Heat Transfer Enhancement Techniques in Shell and Tube Heat Exchangers A Comprehensive Review for Energy-Efficient Applications

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Abstract: *The thorough analysis examines a variety of active and passive heat transfer enhancement strategies for shell and tube heat ex-changers. Passive techniques which greatly enhance thermal performance without additional energy input include surface geometries modifications and insert introduction. To further increase heat transfer rates active methods on the other hand, use external power inputs like pulsating flow or mechanical vibrations. Using nano fluids or fluids engineered with nano particles has become a viable strategy because it offers higher heat transfer coefficients and thermal conductivity. Furthermore, the discussion highlights the significance of sophisticated computational models and their role in heat exchanger design simulating and optimization. This review seeks to provide a comprehensive understanding of the efficacy and applicability of these techniques by synthesizing recent research opening the door for further advancements in heat ex-changer technology. The knowledge gained could help engineers and researchers create thermal management systems that are more effective.*

Keywords: Active, passive, nanofluids, computational models, heat exchanger

I. Introduction

Shell and tube heat exchangers (STHEs) are widely used in various industries, such as power generation, oil refining, and chemical processing, due to their simple design and robustness. However, there is a growing demand to enhance their thermal efficiency and reduce the size and cost of the units. This section will provide an overview of the heat transfer processes in STHEs and highlight the challenges of conventional designs, including inefficient heat transfer, large equipment sizes, and high operational costs. shell and tube heat exchanger is a class of heat exchanger designs. It is the most common type of heat exchanger in oil refineries and other large chemical processes, and is suited for higher-pressure applications [1]. As its name implies, this type of heat exchanger consists of a shell (a large pressure vessel, Figure 1) with a bundle of tubes inside it. One fluid runs through the tubes, and another fluid flows over the tubes (through the shell) to transfer heat between the two fluids. The set of tubes is called a tube bundle, and may be composed of several types of tubes: plain, longitudinally finned, etc. Shell and tube heat exchanger design is based on correlations between the Kern method and Bell-Delaware method [2]. In Bell's method the heat-transfer coefficient and pressure drop are estimated from correlations for flow over ideal tube-banks, and the effects of leakage, bypassing and flow in the window zone are allowed for by applying correction factors. This approach will give more satisfactory predictions of the heat-transfer coefficient and pressure drop than Kern's method; and, as it takes into account the effects of leakage and bypassing, can be used to investigate the effects of constructional tolerances and the use of sealing strips. Bell-Delaware method is more accurate method and can provide detailed results In Kern's method-is based on experimental work on commercial exchangers with standard tolerances and will give a reasonably satisfactory prediction of the heat transfer coefficient for standard designs [3]. The prediction of pressure drop is less satisfactory, as pressure drop is more affected by leakage and bypassing than heat transfer. The shell-side heat transfer and friction factors are correlated in a similar manner to those for tube-side flow by using a hypothetical shell velocity and shell diameter.

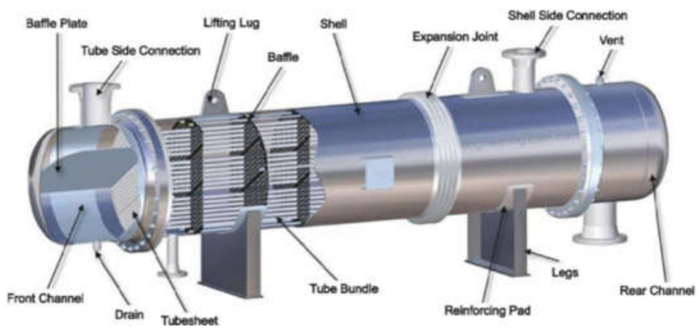


Figure 1. Shell and Tube Heat Exchanger

II. Passive Methods

This approach typically involves modifying the surface or geometry of the flow channel by adding inserts or extra components. Examples include inserting swirl flow devices, using treated or rough surfaces, extending surfaces, utilizing displaced enhancement devices, coiled tubes, surface tension devices, or incorporating fluid additives. The article by Mohammed R. Ali [4] discusses the use of passive techniques to enhance heat transfer (HT) in heat exchangers (HEs). Techniques like vortex generators (VGs), surface roughness, and extending heat transfer areas through fins or dimples are explored. VGs, such as twisted tapes or winglets, improve HT by promoting fluid mixing through turbulence, though they increase frictional resistance. Surface roughness disrupts laminar flow and boosts fluid mixing, enhancing thermal transport. Increasing the HT area through fins or dimples also optimizes performance. Key factors include the geometric parameters of VGs and the design of surface modifications as shown in figure 2.

