Maximizing Heat Exchanger Efficiency through Optimized Perforation Patterns: A Review

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Abstract: *Heat exchangers are key design components influencing energy conversion, thermal control, and process efficiency in a variety of industries, including power generation, HVAC, electronics cooling, and renewable energy systems, although they needlessly inhibit heat transfer, and wishful thinking on reducing pressure drop. Recent years have shown an emergence for effective passive conductive heat exchanger performance improvement with optimized geometry-based perforation patterns on fins, baffle, tube, and insert sheets. The perforations are capable of modifying flow structures which create secondary vortices that disturb thermal boundary layers, intensifying fluid mixing and, therefore, significantly ameliorating heat transfer rates. This review aims to offer a comprehensive review of current perforation-based heat exchanger designs, concentrating on the influence of perforation geometry, size, shape and arrangement, and the perforation effect on thermo-hydraulic performance. Both experimental and numerical works are analyzed in detail, focusing on performance benefits, cost penalties, and resulting overall efficiency improvements. This review also investigates the utility of perforation in integral heat exchangers in various heat exchanger configurations, such as the fin-and-tube heat exchanger, the shell-and-tube heat exchanger, plate heat exchangers, and compact heat exchangers. Emerging trends, for instance, nanofluids, advanced turbulence promoters, and machine learning-based optimization techniques, are discussed as promising directions from the design standpoint of the optimal perforation. Various critical research gaps focused on scalability issues, manufacturing constraints, and unification and development of performance measurement criteria are identified. Through this consolidated review, the aim is to provide thorough insights to researchers and designers who are willing to improve further on perforation-based enhancement strategies for the development of high-efficiency, cost-effective, and energy-saving heat exchanger systems.*

Keywords: *Heat exchangers, Perforation patterns, Heat transfer enhancement, Thermo-hydraulic performance, Pressure drop, Flow disturbance, Design optimization*

I. INTRODUCTION

The heat exchanger is a necessary element, connecting a wide area of thermal systems that transfer energy in power generation, chemical production, refrigeration, air conditioning, automotive engineering, electronics cooling, and renewable energy. The main function of the heat exchanger is to transfer heat effectively from one fluid to another during the performance when exposed to two fluids of fluctuating temperature while sustaining minimal energy losses and operating costs [1]. The heat exchanger's efficiency has a huge impact on the system's capability, fuel being consumed, the environment, and thus it would be a morally sustainable goal. The obvious aim of speeding up the heat exchanger efficiency in the world is energy conservation and elimination of greenhouse gases-such is the unmistakable objective for engineers. A small improvement in heat-transfer performance is like having an unlimited amount of energy saved and much more system reliability over a long time of operational life [2]-[3].

Even with significant advancement in heat exchanger design and materials, conventional heat exchangers often face limitations due to thermal resistance and in efficient fluid flow characteristics. The formation of thermal boundary layers at the surface of heat transfer retards conduction particularly under the transitional flow regime. Moreover, given the compactness of the system requirements, space shortage does not allow a simple increase of the surface area to yield high heat transfer rates. A result of the huge demand for higher heat flux removal and further compacting of the thermal systems, traditional design practices are no longer any good [4]. The necessity for advanced concepts applying enhanced heat transfer techniques to handle considerably higher heat fluxes with much lower pressure drops and much lower power consumptions has been greatly increased by these new challenges.

"Enhancements in heat transfer could be classified into active and passive means. Active means like surface vibration, electromagnetic fields, and external power giving show excellent enhancement in heat transfer; however, there are complex control systems, higher operational costs, with reliability being a questionable factor [5]. Perhaps these cool processes can be referred to as passive means, where only geometrical modifications or surface treatments need to be provided without adopting any kind of external energy input to maximize heat transfer. Among the readily included passive treatments are extended surfaces, roughened surfaces, ribs, baffles, twisted tapes, vortex generators, and surface coatings. Passive methods are greatly welcomed due to their simplicity, ease of installation, low maintenance, and the feasibility of their application in retrofitting existing heat exchangers. Dealing with passive enhancement techniques is essentially figuring out how to manage balanced heat transfers while allowing pressure drops to occur [6].

