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A Critical Review of Heat Transfer Enhancement Strategies in Plate Heat Exchangers: Performance, Trade-offs, and Practical Challenges

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ABSTRACT

This research study covers the latest developments on the field of heat transfer enhancement to be applied in Plate Heat Exchangers (PHEs), which highlight the different surface modifications, flow manipulation devices and advanced working fluids used to enhance the heat transfer. Surface enhancement techniques like offset strip design fins, corrugated fins and wavy (louvered) design fins increase convective heat transfer through surface enhancement, fluid mixing and increase turbulence intensity. Such changes affect the thermal boundary layer and add to the thermal efficiency but also cause a higher pressure drop and higher pump power use. For further improvement in the thermal performance, passive flow enhancement devices such as twisted tapes, wires coil and vortex generator are implemented which promote secondary flows and disrupt the boundary layer. These methods of heat transfer enhancement are appealing for industrial applications as they offer high heat transfer rates with relatively low pressure drop (dp). It further investigates the use of nanofluids that have been shown to enhance convective heat transfer coefficients for metal-oxide based suspensions (Metal oxide (Fe_3O_4, Al_2O_3, CuO)-water) by around 20% under controlled conditions. But, real-life environments typically are not as efficient at benefiting from these because viscosity and fouling are generally raised, as is stability and cost. The hybrid method such as nanofluid with some passive inserts can result in synergistic thermal enhancements but comes with more system complexity and operational difficulty at industrial systems of heat exchangers.

1. Introduction

Plate heat exchangers (PHEs) are small but efficient thermal devices consisting of a row of thin and corrugated plate metals, which are generally gasketed or brazed to create parallel flow channels. Hot and cold fluids move in the same direction in these channels through a series of adjacent passages, allowing the transfer of heat between the two fluid blends across the walls of the thin plate, typically in counterflow or cross-flow configurations. Owing to their high surface area-to-volume ratio, modular construction, and maintenance life, PHEs are widely used in HVAC systems, chemical processing facilities, food and pharmaceutical plants, and renewable energy processes, including solar thermal processes and heat recovery units (Mutumba et al., 2020; Nawaz et al., 2025) .

Although they have these benefits, the efficiency of PHEs is usually limited by the existence of thermal boundary layers along the interface between the plates and fluid, which limits the efficiency of the convective heat transfer. Moreover, when the pressure drop across the channels is excessive, it reduces the flexibility of the operations, and the pumping power requirements can increase. To address this problem, various passive and active heat transfer enhancement methods have been explored over the past few years. Notable methods include modified corrugated or finned plate geometries, turbulence-promoting inserts (turbulators), and advanced working fluids such as nanofluids. This review critically evaluates the recent advances in these strategies in terms of their effects on heat transfer enhancement, pressure drop properties, economic viability, and practical use in real-world systems (Mousavi Ajarostaghi et al., 2022; Said et al., 2025; Sousa, 2025).

2. Finned and Structured Plate Surfaces

Structured surfaces or the addition of fins into the channels of PHE channels laminar flow enhances the mixing of the fluid and results in turbulence, thereby enhancing convective heat transfer. Typically, offset strip fins (OSF), louvered/wavy fins, pin fins, and vortex-generating geometries are commonly used, which are frequently made by embossing or etching fins on the plate faces. Several studies have measured these impacts. The offset-strip fins are much more effective than plain rectangular fins in a plate-fin exchanger in terms of increasing the Nusselt number (heat transfer), albeit with an increased friction factor (pressure drop) (Tang & Fan, 2025) . In a single experiment, the OSF plates were found to transfer heat to a significantly greater extent (approximately 13.4 percent higher heat transfer) than plain fins under similar flow conditions**,** but the friction also increased. Even greater gains are made by louvered fins: the experiments have demonstrated louvered channels to have the largest heat-transfer coefficients between the more common types of fins, and the greatest pressure drop. Overall, the higher the fin density or complexity, the higher the Nusselt number (enhancing the convective coefficient) and friction factor (growing dp).