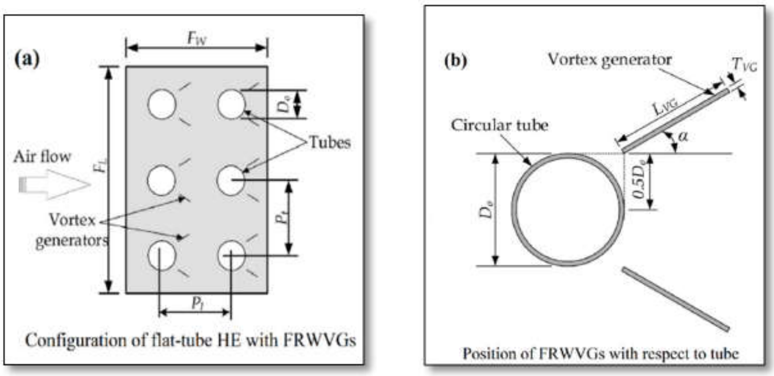
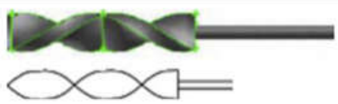


Figure 2. The geometrical configuration of Winglet-type VGs in the fin-tube HE (a) Configuration of flat-tube HE with FRWVGs (b) Position of FRWVGS with reference to the tube

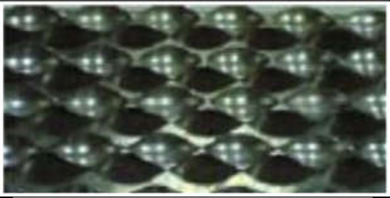
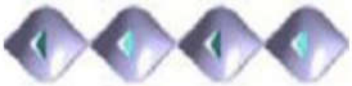
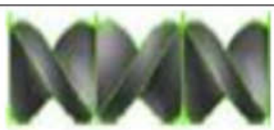
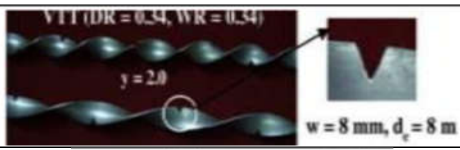
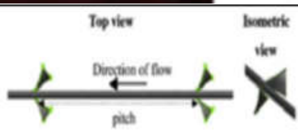
Passive techniques for heat transfer enhancement (HTE) in helical tube heat exchangers (HXs) utilize geometric modifications or secondary devices to enhance heat transfer without requiring external power. Common passive methods for HTE in helical tube HXs include the use of helical fins on the inner or outer surfaces of the tube, as seen in the turbo-electric effect method [5]. Helical fins generate a swirl flow in the fluid, increasing turbulence and enhancing heat transfer. This swirling motion creates a "turbo-electric" effect, which improves the overall heat transfer coefficient (U) [6]. Introducing coiled wire inserts into the helical tube generates swirl flow and turbulence, which enhances heat transfer. These inserts disrupt the flow pattern, promoting better fluid mixing and increasing the heat transfer coefficient (h) [7, 8].

Twisted tape (TT) inserts can be positioned inside the helical tube to disturb the flow and generate turbulence [9, 10], creating a swirling motion that increases the heat transfer coefficient (h) [11]. The twist pitch and width can be adjusted for optimal heat transfer performance. Adding ribs or grooves to the inner surface of the helical tube further enhances heat transfer by promoting turbulence and improving fluid mixing. Additionally, vortex generators placed inside the tube create controlled vortices, boosting heat transfer [12]. Vortex generators disrupt flow patterns, enhancing turbulence and boosting convective heat transfer. Helical baffles inside the tube can further improve heat transfer by inducing a swirling motion in the fluid, acting as turbulators to enhance turbulence and heat exchange with the tube wall [13]. The helical shape of the tube itself also generates natural swirl flow, which promotes mixing and turbulence, improving convective heat transfer without additional inserts. These passive techniques focus on optimizing flow patterns, increasing turbulence, and disrupting the boundary layer to improve heat transfer efficiency in helical tube heat exchangers. The best method depends on the specific HX requirements and fluid properties as tabulated in Table 1.