From various passive augmentation techniques, the perforation method is one innovative way of enhancing heat exchanger efficiency. Perforation added to fins, baffles, tubes, cone inserts and vortex generators; considerably modifies the fluid flow characteristics along with the heat transfer features [7]. These designs provide advantages in flow mixing, creating secondary vortices, and disturbing the thermal and hydrodynamic boundary layers by permitting fluid through the areas of perforation. The latter again increases enhancement for the convective heat transfer coefficients and temperature uniformity over the heat transfer surfaces. Unlike solid enhancements, perforated elements can reduce flow blockage that blocks excessive pressure drop while efficiently enhancing the heat transfer [8].

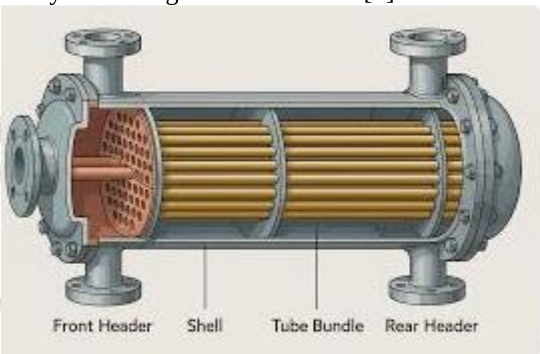

Figure 1: Heat Exchangers [4]

The essence of utilizing passive perforation methods is the capacity to enhance heat transfer performance concurrently with hydraulic performance being evaluated. Geometrical variables relevant to perforation, like shape, dimension, orientation, pitch, and perforation ratio, significantly affect the total performance [9]. Circular, square, elliptical, and conical perforations have all been widely researched as each has its distinct set of advantages in vortex-generation results and redistribution of flow. These carefully thought out perforation patterns enable enhanced heat transfer performance with an acceptable level of frictional loss, making them a good choice for application in compact and high-performance heat exchangers. Some of the additional advantages of the perforated design include engineering efficiencies related to lower material and weight specifications, beneficial for aerospace, automotive, and portable thermal systems [10].

Recent advances in computational fluid dynamics (CFD) and experimental techniques have revolutionized the rapid discovery and exploration of optimized perforation patterns. Computer simulations take simulation results toward increased visualization of developed flow structures and temperature fields aiming to lead an engineer toward the best designs in thermal configurations and to lower the risk of fabrication [11]. To supplement numerical evidence, experimental studies provide insight into the actual performance and fabrication hence increasing practical utility of research in this area. The adornment of developing pathways for a more optimal perforation-mediated enhancement for heat exchange systems is by interaction of other emerging fields-smart nanofluids and parameter learning-based optimization in progress. Combined advances signal that the development of passive perforation-based approaches will emerge as a widely accepted medium of energy-efficient solutions to almost all thermal management challenges present today, encouraging intensive investigation [12].

II. FUNDAMENTALS OF HEAT TRANSFER ENHANCEMENT

Enhancing heat transfer means increasing the exchange of thermal energy with more ease, without primarily influencing system size and thereby promoting energy consumption [12]. The enhancement techniques work in such a way as they, by varying the surface geometry or flow characteristics or fluid properties, promote convective heat transfer while keeping the pressure drop and appropriate operational.

Heat Transfer Mechanisms in Heat Exchangers: - Heat transfer in heat exchangers occurs primarily by conduction, convection and, sometimes, radiation. Conduction dominates the flow of heat between the solid walls separating fluids, while convection controls the transfer of heat between the fluid and solid walls. Forced convection most commonly occurs in industrial heat exchangers, where fluid velocity, turbulence intensity, and thermophysical characteristics of the working fluid significantly govern the performance [13]-[14]. The effectiveness of a heat exchanger depends upon the temperature gradient, heat transfer area, heat transfer coefficient, and the arrangement of the flow; hence the enhancement of convection heat transfer becomes one primary design objective.

Role of Flow Disruption and Boundary Layer Thinning: - Flow disruption-the disruption opposite of the flow-is crucial, perhaps the essential ingredient in convective heat transfer. Reducing boundary layers, producing less flow, other barriers, and getting extruding through holes so many directions of secondary flows, vortices, and turbulence come into existence.

This altogether now brings in a motion of mixing within the flow while also making the wall more critical, where the temperature gradient now appears to indirectly work at thinning the boundary layer [15]-[16]. Converting the hydrodynamic traps helps diminish the thermal resistance that will in turn diminish the estimated heat transfer coefficients. The intrinsic dynamics dictate that the amount of disturbance needs to be precision-controlled lest it becomes necessary to compromise the enhancement-hydraulic performance compromise.