Offset-strip fins (OSF): have small heat-transfer benefits and moderate dp penalties. The boundary layers were thinned by inducing secondary flows in the OSF channels (Tang & Fan, 2025).

Louvered/wavy fins: The greatest increase in the heat transfer rate (typically more than 15-20 percent) with the highest cost pressure-drop increases (Barati et al., 2023) .

Pin/vortex fins: There are designs (e.g., pin fins or fish-grill designs) that provide high heat transfer factors with localized mixing; designs that generate vortices (e.g., using channels) have the highest j-factor in comparative tests (Hu et al., 2025; Tran et al., 2025), but still with large f-factor penalties.

Technique	**Δ Heat Transfer**	**Δ Pressure Drop**	**Remarks**
Offset-strip fins	≈+13% Nusselt (vs plain)	Moderate increase	Simple manufacturing; improved j-factor vs. plain; higher f factor.
Louvered/wavy fins	+20–30% (highest)	+ significant (highest)	Complex fabrication, large Δp, and high j-factor gains are required.
Nanofluid (e.g. Fe_3O_4–water 1.0%)	+21.9% h_n (Fe_3O_4)	+10.1% (Fe_3O_4)	Requires fluid preparation, enhanced k and μ, and costs of particles.
Wire-coil turbulator	Moderate increase	Small increase	Low-cost retrofit:

	(synergistic)		best thermal efficiency per Δp.
Twisted-tape insert	+3.1% Nusselt (double-pipe example)	+64% (double-pipe)	Simple; large Δp (demonstrated in tube HX); seldom used in plate form.
Combined (nanofluid+turbulator)	Synergistic ↑ (not quantified)	Higher than individual	This potentially results in the highest k_eff, complexity, and Δp stack.

Table 1. *Comparison of recent enhancement methods (fins, nanofluids, and turbulators) in plate/plate-fin heat exchangers. Percentage changes are illustrative from the selected studies.*

Overall, adding fins or embossed patterns can noticeably boost the thermal performance, but designers must trade off the pressure-drop penalties. In practice, fin selection balances the desired ΔT vs. pumping power and material cost. Complex fin shapes (louvers, pin fins) yield the best j-factor but can more than double Δp in some cases (A. Kumar et al., 2022; Venkatesh et al., 2023) .

3. Nanofluids

In heat exchangers, Nanofluids - Metallic or oxide nanoparticle suspensions in a base fluid, are a common category of working fluids. This is to take advantage of the increased thermal conductivity and change in the rheology of the suspension to increase the convective heat transfer coefficient of the suspension. Recent PHE studies have claimed small-to-large improvements. As an illustration, Al_2O_3, SiC, CuO, and Fe_3O_4 nanofluids (0-1 wt%) were experimentally tested (using a corrugated-plate exchanger) by (Zheng et al., 2020); the Fe3O4-water nanofluid (1.0 wt) exhibited a 21.9% higher convective heat transfer coefficient than pure water, with the penalty of an increase in pressure drop by 10.1%. Comparable results have been reported in other studies, which claimed less than 10-30% enhancement in the Nusselt number or heat transfer coefficient of single nanofluids in plate-type geometries (Alikhan et al., 2025).

Nonetheless, a word of caution from critical reviews is that most published gains are likely to be exaggerated. A recent meta-analysis indicated that even when convective heat transfer is recalculated in multiple aspects, most of the purported improvements are reduced to a few percent (or vanish altogether).

For example, h-enhancements reported an increase to a maximum of approximately 27-48 in many cases, diminishing to typically around 3-5 when evaluated rigorously. The real effect can be covered by factors such as variations in fluid viscosity, measurement errors, and uneven distributions of particles. In addition, nanoparticle suspensions have system problems: agglomeration and settling of particles can change the viscosity and foul surfaces and heat-toxic surfaces. The high cost of most nanoparticles (e.g., gold = -80/g, silver = -6/g) is economically prohibitive. According to Said et al., the entire mechanism, particularly at the nanofluid scale, requires further improvement, and issues of maintenance and implementation, particularly agglomeration, poor heat transfer, and high expense, are still present(Choi et al., 2023; Sundararaj et al., 2018) .