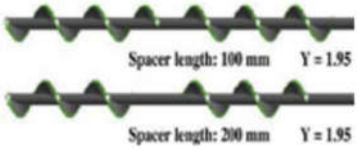
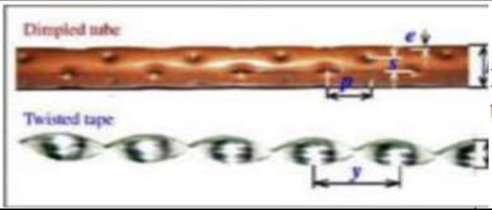
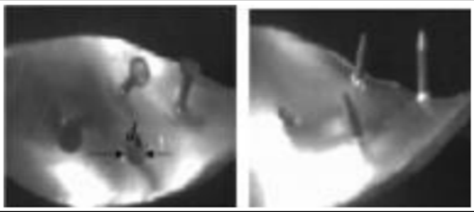
Table 1. Various Geometric views of Twisted Tape

Geometric views	Name	Reference
	Twisted tape with various widths	[14]
	Typical twisted tape	[15]
	Left and right twist tape with rod and space	[16,17]

III. Active Methods (like external power inputs)

	Jagged twisted tape	[18]
	Short-length twisted tape	[19]
	Peripherally-cut twisted tape with an alternate axis.	[20]
	Twist tape with alternate axis	[21]
	Multiple twisted tape	[22]
	Twisted tape with center wing	[23]
	Twisted tape with trapezoid-cut	[24]
Various Geometric views of Twisted Tape		
Geometric views	Name	Reference
	Left-right twisted tapes	[25]
	Twisted tape with various twist ratios	[26]
	Twisted tapes with alternate-axes and triangular, rectangular and trapezoidal wings	[27]
	V-cut twisted tape insert	[28]
	Butter fly inserts	[29]

Active techniques involve the use of external power to enhance heat transfer. These include mechanical agitation, flow pulsation, electric and magnetic fields, and jet impingement. While more complex than passive methods, active methods offer substantial increases in heat transfer rates. Numerous researchers have conducted

	Helical screw tape with various spacer length	[30]
	Dimpled tube fitted with twisted tape	[31]
	Twisted tape consisting wire nails	[32]
	Wire coil in pipe	[33]
	Twisted-tape with oblique teeth	[34]

experimental, analytical, and numerical investigations on fluid flow and heat transfer in pulsating flows. Zhao and Cheng [26] explored the behavior of laminar pulsating flow in a long pipe under constant wall heat flux through both experimental and numerical approaches. Their findings, including time-resolved fluid temperature and space-cycle averaged Nusselt number, showed strong agreement between the two methods. Habib [27] also performed an experimental study on laminar pulsating pipe flow with constant wall heat flux, revealing that the Nusselt number is more significantly influenced by pulsation frequency than by Reynolds number. An analytical investigation by Yu et al. [28] on pulsating laminar convection heat transfer in pipes indicated that pulsation does not impact the time-averaged Nusselt number. Guo and Sung [29] analyzed pulsating laminar flows at various amplitudes and observed that while small amplitudes yield inconsistent Nusselt number results, higher amplitudes consistently enhance heat transfer. Hsiao [30] conducted a theoretical analysis of steady, two-dimensional, incompressible laminar flow involving micropolar and nanofluids over a stretching sheet, presenting profiles of local convective heat transfer coefficients and temperature distributions. Several dimensionless parameters including the Prandtl number, Eckert number, and Brownian motion number were found to significantly influence the heat and mass transfer characteristics of the stretching sheet.