III. PERFORATION PATTERNS AND GEOMETRIC PARAMETERS

Perforation patterns and geometric parameters play a decisive role in controlling flow behavior and thermal performance in heat exchangers by regulating turbulence generation, mixing intensity, and pressure drop characteristics.

Types of Perforations

Perforation types may disrupt flow differently depending on the perforation shape. The circular perforation is largely used because of its ease of making and smooth surface stress somewhat distributed. Being able to create strong vortices at low flow rates and high turbulence levels that somewhat favors heat transfer, square and elliptical perforations are used. Conical perforations, however, make for smooth transition for flow acceleration with decreased pressure loss, offering many advantages, including good hydraulic and thermal features in a single system.

Perforation Size, Shape, Pitch, and Orientation

Perforation size and form influence jet formation and wake interaction behind perforated surfaces. Smaller perforations with optimized pitch enhance the intensity of turbulence, whereas very many perforations may reduce structural stability. The orientation of the perforations with respect to the direction of the flow has a role in flow splitting and vortex induction. Geometric optimization will result in an improvement in heat transfer without excessively losing of friction.

Effect of Perforation Ratio and Arrangement

The perforation ratio, or the ratio of the open area to the total surface area, has a significant influence on the thermo-hydraulic performance. Mild values of perforation ratios trigger heat transfer through introducing bright mixing and boundary layer displacement. Compared to both lesser and greater values, almost equal perforation ratios have a significant effect on vortex interaction and uniform flow. Among different hole configurations, we must choose the ones that will affect positively towards better heat transfer enhancement combined with only a slight increase in pressure drop enacted.

IV. PERFORATED ELEMENTS IN HEAT EXCHANGER COMPONENTS

Numerical studies have revealed that perforating circular fins grossly enhances the turbulence intensity, distorting the thermal boundary layer, thereby leading to a considerable increment in the Nusselt number while incurring only a small sacrifice in the pressure drop. They underscore the importance of hole size and spacing in fin-and-tube heat exchangers [1]. The variation in tubing geometries was also shown to affect thermal-hydrodynamic performance, wherein asymmetric tube cross-sections induce flow separations and secondary vortices thereby increasing heat transfer while raising the pressure loss. White in view of this is the need for geometrically modifying compact heat exchangers [2]. Turbulators are successfully employed as passive means, which have been well-studied and justified by the increase in turbulence and an associated rise in heat-transfer coefficients, despite the increase of friction factors-this, however, confirms the power of turbulators in passive heat-transfer enhancement [3]. Comprehensive reviews of compact fin-and-tube heat exchangers have pointed out the geometry of fins, flow behavior, pressure drop, and fouling as prime performance-influencing factors; in automotive and HVAC areas, these are most critical [4].

Use of nanofluids combined with geometric modification is showing enhanced heat transfer rates, especially in the case of staggered arrangements of cylinders. Performance of special geometries is a question mark in such a scenario with increasing nanoparticle load, as this will also lead to higher pumping pressure [5]. It was further concluded that swirl flow modification generates an intense heat transfer system around a perforated twisted tape with a V-cut profile [6]. A double-cut configuration performed much better in heat transfer while moderately evaluating resistance to flow than a single-cut version. Geometric modifications in impingement heat transfer systems, which include nozzle shapes and surface features, have a profound influence on turbulence development and heat transfer enhancement, particularly in cryogenic cooling technologies [7]. Novel baffle shapes-like flower-type and corrugated-increase flow mixing and secondary vorticities, increasing heat transfer and allowing for acceptable pressure drop increments [8,9].

Microstructured pin-fin heat sinks with perforations demonstrate less hydraulic resistance yet maintain high heat transfer coefficients, thus necessitating a notifier of how relevant it is to improvement made in cooling of electronics slices [10]. Surprisingly, the synergistic improvements of nanofluids can be found when combined with turbulators, as these nanofluids improve heat transfer performance, even though they enhance friction [11]. Microchannel heat sinks with fin designs allow better heat transfer by improved fluid mixing and results in a modest rise in pressure drop [12]. Baffles in circular channels show enhanced heat transfer when they exist in a staggered arrangement, without doubt, but only with amplified pressure loses [13].