In conclusion, nanofluids have the potential to slightly improve the thermal performance of PHEs (particularly when loaded with a higher nanoparticle concentration); however, this performance tends to be at the cost of higher pumping power (higher viscosity) and higher cost of materials/fluids. However, its practical applications require stable and laborious filtration. Hybrid nanofluids (two types of nanoparticles) have been considered to further develop conductivity, but with the same type of challenges. It is important to note that nanofluids can be synergized with other technologies (e.g., turbulators), and a combination of the two approaches is likely to result in an increased total heat transfer compared with the isolated method(Adun et al., 2020; Bharadwaj & Dogra, 2024) . These combinations are interesting but challenging to design and analyze separately.

4. Turbulators and Inserts

Turbulators are passive inserts (wire coils, twisted strips, and swirl promoters) installed in the flow to generate vortices and mixing. When a turbulator is inserted into a PHE channel, the fluid causes the plate to swirl and continuously interrupts the boundary layer. This resulted in greater local heat transfer, albeit at the cost of additional form drag. Recent reviews have highlighted that turbulators are cost-effective when combined with nanofluids (Said et al., 2025). An example is twisted-tape inserts (typical of tube exchangers), which generate a vigorous swirling. An experimental (numerical) study (two-pipe arrangement) with various quadruple twisted-tape fins found that the Nusselt number of the pipe increased by approximately 3.1 percent, but the pressure decreased by 64 percent (Ramadhan Al-Obaidi & Chaer, 2021). Although results with isolated tubes (dubbled) cannot be directly scaled to plate channels, these results show that dietary gains in pressure drop are compensated with small increases in heat transfer.

The other aesthetics of the turbulator performed better. Among the numerous swirl-inducing designs (coiled wires, perforated baffles, etc.), coiled-wire inserts have been found to be the most efficient in terms of thermal efficiency (h/dp), providing significant gains in heat transfer with minimal pressure loss. The coil turbulators formed continuous longitudinal vortices that were used to mix the hot and cold streams. There have also been studies on swirl generators and perforated tubes that tend to gain heat-transfers of 10-30 per cent in tube/plate-based applications but gain a dp of 10-50 per cent. Generally, turbulators tend to enhance the mixing ability by increasing the velocity of the surface, thereby thinning the thermal boundary layer (Çelik & Erbay, 2021; Emani et al., 2019; Said et al., 2025; Seerangan et al., 2021).

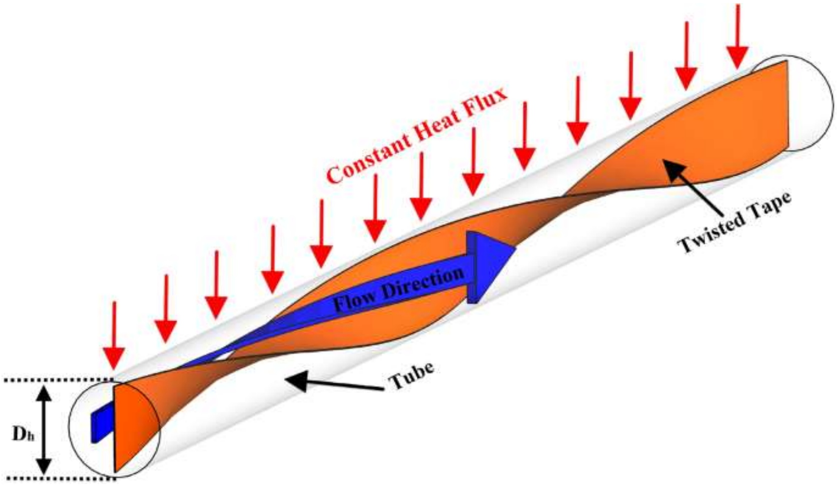

Figure: *Abstract visualization of fluid swirl. Turbulators, such as twisted tapes or wire coils, induce vortices (as illustrated) that enhance the mixing in plate channels, thereby increasing the convective heat transfer. (Image: swirling flow analogy.)*