Elsayed A.M. [31] experimentally studied heat transfer in pulsating turbulent air flow through a pipe under uniform heat flux conditions (Figure 3). The Nusselt number was significantly influenced by both pulsation frequency and Reynolds number, with more noticeable effects near the pipe entrance. Despite small deviations, the mean Nusselt number showed frequency-dependent trends, especially at higher Reynolds numbers, aligning qualitatively with the turbulent bursting model. Guanming G [32] investigated turbulent pulsating flow and heat transfer in straight and 90° curved square pipes using both experiments and CHT simulations. The study compared steady and pulsating flows at a time-averaged Reynolds number of ~60,000 and a Womersley number of 43.1 (30 Hz frequency). In curved pipes, the Dean number was around 31,000. Results showed higher local heat flux in pulsating flow near the pulsation source, but overall lower total heat flux compared to steady flow. Simulations revealed flow behaviors like core impingement, flow separation, and reverse flow, which contributed to heat transfer suppression.

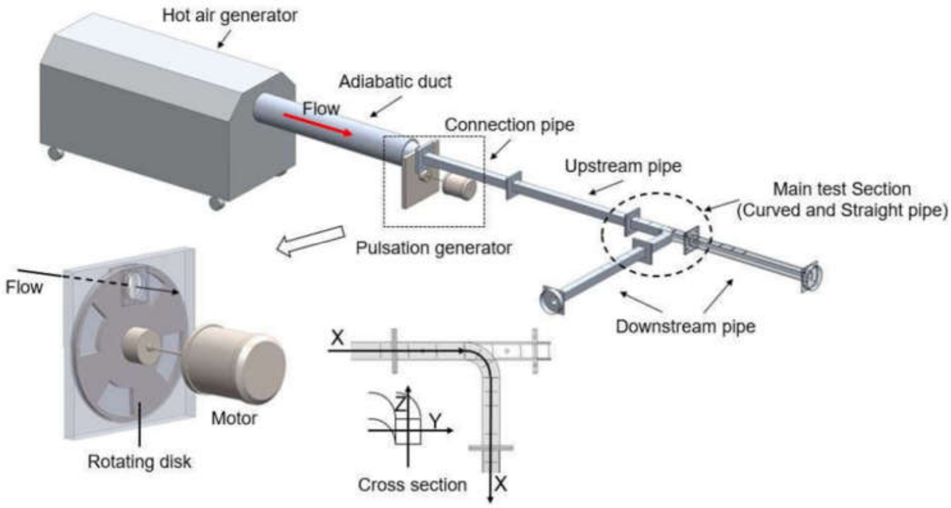


Figure 3. Experimental Setup for Heat Transfer In Pulsating Turbulent Air Flow Through a Pipe Under Uniform Heat Flux

IV. Presence of Nanofluids

Nanofluids, suspensions of nanoparticles in base fluids (e.g., water, oil), have emerged as highly efficient working fluids that enhance thermal properties such as conductivity and heat capacity. Nanofluids are advanced fluids created by dispersing nanoscale materials into base liquids. Common base fluids include water, oils, glycols, refrigerants, and bio-fluids. Titanium dioxide (TiO_2) is widely used for heat transfer enhancement due to its stability. TiO_2 nanoparticles are cost-effective and readily available in the market. They are commonly applied in heat exchangers like circular, double tube, and shell-and-tube types. [33]. explored TiO_2-water nanofluids for advanced heat transfer enhancement. Azad's study showed alumina nanofluids boosted heat transfer by 185% in shell and tube exchangers. This led to reduced size, energy use, and pressure drop, cutting costs by over 55%. A numerical study using ANSYS Fluent analyzed CuO-water nanofluid in a shell and tube heat exchanger under turbulent flow. CuO nanoparticles (29 nm) were tested at loadings from 0.1% to 1% and Reynolds numbers from 17,000 to 71,000. Higher particle loading and Reynolds number improved heat transfer but also increased pressure drop. A 48% heat transfer enhancement was observed at 1% loading, with pressure drop doubling. Optimal performance was achieved at low particle loading (≤0.25%) and Reynolds number, with minimal flow behavior difference from water [34]. The explored the use of alumina nanofluid to optimize shell and tube heat exchangers in industrial applications. The study showed that alumina nanofluid significantly increases the Nusselt number, enhancing the heat transfer coefficient [35]. This improvement allows for shorter tube lengths and reduced flow velocity, resulting in a pressure drop reduction of up to 94%. In the case analyzed, the tube-side heat transfer coefficient increased by over 185%, leading to a cost reduction of more than 55%. The study recommends nanofluid application as a practical and efficient approach for heat exchanger design.