Twist-fin arrays when placed in rectangular channels, bring upon favourable swirls and secondary flows that enhance heat-transfer performance while at the same time taking on additional pressure drop costs- hence the relevance of the choice of orientation and twist ratio [14]. Artificial intelligence methodologies such as artificial neural networks have shown good accuracy in predicting thermal performance with significantly less man-hours (computational costs), supporting the intelligent search for optimal thermal systems [15]. Surface-enhanced inserts such as dimpled twisted tapes largely hold a better performance edge over the smooth-channel heat exchanger inserts by increasing intensity in turbulence and, hence, enhancing efficiency over the highest value of overall efficiency [16]. Another significant improvement mechanism is provided by corrugated tubes in shell-and-tube heat exchangers that enhance surface areas and flow disarray to justify the otherwise attractive gains in efficiency with the penalty on pressure drop [17].

Sustained enhancement of heat transfer in heat exchangers due to better thermal conductivity was considered one of the significant outcomes for overcoming the obstacles of increased viscosity, instability, and so on [18]. The assessments carried out on circular plates perforated raised the importance of optimal perforation designs from the viewpoints of stress concentration alleviation and mechanical integrity of heat exchange components [19]. And lastly, the natural convection counterpart research characterizing solid, hollow, and perforated pin fins favor the latter with substantial thermal performance improvement over solid fins in low heat resistance and increased flow properties, supporting the lines of adoption for cost-effective thermal systems [20].

Table 1: Numerical and Experimental Studies on Heat Transfer Enhancement

Ref	Study Focus / Method	Results	Limitations
[1]	Numerical study on perforated circular fins in fin-and-tube heat exchangers	Perforations increase turbulence and disrupt thermal boundary layers; Nusselt number significantly enhanced with moderate pressure drop; importance of hole size and spacing highlighted	Limited to circular fins; pressure drop effects need careful design
[2]	Effect of tube geometry on heat transfer in tube-in-fin heat exchangers	Asymmetric tube cross-sections induce flow separation and secondary vortices, enhancing heat transfer; geometric modification needed	Higher pressure drop; complex tube shapes may increase fabrication cost
[3]	Use of turbulators as passive heat transfer enhancement	Turbulators increase turbulence, raising heat transfer coefficients despite higher friction	Friction factor increase; performance depends on placement and design
[4]	Review of compact fin-and-tube heat exchangers	Fin geometry, flow behavior, pressure drop, and fouling are key performance factors; critical for automotive and HVAC applications	Mainly a review; no experimental validation
[5]	Nanofluid-enhanced heat transfer with staggered cylinder arrangements	Heat transfer significantly improved; increased nanoparticle concentration increases pumping pressure	Higher viscosity and pumping cost at high nanoparticle loads
[6]	Perforated twisted tape with V-cut profiles	Swirl flow enhances heat transfer; double-cut performs better than single-cut with moderate flow resistance	Friction factor still present; optimal cut design needed
[7]	Geometric modifications in impingement heat transfer (nozzle shapes, surface features)	Enhanced turbulence and heat transfer, useful for cryogenic cooling	Specific to impingement zones; design complexity
[8,9]	Novel baffle geometries (flower-shaped, corrugated)	Increase flow mixing, secondary vortices, and heat transfer; pressure drop acceptable	May require complex manufacturing; pressure drop management
[10]	Perforated micro pin-fin heat sinks	Reduced hydraulic resistance, high heat transfer coefficients; beneficial for electronics cooling	Limited to microchannel applications; optimization of perforation required
[11]	Nanofluids with turbulators	Synergistic enhancement of heat transfer; friction increased	Friction penalty; requires careful design
[12]	Microchannel heat sinks with fin structures	Improved fluid mixing, higher heat transfer; modest pressure drop	Design optimization needed for different configurations
[13]	Baffle arrangement in circular channels	Staggered baffles enhance turbulence and heat transfer; inline baffles less effective	Increased pressure losses; baffle placement critical

[14]	Twisted fins in rectangular channels	Swirls and secondary flows enhance heat transfer; orientation and twist ratio critical	Increased pressure drop; requires optimization
[15]	AI prediction (ANN) for solar air-heater performance	Accurate thermal performance prediction; reduced computational cost	Model dependent on training data quality
[16]	Dimpled twisted tape inserts	Increased turbulence and heat transfer; higher overall efficiency	Friction factor rises; requires surface modification
[17]	Corrugated tubes in shell-and-tube exchangers	Enhanced surface area and flow disturbance; improved thermal efficiency	Pressure drop penalty; fabrication complexity
[18]	Nanofluid-based heat exchangers	Improved heat transfer due to higher thermal conductivity	Challenges with viscosity, stability, and pumping
[19]	Structural analysis of perforated circular plates	Optimal perforation reduces stress concentration; maintains mechanical integrity	Focuses on structural aspects; does not consider full thermal performance
[20]	Natural convection from solid, hollow, and perforated pin fins	Perforated/hollow fins outperform solid fins; better thermal performance, reduced thermal resistance	Mainly natural convection; may differ under forced convection conditions