Notably, turbulators can be frequently retrofitted in preexisting heat exchangers at a low cost, and are therefore appealing. Additional gain can be achieved by using turbulators with nanofluids, as the coils mix the nanoparticle-containing fluid and increase the effectiveness of both processes. However, system designers should ensure that the added pressure drop is reasonable enough. Overall, a viable passive solution is the use of turbulators, such as coils of wire, which can significantly enhance heat transfer at a relatively low cost in terms of pressure drop (Çelik & Erbay, 2021; Najim, 2024; Said et al., 2025)**.**

5. Other Passive Techniques

In addition to fins and turbulence-generating inserts, new passive strategies have emerged. Others have examined surface microstructures, such as dimples, grooves, or embossments on the plates, which form local vortices (similar to the dimples used on golf balls). Other studies have examined coated/roughened surfaces to break the flow. An example of this is a study on PHE channels that observed that the addition of engineered surface roughness on chevron plates had a significant effect on increasing the j-factor, but at a higher f-factor (pressure drop). Bio-inspired patterns and magnetically actuated inserts have also been proposed; however, these are still largely in the proof-of-concept phase(Pulagam et al., 2025).

In addition, there is a method of flow arrangement optimization: crossflow mixing can be achieved by rotating the channel or staggering the plates. The performance depends on the corrugation orientation (angle at which the chevron plate is corrugated) of the corrugated PHE. One study reported that low-angle plates demonstrated a low NTU slightly higher than steeper angles and a slightly higher dp(C.-Y. Yang & Hsieh, 2024) . Nevertheless, specific information about this geometrical adjustment in contemporary PHEs is difficult to obtain.

In general, the majority of "other" methods increase convection only in the near future and usually do not scale well to large flow rates, making fins and turbulators the best enhancement methods.

6. Comparison and Trade-offs

Table 1 and the figure show the overall trends: all methods of enhancing heat transfer increased heat transfer at the expense of either the pressure drop or complexity. Fins (OSF, louvers) and turbulators modify the geometry of the flows directly, whereas nanofluids change properties of the fluids. The following are some of the major comparisons made in the contemporary literature:

- **Effectiveness:** Louvered fins and vortex-generating inserts provide the best j-factors of the designed products studied(Valencia & Muñoz, 2023) , and the p. j. gain is usually–20-30% or more. In some cases, nanofluids containing high-conductivity nanoparticles (Fe_3O_4, CuO) have demonstrated assumptions of aging convective coefficients of up to approximately 20 percent **[7]**. Single-digit percent gains in the Nusselt number per pass are typically observed with twisted tapes/turbulators, although very violent (e.g., multiple tapes) can be employed (Thapa et al., 2021).

- **Pressure Drop:** Pressure drop can be increased by more than twice with louvered fins and dense turbulator inserts. For example, a four-tape twisted insert increased the dp by 64 percent (Thapa et al., 2021). Conversely, nanofluids (with less than one percent nanoparticles) tend not to achieve such significant increases in dp **[7]**, as the viscosity increases only slightly. Wire-coil inserts are more likely to impose a reduced dp per unit heat gain than other types of turbulators (R. Kumar et al., 2022).

- **Cost and Practicality:** Simple Fins: plain, offset Use plain and offset fins Simple fins require no additional cost and may increase the cost of complex fins (louver, pin fins). Multilayer inserts Multilayer inserts provide more benefit and complexity compared to plain and offset fin 1/2Again Fin: simple and offset PIN GABAICDOACCRH ½ Fin yield generally PIN GABAICDOACCRH 1/2 differences give further benefits but are costlier to produce (of course complex shapes may be created on fin edges). Nanofluids incur continuous fluid and system costs (filters and pumps); thus, expensive nanoparticles hinder their commercialization (Prem & Anand, 2024). Retrofittable turblators, such as wire coils, require space and are low-cost. Fouling and stability (nanoparticle settling) remain challenges for nanofluids in real systems(Chakraborty & Kumar, 2022) .

