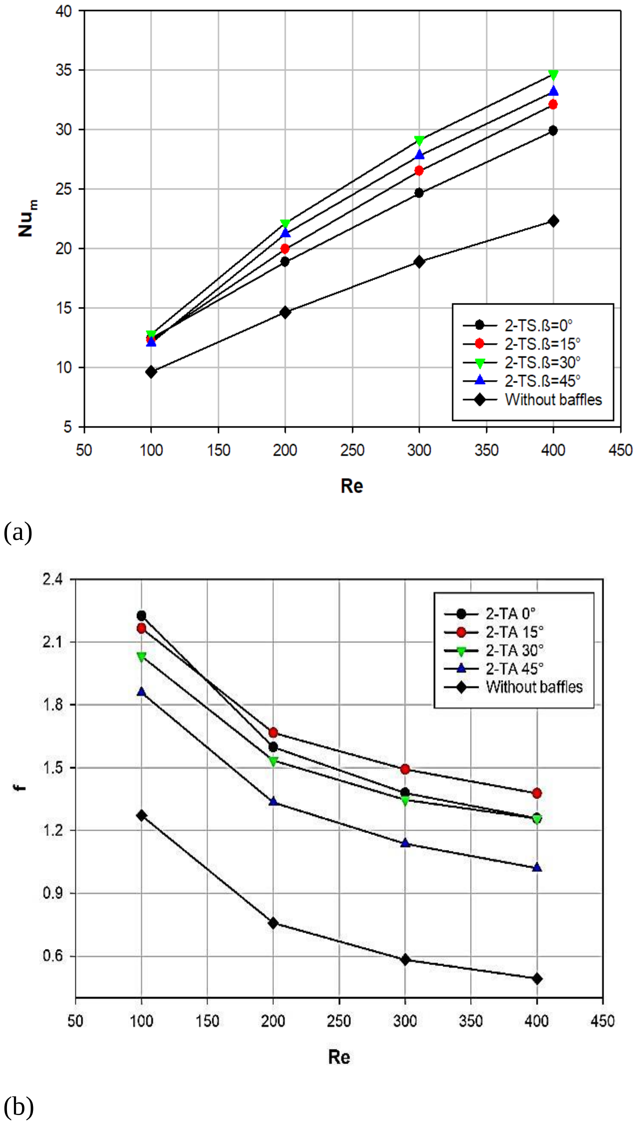
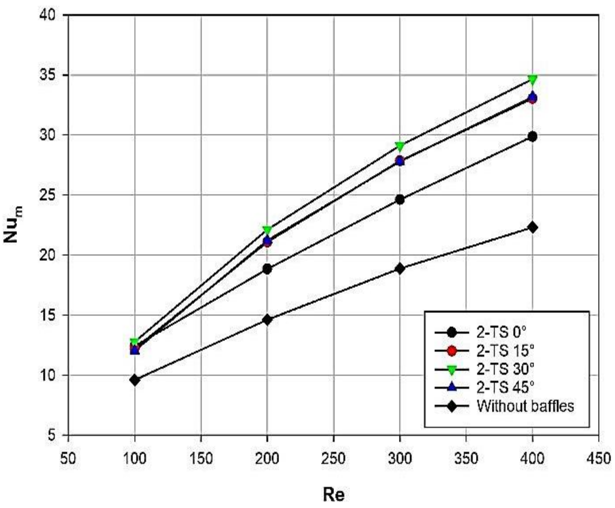
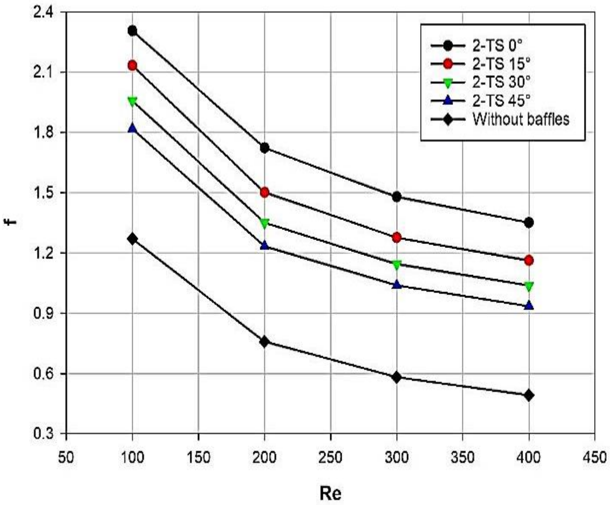


Fig. 10 Influence of angle of attack on (a) Mean Nusselt number (Nu) and (b) Friction factor (f) in the aligned baffles configuration



(a)



(b)