Table 2. Comparison between optimized exchanger (with nanofluid) and designed in the Kern's book.

S.No.	Design parameter	Kerns book	Optimized with nano fluid
1	d (m)	0.016	0.0123
2	L (m)	4.88	1.2100
3	B (m)	0.3048	0.4765
4	D (m)	0.387	0.7158
5	Pitch (m)	0.023	0.0204
6	Cl (m)	0.004	0.0041
7	Nt	160	909
8	Pr_t	6.2	6.2323
9	de (m)	0.0139	0.0118
10	Pr_s	5.4	5.5548
11	C_{total} (€)	43.989	19.709
12	V_i (m/s)	2.04	0.6562
13	V_o (m/s)	0.94	0.3252
14	Re_i	36.400	8754.1

15	Re_o	16.200	4640.7
16	hi (w/m^2k)	6558	4349.3
17	ho (w/m^2k)	5735	3510.6
18	Δp_t (pa)	51710.6	2766
19	Δps (pa)	53089.6	3299.7
20	A (m^2)	46.6	56.2734
21	u (w/m^2k)	1471	1169.9

The performed a numerical study using ANSYS Fluent to analyze CuO-water nanofluid behavior in a shell and tube heat exchanger under turbulent flow. Simulations used 29 nm CuO particles with varying loadings (0.1–1% vol) and Reynolds numbers (17,000–71,000). Results showed that increasing particle loading and Reynolds number enhanced heat transfer, with a maximum 48% improvement, though pressure drop also increased significantly [36]. Optimal performance indices (>1) occurred at low particle loading (<0.25% vol) across all Reynolds numbers. While flow behavior remained similar to water, thermal profiles confirmed improved heat transfer for nanofluids as shown in figure 4.