Practically, engineers must trade off the heat transfer requirements with the pumping energy and initial capital cost. Numerous articles have criticized the cost-effectiveness of these methods. As an example, Said et al. observe that nanofluids in combination with passive inserts have a bright future due to the ability to achieve high performance, but at the same time, be practical and comparatively low to install(Bertsche et al., 2022; V. Kumar & Sahoo, 2022) . That is, active controls, such as active power and movement of parts, are frequently not required because passive inserts (do not require any moving parts or power) and the use of low-cost nanofluids can frequently reach the optimal combination of good performance without exotic controls.

One of the trends concerns integrated strategies. It is known that a nanofluid flowing over enhanced surfaces or by turbulators performs better than either of the measures separately (Karakus et al., 2025; Said et al., 2025). For example, when a channel filled with Fe_3O_4-water has wire coils, a greater net h is obtained compared to plain-water coil wire coils or coil-free Fe_3O_4 **[9]**. However, the specific benefits are highly dependent on the flow regime, geometry, and interactions (along with particle alignment by vortices).

7. Practical Implementation and Challenges

In addition to performance, implementation issues are crucial. Fins and turbulators should be within the range of the plate spacing; too aggressive designs can infiltrate and/or involve the assembly process. The precision that can be achieved depends on the limits of extreme fin geometries. Nanofluids are difficult to maintain because the particles tend to settle during downtime, foul the plates, or get trapped in corners, and the thermal behavior of nanofluids can decline over time. Corrosion and compatibility with chemicals are also issues (e.g., certain oxides are chemically reactive)(Said et al., 2025; Wang et al., 2023).

Cost-effectiveness must consider the overall lifecycle. The use of cheap aluminum or steel fin plates will incur little cost to the fluid power, but the use of exotic nanofluids or high-speed pumps to run very rough plates adds to the costs of operation. Said et al. point out that wire coil turbulators are more efficient in terms of thermal wise, with lower pressure drop that are cost-effective in terms of the payback. However, the cost of gold or diamond nanoparticles is prohibitively high; thus, sequential nanofluids employ less-expensive oxides or carbons .

Fouling of nanoparticles is a minor problem: nanofluids can slow down some traditional fouling (because of better agitation), but the nanoparticles themselves will deposit on the plate surfaces, and thus, they effectively poison the heat-transfer surfaces. Recent studies have indicated that powerful filtration and re-dispersion processes are necessary, which increases the cost and complexity of the systems(Kamel & Lezsovits, 2019; Waware et al., 2024).

Finally, control and optimization are operational research fields. Owing to the fluctuating loads on which PHEs frequently operate, adaptive technologies (e.g., alternate operation of nanofluid concentration modes or bypassing coils) have also been suggested, although they remain in the experimental phase. Design problems arise because of uncertainties in the performance prediction (e.g., the effective thermal conductivity of a particular nanofluid).

8. Conclusions

Recent studies have broadened the instrumentation for improved plate heat exchanger functioning. Structured fins (nonplanar, louvered, wavy, or swirling) and passive inserts (wire coils and swirl generators) can substantially increase the coefficient of study at higher pressure drops. Another enhancement is provided by nanofluids, which increase the fluid conductivity; however, in practical terms, this can only be marginal, and the viscosity and price increase. The ideal returns are most likely to be realized when approaches are used in combination, for example, turbulent inserts with nanofluids, because they can take advantage of several mechanisms (Abed et al., 2021; Azmi et al., 2021; Bunpheng & Dhairiyasamy, 2024; Singh et al., 2023).

Regarding trade-offs, fins and turbulators would either have to be physically redesigned or new components added (but once fitted, no new consumables are needed), and nanofluids would need to control their fluids and invest in nanoparticles. Each system increases the complexity of the system and frequently pumps the work. Cost-effectiveness analyses imply that inserts made of wire coils (low increase in dp) and those made of nanoparticles (low volume fractions) are both cheaper improvements (Azmi et al., 2021; Farajollahi et al., 2022; Said et al., 2025).