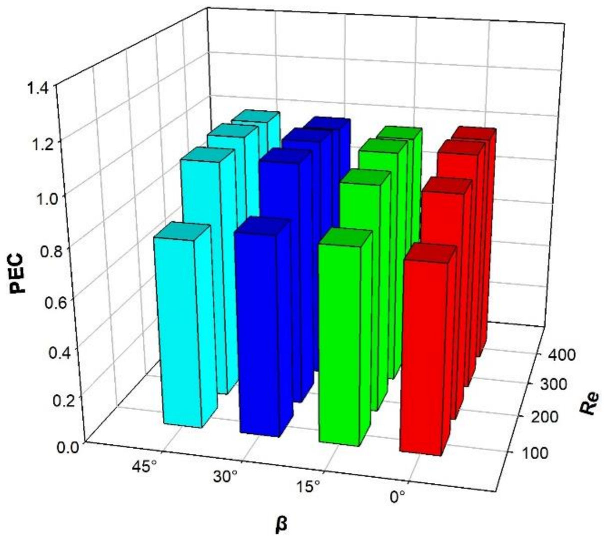
Fig. 11 Angle of attack's influence on (a) Nu_m and (b) f in the staggered baffles arrangement

The utilization of VGs is seen to promote turbulence, leading to significant interactions between the boundary layer and the core fluid, and enhancing fluid mixing. However, it's important to note that turbulence and increased flow resistance result in pressure loss.

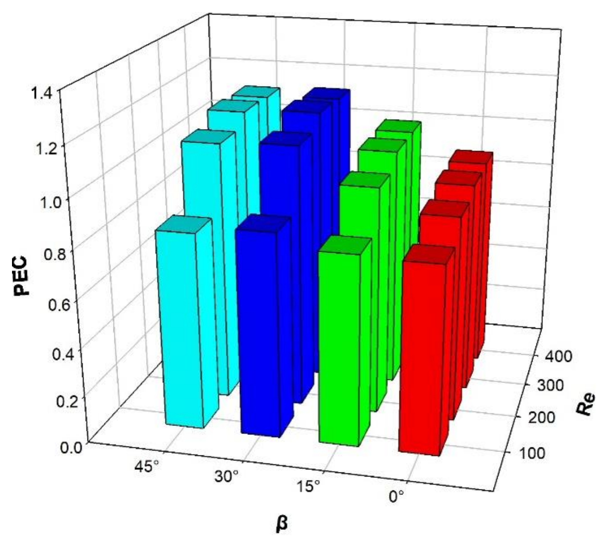
Figure 10(b) demonstrates the influence of the angle of attack on the factor of friction (f) for aligned baffles. This factor reduces with an elevation in the Re value, regardless of the specific angle of attack.

In comparison to the case without baffles, all angles of attack show a higher f value within the studied spectrum of Re numbers. Notably, the maximum f value is attained when the baffle angle (β) is set at 15°.

Figure 11(a) portrays the impact of varying the angle of attack on the average value of Nusselt (Nu_m) when using staggered baffles. It is evident that Nu_m augments with an increasing Re number in all cases, irrespective of the angle of attack values. Within the examined range of Re numbers, all angles of attack yield a higher Nu_m value than the case without baffles. Notably, the Nu_m value consistently increases with a rising angle of attack up to 30°, but decreases at a 45° baffle angle (β). This behavior is distinct from that observed in the aligned case, suggesting that the arrangement and placement of baffles contribute to enhancement.



(a) Aligned configuration



(b) Staggered configuration

Fig. 12 Plot of PEC against angle of attack and Re for two baffle configurations

The correlation between the angle of attack and the factor of friction (f) with staggered baffles is visualized in Fig. 11(b). This factor, f, diminishes with an increase in the Re number, irrespective of the specific angle of attack values. In comparison to the case without baffles, all angles of attack result in a higher friction factor. It's significant to observe that, within the range of Re numbers under investigation, the f factor consistently diminishes as the β angle increases, with the highest f factor value achieved when the baffle angle (β) is set at 0°.

Figure 12 depicts the evaluation of PEC performance concerning the β angle and Re. For staggered baffles, the PEC value shows a rising trend with improved β angles. At β = 15° and β = 30°, there's a linear increase, peaking at 1.139 at Re = 400, marking a 26.6% performance enhancement compared to β = 0°,

Table 3 Comparison of the different geometries relevant to laminar flow

Design and arrangement of VGs	Fluids in operation and Re	Nu	*f*	Observations	Study authors
HE tube with hyperbolic-cut twisted ribbon inserts	Water (Re = 100-1500)	12.5	0.75	Reduced friction losses and also inferior convective heat transfer efficiency	(Rajan & Prasad, 2021)
HE tubes featuring drumet-cut twisted ribbon inserts	Water (Re = 100-1500)	12.50	0.80	Reduced friction losses but compromised convective heat transfer efficiency.	(Kumar & Prasad, 2023)
HE equipped with multiples conical strips inserts	Water (Re = 300-1500)	23.00	2.10	Friction loss is lower, and convection heat transfer efficiency is acceptable	(Liu et al., 2018)
Enhanced hydrothermal performance with conical mesh inserts	Water (Re = 100-1000)	10.50	4.00	High friction losses and inferior convective heat transfer efficiency	(Cao et al., 2017)
Improved thermal systems with nanofluid and inserted conical strip (φ =0)	Water (Re = 100-1500)	21.00	1.35	Friction loss is smaller and convective heat transfer efficiency is acceptable	(Mashayekhi, et al. 2017)
Corrugated tube with baffles inserted (2-TS. β = 30°)	Water (Re = 100-400)	29.12	1.14	Friction loss is greatly reduced and convective heat transfer is more efficient.	Present Study

where PEC is lower. Conversely, in the case of aligned baffles, a 15° angle yields the lowest performance at higher Re, despite having the highest Nu_m value. This discrepancy is attributed to the significant pressure loss associated with this angle.