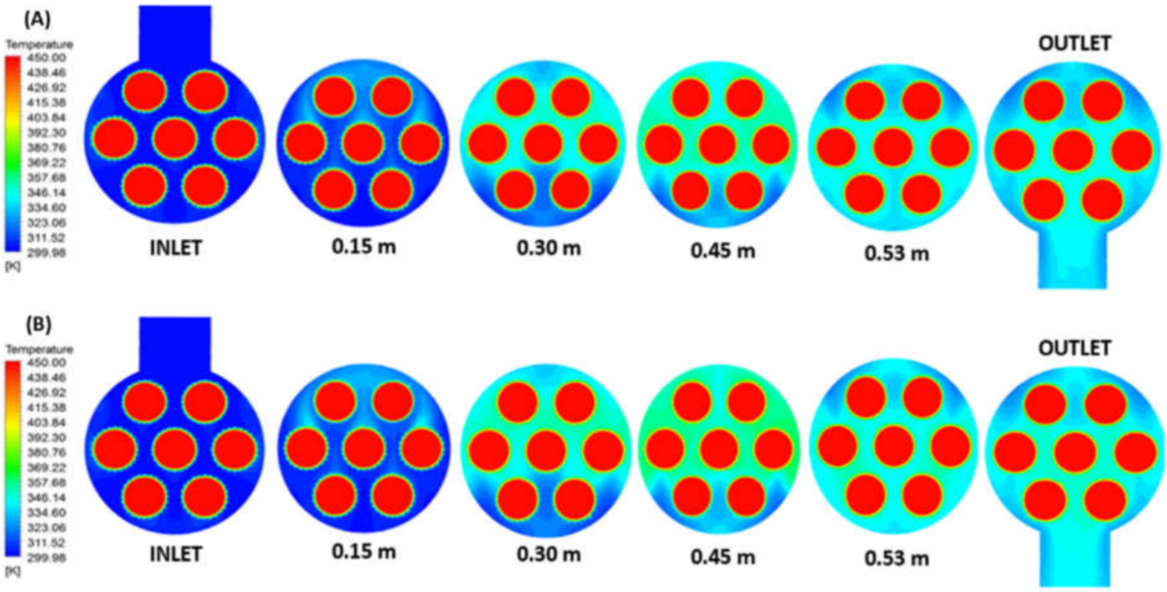


Figure 4. Comparison of the cross-sectional temperature contours for (A) water; and (B) 0.1%vol CuO-water nanofluid (right) at Re = 17,804.

V. Advanced computational models

Computational Fluid Dynamics (CFD) is used to analyze fluid flow, heat transfer, and chemical reactions by solving mathematical equations numerically. It breaks down a system into small cells and applies governing equations to each to find values like pressure and temperature. CFD enables virtual prototyping, predicting system performance before physical testing using visual and numerical outputs. It is widely used in designing engines, gas turbines, furnaces, and heat exchangers. CFD has become a powerful tool, comparable to other CAE tools like stress analysis software. The study by Vivek Singh Parihar focuses on optimizing the performance of a shell and tube heat exchanger using computational fluid dynamics (CFD). Various models of the heat exchanger were developed, replacing straight tubes with helical tubes, and incorporating different numbers of helical baffles. A total of ten models were analyzed, including variations in turns, baffle numbers, and spacing. The results showed that the model with 6 turns, 14 baffles, and CuO nanofluid (Model XI) achieved the highest heat transfer, improving performance by 40% compared to the baseline model [37]. Erica Jacqueline Fernandes [38] explores the design and performance of shell and tube heat exchangers, widely used in industries like HVAC, particularly in chiller plants. The study focuses on how material selection and baffle spacing impact heat transfer efficiency. Using PTC Creo for design and ANSYS Fluent for CFD analysis, materials such as copper, aluminum, and steel were evaluated. The results show that copper, with minimal baffle spacing, demonstrated the best heat transfer performance compared to aluminum and steel [39].

The rising energy demand in industries has led to the need for efficient heat exchangers, with shell and tube types being widely used, especially in HVAC systems like chillers. Their effectiveness largely depends on material selection, as it influences heat transfer performance. This research focuses on designing and analyzing shell and tube heat exchangers using different materials such as copper, aluminum, and steel. Baffle spacing is studied as a key factor affecting heat transfer efficiency. The design was created using PTC Creo, and CFD analysis was conducted in ANSYS Fluent. Results show that copper, with minimum baffle spacing, provides the best heat transfer performance among the materials tested. Hamid Bin Zahid [40] conducted a 3D CFD study using ANSYS to compare the thermo-hydraulic performance of shell and tube heat exchangers (STHX) with novel triangular (TRI) and tri-flower (TF) baffles against conventional segmental (SG) baffles. Simulations assessed heat transfer coefficient, pressure drop, and overall performance at varying flow rates. Results showed that TF-STHX provided the highest heat transfer but with increased pressure drop, while TRI-STHX delivered the best overall performance (hs/Δp ratio). The use of twisted tapes further enhanced heat transfer on the tube side. Additionally, TRI-STHX reduced shell-side vibrations, improving overall STHX efficiency.