One of the lessons learned is that although there have been numerous proven improvements in controlled experiments, the practice in the real world necessitates a close consideration of the gains in heating versus pumping and material expenses. There are still limitations in extrapolating laboratory results to PHEs in industrial environments. The long-term stability of nanofluids over thousands of working hours is under investigation. Similarly, the most belligerent fin/turbinator schemes must be tested faithfully with multiphase or dirty flow(Koca et al., 2025; Maher et al., 2020).

Future work is likely to be based on optimization (distinguishing between h and dp owing to AI application or multicriteria design), durability (long-lasting tests of nanofluid loops), and hybrid systems (a combination of passive and active actions towards measured paths). Altogether, the last five years have seen significant improvements in PHE methods, but each of them has its own limitations. When determining the enhancement course, engineers must consider not only the thermal performance but also the pressure drop, costs, and maintenance. Ongoing studies are required to fine-tune the correlations and models to enable designers to anticipate the net worth of such innovations within realistic scenarios of operating conditions(Balbino Barbosa Filho & Mauro Da Silva Neiro, 2020; Narziev, 2021; R. Yang, 2025) .

References

1. Abed, N., Afgan, I., Iacovides, H., Cioncolini, A., Khurshid, I., & Nasser, A. (2021). Thermal-Hydraulic Analysis of Parabolic Trough Collectors Using Straight Conical Strip Inserts with Nanofluids. Nanomaterials, 11(4), 853.
2. Adun, H., Wole-Osho, I., Okonkwo, E. C., Bamisile, O., Dagbasi, M., & Abbasoglu, S. (2020). A neural network-based predictive model for the thermal conductivity of hybrid nanofluids. International Communications in Heat and Mass Transfer, 119, 104930.
3. Alikhan, A., Mery, H., Sadiq, S., & Mohammed, O. (2025). THE INFLUENCE OF PLATE CONFIGURATION AND CUO NANOFLUIDS ON HEAT TRANSFER AND PRESSURE DROP IN PLATE HEAT EXCHANGERS. Kufa Journal of Engineering, 16(3), 624–638.
4. Azmi, W. H., Abdul Hamid, K., Ramadhan, A. I., & Shaiful, A. I. M. (2021). Thermal hydraulic performance for hybrid composition ratio of TiO2–SiO2 nanofluids in a tube with wire coil inserts. Case Studies in Thermal Engineering, 25, 100899.

5. Balbino Barbosa Filho, A. C., & Mauro Da Silva Neiro, S. (2020). Fine-Tune Robust Optimization. In Preprints.org. Mdpi Ag.
6. Barati, D., Nimafar, M., & Salehi, G. (2023). Investigation on the Effect of Length and Amplitude of Sinusoidal Wavy Vortex Generators on the Heat Transfer Rate, Pressure Drop, and London Factor in Compact Heat Exchangers. Journal of Mechanical Materials and Mechanics Research, 6(2), 1–13.
7. Bertsche, D., Knipper, P., Meinicke, S., Dubil, K., & Wetzel, T. (2022). Experimental Investigation on Heat Transfer Enhancement with Passive Inserts in Flat Tubes in due Consideration of an Efficiency Assessment. Fluids, 7(2), 53.
8. Bharadwaj, G., & Dogra, S. (2024). Thermal conductivity of hybrid nanofluids and their application in heat transfer augmentation. AIP Conference Proceedings, 3007, 030003.
9. Bunpheng, W., & Dhairiyasamy, R. (2024). Enhancement in Turbulent Convective Heat Transfer Using Silver Nanofluids: Impact of Citrate, Lipoic Acid, and Silica Coatings. ChemEngineering, 8(4), 65.
10. Chakraborty, S., & Kumar, P. (2022). Nanofluids Long-term Stability Challenges and Guidelines (pp. 71–146). Royal Society of Chemistry.
11. Choi, E., Cho, Y. I., & Lorsch, H. G. (2023). ENHANCEMENT OF CONVECTIVE HEAT TRANSFER WITH PHASE-CHANGE PARTICLES. 1003–1008.
12. Emani, M. S., Nayak, A., Chowdhuri, A. K., Mandal, B. K., & Saha, S. K. (2019). EXPERIMENTAL INVESTIGATION ON HEAT TRANSFER AUGMENTATION IN HORIZONTAL TUBE USING COILED WIRE INSERTS. Enhanced Heat Transfer/Journal of Enhanced Heat Transfer, 26(5), 513–534.
13. Farajollahi, A., Mokhtari, A., Rostami, M., Imani, K., & Salimi, M. (2022). Numerical study of using perforated conical turbulators and added nanoparticles to enhance heat transfer performance in heat exchangers. Scientia Iranica.
14. Hu, L., Zuo, Q., & Rao, Y. (2025). Heat Transfer Enhancement in Turbine Blade Internal Cooling Channels with Hybrid Pin-Fins and Micro V-Ribs Turbulators. Energies, 18(13), 3296.
15. Kamel, M., & Lezsovits, F. (2019). Boiling heat transfer of nanofluids: A review of recent studies. Thermal Science, 23(1), 109–124.
16. Karakus, T., Firat, I., Yildirim, O., Sonmez, F., Cicek, K., Yildiz, A., Karagoz, S., & Comakli, O. (2025). Experimental investigation of thermal performance and entropy analysis of sphere turbulators. Thermal Science, 29(1 Part A), 117–129.