V. THERMO-HYDRAULIC PERFORMANCE ANALYSIS

Thermo-hydraulic performance embodies the comprehensive evaluation of heat and mass transfer enhancement with regard to hydrodynamic displacement elements, disturbance devices for flow breaking, fins, turbines, blades, or excursiveness, and butterflies. The design optimization of perforation patterns, fin geometries, and flow-disrupting elements envisages much higher thermal efficiency easily at reduced hydraulic losses [18. The perforated fin, twisted tapes, and baffles have, from both numerical and experimental studies, shown some considerable effects in the flow behavior; turbulence intensity; and thermal boundary layer disruption. In the very event that perforated circular fins and pin-fin arrays offer relatively increased turbulence and thus the potential of a higher Nusselt number, the corresponding pressure drop is made only high enough. Again, staggered tubes and corrugations and flowers of baffles, for example, generate much more secondary flows and considerable mixing, thus increasing heat transfer rates [19]. The use of nanofluids also increases the thermo-hydrauilc performance by increasing fluid thermal conductivity but adds to the pumping requirement in most cases. Performance evaluation is mostly carried out based on the Performance Evaluation Criterion (PEC), which combines the Nusselt number relation and friction factor relationship as an overall measuring yardstick for enhancement efficacy. The whole thermo-hydraulic compromise depends critically on perforation size, shape, orientation, and array configuration. The aim of optimized design lies in utilizing the maximum in heat transfer with minimal pressure drop across devices, thereby guaranteeing efficient utilization of energy and considerably increasing the equipment life cycle, especially in applications ranging from electronic cooling to HVAC and renewable energy systems.

VI. MACHINE LEARNING AND OPTIMIZATION APPROACHES

Studies (experimental and numerical) conducted toward novel geometry of perforations and ribs have indicated their promising potential for augmenting heat exchanger efficiency. Contrarily, arc-shaped ribs uhder solar air heating appeared to induce high fluid turbulence with increased flow mixing and hence raised Nusselt number significantly leading to enhanced overall heat transfer [21]. The design of the perforations on which fins applied thermal performance implications, wherein the optimality concerning the size, be heavy and placement of square perforations can maximize the convective heat transfer while, in the meanwhile, limiting pressure drop losses [22]. Perforated anchors in nanofluid flows within tubes demonstrated that perforated anchors within tubes succeeded in promoting in dropping unfavorable effects on heat transfer rate (that they happened to create in terms of turbulence) and the secondary flow, whereas only moderate friction pressure drop is incurred [23]. Investigation of diverging perforated cones within heat exchanger tubes evaluated their effects on the thermal-hydraulic characteristics. Results showed that the diverging design directed swirling flow intensification, thus up the heat transfer, while causing low pressure loss penalties [24].

The use of twisted tapes with curved profiles as a passive heat transfer augmenter induces swirl flow development and boundary layer disruption, ultimately enhancing the thermal performance over a wide range of Reynolds numbers [25]. Furthermore, optimization of hole and dimple placement in the twisted tape study revealed very specific orientations could dictate the effectiveness on heat transfer and the accompanying pressure losses, and design geometries must be made with particular considerations of practical field performance [26]. Three-dimensional studies could be carried out on perforated plates with the intention that the hole diameter, pitch, and orientation could govern performance and minimization of friction loss [27]. In principle, a combination of secondary flow paths in rectangular winglet VGs and the novel approach of additional circular punched holes changed the concept of convective heat transfer enhancement in fin-tube configurations by spawning more formed vortices [28]. Germination of dual twisted tapes in a double tube heat exchange system which works with both active and passive reinforcements did not disappoint. Even more, these mixed attack patterns of dual twisted tapes-shaped passive approaches could be majorly switchees for improved heat transfer with acceptable pressure losses [29]. Finally and essentially, it can be said that baffle geometry and orientation in rectangular channels will largely dictate turbulence initiation and flow redistribution. "Well-aligned fins with less vertical walls" really augmented in increasing secondary flow and mixing, hence higher Nusselt numbers, while retaining acceptable friction factors [30].