In Table 3, a comparative geometric analysis under laminar flow conditions at Re = 300 indicates some notable performance trends. Compared to our proposed geometry, friction losses are significantly reduced, which indicates an improvement in fluid flow characteristics. In addition, convective heat transfer efficiency is significantly higher, thus demonstrating the favorable balance achieved in our design.

In contrast, other geometries show less optimal results. One geometry reveals high friction losses associated with reduced heat transfer efficiency, indicating a less desirable compromise. Another geometry demonstrates lower friction losses but reduced heat transfer efficiency. These results underline the superiority of our geometry for efficient, balanced laminar flow applications. Our results underline the superior performance of the proposed geometry, highlighting its potential for more efficient and balanced laminar flow applications.

5. Conclusions

In this study, the primary emphasis was on a comprehensive investigation of heat transfer and fluid flow attributes in corrugated tubes incorporating baffle inserts. The research scrutinized the impact of baffle positioning and the angle of attack on the overall system effectiveness, providing an extensive examination by contrasting the outcomes with cases devoid of baffles.

The principal discoveries of this research can be concisely condensed as follows:

- The introduction of baffles serves to induce longitudinal swirls within the flow, which effectively disrupt and disperse thermal boundary layers. This leads to an improved homogenization of hot and cold fluids within the tube, ultimately resulting in a more desirable temperature distribution.
- At various Reynolds number values, it becomes evident that the heat transfer rates for both aligned and staggered baffles experience significant enhancements compared to the baffle-free scenario. Notably, aligned baffles display an impressive increase of approximately 43.6%, while staggered baffles exhibit an even more remarkable enhancement in heat transfer coefficient, amounting to approximately 55.3%.
- When assessing friction coefficients, it is observed that both aligned and staggered baffles yield higher values compared to the case without baffles, with an increase ranging from approximately 1 to 2 times, contingent upon the angle of attack under consideration.
- The pinnacle of system performance, as measured by the performance evolution criteria, is attained with staggered baffles at an angle of 30°, indicating superior overall performance. Conversely, aligned baffles at an angle of 15° register comparatively lower PEC values.

Realistic applications encompass a broad array of practical scenarios where the findings and insights from the study can be implemented. These include :

- HEs in HVAC systems: Implementing VGs in HEs used for heating, ventilation, and air conditioning (HVAC) systems can enhance thermal efficiency and reduce energy consumption.

- Automotive radiators: Incorporating VGs in automotive radiators can improve heat transfer performance, leading to better engine cooling and increased fuel efficiency.
- Solar thermal collectors: Enhancing heat transfer in solar thermal collectors with VGs can boost energy capture efficiency, making them more effective for solar energy harvesting.
- Industrial process HEs: Applying VGs in industrial process HEs can optimize thermal performance, leading to increased productivity and cost savings.
- Electronics cooling: Utilizing VGs in heat sinks for electronic devices can enhance heat dissipation and prolong the lifespan of electronic components.

In the context of prospective paper expansion, a multitude of recommendations have been posited, including the following :

- Optimization of baffle configuration: Further investigations can be conducted to fine-tune the baffle geometry and placement to maximize heat transfer efficiency while minimizing pressure drop, with a focus on different geometric parameters and materials.
- Flow control strategies: Exploring advanced flow control techniques, such as using variable angle of attack baffles or employing active control methods, could lead to improved heat transfer performance.
- Materials and Surface Modifications : Investigate the use of advanced materials and surface treatments to enhance heat transfer efficiency and reduce fouling in corrugated tube HEs.
- Transitional and Turbulent Flows : Extend the research to cover a broader range of flow conditions, including transitional and fully turbulent regimes, to provide a comprehensive understanding of baffle effects.
- Environmental and Sustainability Aspects : Assess the environmental impact and energy efficiency of the heat exchanger system, considering factors like carbon emissions and energy consumption, to contribute to sustainable engineering practices.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHORS CONTRIBUTION

E. Bennour spearheaded the project with conceptualization, framing the overarching ideas and objectives. **C. Kezrane** meticulously designed the methodology, providing the structured framework for data collection and analysis. **N. Kaid** led the numerical investigation, delving into the intricacies of the mathematical aspects of the study. **M. A. Alkhafaji** undertook the responsibility of numerical validation, ensuring the accuracy and reliability of the computational results. **M. S. Alhassan**, with a keen eye for detail, conducted a thorough review and contributed to the editing process, enhancing the overall quality of the manuscript. Lastly, **Y. Menni** took charge of the preparation and supervision, guiding the team through the research process.

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