17. Koca, A., Mustafaoğlu (Nasiri Khalaji), M., & Yeşilyurt, M. K. (2025). Numerical Hydrothermal Investigation of Multiphase Flow of Aqueous Alumina Nanofluids in Millichannels. Engineering Perspective, 5(4), 162–182.
18. Kumar, A., Das, B. N., Panigrahi, S., Chaubdar, P., & Harichandan, A. B. (2022). Aerodynamic Cooling of Electronic Pin Fins (pp. 161–168). Springer Nature Singapore.
19. Kumar, R., Kumar, M., & Patil, A. K. (2022). Exergetic Performance Analysis of Energy Storage Unit Fitted With Wire Coil Inserts. Journal of Solar Energy Engineering, 145(2).
20. Kumar, V., & Sahoo, R. R. (2022). Energy-Economic and Exergy-Environment Performance Evaluation of Compact Heat Exchanger With Turbulator Passive Inserts Using THDNF. Journal of Thermal Science and Engineering Applications, 15(2).
21. Maher, D., Hana, A., & Habib, S. (2020). Investigation of heat-transfer and fluid dynamic of nanofluids used in heating building. Nanomaterials and Energy, 9(2), 202–214.
22. Mousavi Ajarostaghi, S. S., Zaboli, M., Javadi, H., Badenes, B., & Urchueguia, J. F. (2022). A Review of Recent Passive Heat Transfer Enhancement Methods. Energies, 15(3), 986.
23. Mutumba, A., Karayiannis, T., Coletti, F., & Reip, A. (2020, October 1). Flow Boiling Heat Transfer in Coated and Uncoated Plate Heat Exchangers.
24. Najim, F. T. (2024). Heat Transfer Enhancement Inside a Duct Using Turbulators, Vortex Generators, and Baffles. KHWARIZMIA, 2024, 39–44.
25. Narziev, S. O. (2021). Selection of method for optimization of vehicle maintenance and repair system taking into account operating conditions. ACADEMICIA: An International Multidisciplinary Research Journal, 11(5), 949–951.
26. Nawaz, K., Li, K., Brechtl, J., & Guy, E. (2025). Joining Study for Formed Plate Heat Exchangers (Final Report). Office Of Scientific Technical Information.
27. Prem, A., & Anand, S. (2024). Blood Filters and Pumps (pp. 744–745). Oxford University Pressnew York.
28. Pulagam, M. K. R., Rout, S. K., & Sarangi, S. K. (2025). Single-phase flow and pressure drop between a pair of chevron plates with sinusoidal corrugations – a CFD study using periodic boundary condition. Numerical Heat Transfer, Part A: Applications, 87(1), 1–17.
29. Ramadhan Al-Obaidi, A., & Chaer, I. (2021). Study of the flow characteristics, pressure drop and augmentation of heat performance in a horizontal pipe with and without twisted tape inserts. Case Studies in Thermal Engineering, 25, 100964.