VI. CONCLUSION AND FUTURE WORK

This review highlights the significant potential of optimized perforation patterns and geometric modifications in enhancing the thermo-hydraulic performance of heat exchangers. Many researchers have conducted a few studies, showing that increased throughputs, perforated fins, twisted tapes, and baffles created greater turbulence, destroyed thermal boundary layers, and formed secondary flows, all of which effectively increase heat transfer. Simulations and experiments suggest that the size, shape, pitch, and orientation of perforations screwsly affect the trade-off between heat transfer augmentation and pressure drop. Passive devices, including turbulators or baffles, have shown great results in enhancing the heat transfer without requiring additional energy input. The integration of nanoparticles with geometric modifications adds up to improved thermal performance, albeit introducing additional considerations in terms of higher viscosity and more pumping power. Advanced computational methods, such as artificial intelligence and machine learning, would considerably aid heat transfer predictions, design optimization, and reduction in experiment time. Though commendable progress has been made, more challenges still come along. It remains to further explore various perforation designs, different techniques' interaction characteristics, and heat-transfer-vs-pressure-loss implications. Investigate the implications of long-term operational phenomena, fouling, and material limitations in the context of perforated structures. Indeed, the prospect of future research should dwell on the assimilation of active and passive techniques with perforation patterns, whereby nanofluids are also introduced, along with machine-learning-aided optimization, to inherently take shape into smaller and quite efficient heat exchangers viable for diverse applications including industrial, HVAC, and renewable energies. The experimental realization of numerical evaluation while defining standardized design guidelines is highly required so as to put forth potential activities for these heat transfer-enhancement strategies.

REFERENCES

[1] Rai, Ankur, Sushant S. Bhuvad, and R. M. Sarviya. "Enhancement of Heat Transfer in Perforated Circular Finned-Tube Heat Exchangers: A Numerical Investigation." *Journal of Physics: Conference Series*. Vol. 1473. No. 1. IOP Publishing, 2020.

[2] Djeffal, Fares, et al. "Numerical investigation of thermal-flow characteristics in heat exchanger with various tube shapes." *Applied Sciences* 11.20 (2021): 9477.

[3] Çelık, Hamdi Selçuk, and L. Berrin Erbay. "Heat transfer enhancement using different types of turbulators on the heat exchangers." *Journal of Thermal Engineering* 7.7 (2021): 1654-1670.

[4] Adam, A. Y., et al. "State of the art on flow and heat transfer performance of compact fin-and-tube heat exchangers." *Journal of Thermal Analysis and Calorimetry* 139.4 (2020): 2739-2768.

[5] Asif, Mohd, Rashi Chaturvedi, and Amit Dhiman. "Heat transfer enhancement from inline and staggered arrays of cylinders in a heat exchanger using alumina–water nanofluid." *Journal of Thermal Science and Engineering Applications* 13.4 (2021): 041025.

[6] Kumar, Bipin, et al. "Performance enhancement by perforated twisted tape tube insert with single and double v cuts in a heat exchanger tube." *Heat Transfer Research* 51.5 (2020).

[7] Dutta, Sandip, and Prashant Singh. "Impingement heat transfer innovations and enhancements: A Discussion on selected geometrical features." *Turbo Expo: Power for Land, Sea, and Air*. Vol. 84980. American Society of Mechanical Engineers, 2021.

[8] Sahel, Djamel. "Thermal performance assessment of a tubular heat exchanger fitted with flower baffles." *Journal of Thermophysics and Heat Transfer* 35.4 (2021): 726-734.

[9] Ameur, Houari. "Effect of corrugated baffles on the flow and thermal fields in a channel heat exchanger." *Journal of Applied and Computational Mechanics* 6.2 (2020): 209-218.

[10] Gupta, Deepa, Probir Saha, and Somnath Roy. "Computational analysis of perforation effect on the thermo-hydraulic performance of micro pin-fin heat sink." *International Journal of Thermal Sciences* 163 (2021): 106857.

[11] Bashtani, Iman, Javad Abolfazli Esfahani, and Kyung Chun Kim. "Effects of water-aluminum oxide nanofluid on double pipe heat exchanger with gear disc turbulators: A numerical investigation." *Journal of the Taiwan Institute of Chemical Engineers* 124 (2021): 63-74.