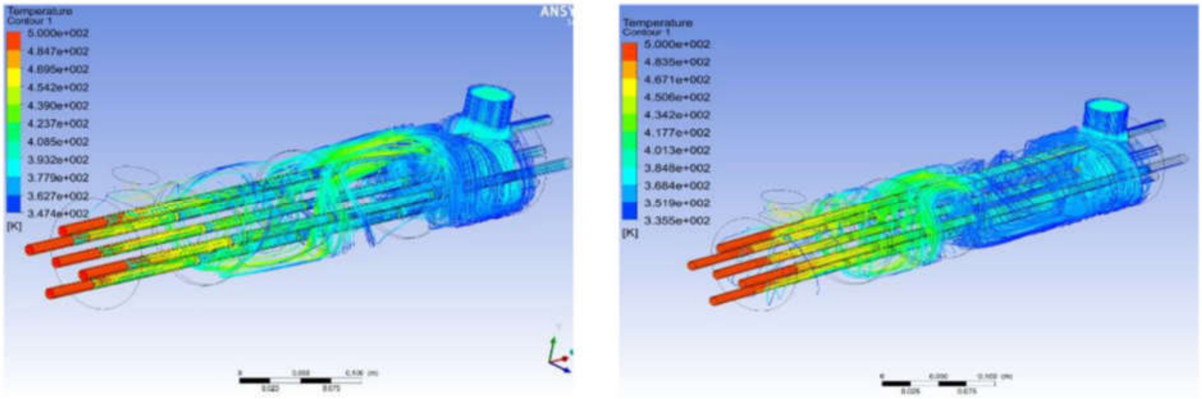


Figure 5. Temperature Distribution contour for 250mm and 125mm baffle pitch.

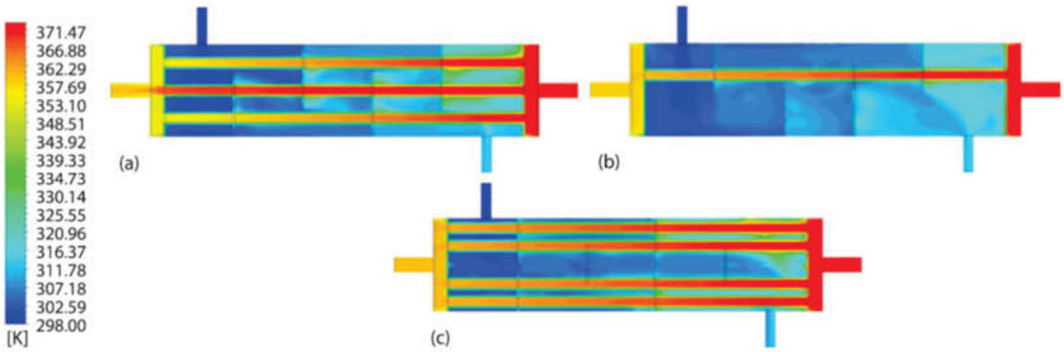


Figure 6. Temperature distribution; (a) SG-STHX, (b) TRI-STHX, and (c) TF-STHX

VI. Conclusion

The conclusion summarizes the key findings of the review and provides insights into the future direction of heat transfer enhancement techniques in STHEs. While passive methods are simple and cost-effective, active methods provide greater control, and nanofluids offer promising improvements in thermal efficiency. Computational models will continue to revolutionize the design and optimization of STHEs, driving innovation and efficiency in industrial applications. This paper presents a critical review of passive heat transfer enhancement methods, focusing on swirl flow devices like metallic twisted tape inserts. These inserts disturb the boundary layer and induce turbulence, improving convective heat transfer. Most reviews do not incorporate nanofluids in evaluating heat exchanger performance. The study emphasizes the effects of various twisted tape geometries on heat transfer, showing improvements in the Nusselt number and heat transfer coefficient. However, the use of twisted tapes also leads to an increase in pressure drop within the tube. Elsayed A.M. Elshafei (2008) experimentally studied the impact of frequency and Reynolds number on heat transfer in pulsating turbulent pipe flow under uniform heat flux. Results showed that the local Nusselt number—and thus the heat transfer coefficient—can either increase or decrease based on flow conditions. Higher heat transfer was observed near the pipe entrance. A maximum enhancement of 9% occurred at Re = 37,100 and f = 13.3 Hz, where bursting and pulsation frequencies likely interacted. Conversely, a maximum reduction of 12% was observed at Re = 13,350 and f = 42.5 Hz. CFD analysis revealed that increasing CuO-water nanofluid concentration enhances heat transfer but also significantly raises pressure drop. Even a low particle loading of 0.1%vol can improve heat transfer by 9–12%, while 1%vol yields up to 48% enhancement. However, beyond 0.25%vol, the pressure drop rises disproportionately compared to heat transfer gains, nearly doubling at 1%vol.

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