30. Said, Z., Mwesigye, A., Syam Sundar, L., Tiwari, A. K., Balasubramanian, K., Ali, H. M., Bellos, E., Gim, C., Ahmed, M. S., & Hwang, J. (2025). Sustainable Thermal Solutions: Enhancing Heat Transfer with Turbulators and Nanofluids. Advanced Energy and Sustainability Research, 6(5).
31. Seerangan, I., Huang, T.-H., & Liu, Y.-H. (2021). Heat transfer enhancement in Minichannel heat sinks using fully and partially filled coiled wire inserts. Heat and Mass Transfer, 57(7), 1183–1192.
32. Singh, S. K., Kumar, V., Kumar, A., & Yadav, S. (2023). Experimental study of the thermal characteristic of a double tube heat exchanger with tapered wire coil inserts using PCM-dispersed mono/hybrid nanofluids. Experimental Heat Transfer, 37(7), 1067–1083.
33. Sousa, A. C. M. (2025). Heat Transfer Enhancement: Exploring Nanofluids and Devices. Journal of Physics: Conference Series, 2940(1), 012001.
34. Sundararaj, A. J., Pillai, B. C., & Asirvatham, L. G. (2018). Convective heat transfer analysis of refined kerosene with alumina particles for rocketry application. Journal of Mechanical Science and Technology, 32(4), 1685–1691.
35. Tang, J., & Fan, X. (2025). Thermal-Hydraulic Characteristics of Offset Strip Fins at Different Flow Angles. 121–126.
36. Thapa, S., Samir, S., & Kumar, K. (2021). Performance evaluation of solar parabolic trough receiver using multiple twisted tapes with circular perforation and delta winglet. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 236(4), 1296–1307.
37. Tran, D.-Q., Le, V.-H., Kim, J.-H., Ngo, C.-L., Pham, G.-D., Carbonneau, X., & Dinh, C.-T. (2025). Numerical investigation on heat transfer characteristics of internal cooling channels with perforated pin-fins in gas turbine blade. Physics of Fluids, 37(8).
38. Valencia, A., & Muñoz, S. (2023). Comparative Analysis of Longitudinal Vortex Generators and Louvered Fins in Enhancing Thermal Performance in Compact Heat Exchangers. International Journal of Heat and Technology, 41(4), 919–928.
39. Venkatesh, G., Meenakshi Reddy, R., & Mallikarjuna Rao, P. (2023). Endwall heat transfer in wedge channel with teardrop pin fins, circular fins and oblong pin fins. International Journal of Turbo & Jet-Engines, 41(3), 565–579.
40. Wang, L., Wang, J., Tang, J., & Zho, X. (2023). Enhancing heat exchanger efficiency with novel perforated cone-shaped turbulators and nanofluids: a computational study. Chemical Product and Process Modeling, 19(1), 147–158.
41. Waware, S. Y., Chougule, S. M., Yadav, R. S., Biradar, R., Patil, P., Munde, K. H., Kardekar, N. B., Nimbalkar, A. G., Kurhade, A. S., Murali, G., & Kore, S. S. (2024). A Comprehensive Evaluation of

Recent Studies Investigating Nanofluids Utilization in Heat Exchangers. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 119(2), 160–172.

42. Yang, C.-Y., & Hsieh, M.-T. (2024). Flow boiling heat transfer in a plate heat exchanger with mixed chevron angle plates. Journal of Physics: Conference Series, 2766(1), 012145.
43. Yang, R. (2025). DP-Adam-AC: Privacy-preserving Fine-Tuning of Localizable Language Models Using Adam Optimization with Adaptive Clipping. In ArXiv.org. Societa Italiana Di Fisica.
44. Zheng, D., Wang, J., Chen, Z., Baleta, J., & Sundén, B. (2020). Performance analysis of a plate heat exchanger using various nanofluids. International Journal of Heat and Mass Transfer, 158, 119993.
45. Çelik, H. S., & Erbay, L. B. (2021). Heat transfer enhancement using different types of turbulators on the heat exchangers. Journal of Thermal Engineering, 7(7), 1654–1670.