[12] Yan, Yunfei, et al. "Numerical investigation on the characteristics of flow and heat transfer enhancement by micro pin-fin array heat sink with fin-shaped strips." *Chemical Engineering and Processing-Process Intensification* 160 (2021): 108273.

[13] Al Nuwairan, M., and B. Souayeh. "Augmentation of Heat Transfer in a Circular Channel with Inline and Staggered Baffles. Energies 2021, 14, 8593." 2021,

[14] Maouedj, Rachid, and Ahmed Youcef. "Impact of Twisted Fins on the Overall Performances of a Rectangular-Channel Air-Heat Exchanger." *Mathematical Modelling of Engineering Problems* 7.3 (2020).

[15] Bhattacharyya, Suvanjan, et al. "Application of new artificial neural network to predict heat transfer and thermal performance of a solar air-heater tube." *Sustainability* 13.13 (2021): 7477.

[16] Singh, Sanjay Kumar, and Arvind Kumar. "Experimental study of heat transfer enhancement from dimpled twisted tape in double pipe heat exchanger." *Int. J. Mech. Prod. Eng. Res. Dev* 10.1 (2020): 469-482.

[17] Navickaitė, Kristina, et al. "Performance assessment of double corrugated tubes in a tube-in-shell heat exchanger." *Energies* 14.5 (2021): 1343.

[18] Li, Zhixiong, et al. *Nanofluid in Heat Exchangers for Mechanical Systems: Numerical Simulation*. Elsevier, 2020.

[19] Albayrak, Uğur. "Stress and displacement analysis of perforated circular plates Mustafa Halûk Saraçoğlu." *CHALLENGE* 6.3 (2020): 150-159.

[20] Mousa, A. M. "Numerical study of natural convection heat transfer from a horizontal plate using solid, hollow and hollow/perforated pin fins." *Nile Journal of Basic Science* 1.1 (2021): 35-48.

[21] Kazemi Moghadam, Hamid, Seyed Soheil Mousavi Ajarostaghi, and Sébastien Poncet. "Numerical modeling of an innovative arc shape rib based solar air heater." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 235.24 (2021): 7992-8012.

[22] Ibrahim, Thamir K., et al. "The impact of square shape perforations on the enhanced heat transfer from fins: Experimental and numerical study." *International Journal of Thermal Sciences* 149 (2020): 106144.

[23] Adibi, Omid, Saman Rashidi, and Javad Abolfazli Esfahani. "Effects of perforated anchors on heat transfer intensification of turbulence nanofluid flow in a pipe." *Journal of Thermal Analysis & Calorimetry* 141.5 (2020).

[24] Srivastava, Gaurav Prakash, Anil Kumar Patil, and Manoj Kumar. "Parametric effect of diverging perforated cones on the thermo-hydraulic performance of a heat exchanger tube." *Heat and Mass Transfer* 57.9 (2021): 1425-1437.

[25] Outokesh, Masoud, et al. "Numerical evaluation of the effect of utilizing twisted tape with curved profile as a turbulator on heat transfer enhancement in a pipe." *Journal of Thermal Analysis and Calorimetry* 140.3 (2020): 1537-1553.

[26] Dagdevir, Toygun, Mahmut Uyanik, and Veysel Ozceyhan. "The experimental thermal and hydraulic performance analyses for the location of perforations and dimples on the twisted tapes in twisted tape inserted tube." *International Journal of Thermal Sciences* 167 (2021): 107033.

[27] Xu, Xiaogang, et al. "3D numerical investigation of energy transfer and loss of cavitation flow in perforated plates." *Engineering Applications of Computational Fluid Mechanics* 14.1 (2020): 1095-1105.

[28] Modi, Ashish J., Navnath A. Kalel, and Manish K. Rathod. "Thermal performance augmentation of fin-and-tube heat exchanger using rectangular winglet vortex generators having circular punched holes." *International Journal of Heat and Mass Transfer* 158 (2020): 119724.

[29] Pourahmad, Saman, et al. "Experimental study of heat transfer and pressure drop analysis of the air/water two-phase flow in a double tube heat exchanger equipped with dual twisted tape turbulator: Simultaneous usage of active and passive methods." *Journal of Energy Storage* 44 (2021): 103408.

[30] Menni, Younes, et al. "Baffle orientation and geometry effects on turbulent heat transfer of a constant property incompressible fluid flow inside a rectangular channel." *International Journal of Numerical Methods for Heat & Fluid Flow* 30.6 (2020): 3027-3052.