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Strategies For Boosting Heat Exchanger Efficiency: A Thorough Review

Sunil Shinde[1], Rajkumar Bhagat[2], Atharv Kadam[3*], Om Kadam[4], Rudra Joshi[5], Harshit Rathore[6], Neeraj Kadam[7]

[1]*Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, India – 411 037, sunil.shinde@vit.edu*
[2]*Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, India – 411 037, rajkumar.bhagat@vit.edu*
[3*]*Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, India – 411 037, atharv.kadam21@vit.edu*
[4]*Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, India – 411 037, om.kadam21@vit.edu*
[5]*Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, India – 411 037, rudra.joshi21@vit.edu*
[6]*Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, India – 411 037, rathore.harshit21@vit.edu*
[7]*Department of Chemical Engineering, Vishwakarma Institute of Technology, Pune, India – 411 037, neeraj.kadam21@vit.edu*

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ABSTRACT

Economic losses stemming from compromised heat exchanger performance underscore the urgency of enhancing their efficiency. This paper investigates diverse methodologies to bolster heat exchanger performance, focusing on advanced surface geometries, coatings, and other techniques. Our methodology involves a comprehensive review of existing research literature. Analysis reveals that optimizing geometrics, manufacturing methods, and surface texturing significantly enhance heat exchanger efficiency, offering promising avenues for industry improvement.

Keywords— Additive Manufacturing, Micro Channeling, Surface Texturing, Topology Optimization.

I. INTRODUCTION

In the intricate web of industrial processes, the role of heat exchangers stands paramount. These devices act as the unsung heroes, facilitating the seamless transfer of thermal energy between fluids, driving the efficiency of countless applications from power generation to HVAC systems. At their core, heat exchangers operate on the fundamental principle of exchanging heat to optimize temperature differentials, ensuring the smooth flow of energy within diverse engineering systems

Despite their ubiquitous presence and pivotal role, heat exchangers are not immune to challenges that compromise their efficiency. One major challenge they face is the gradual buildup of scale on their surfaces, which greatly adds to energy wastage. Scale, often originating from the deposition of minerals and impurities in the circulating fluids, acts as an insulating layer, hindering the efficient transfer of heat.

The repercussions of energy losses in heat exchangers extend beyond mere operational inefficiency; they reverberate through economic channels. Increased energy consumption and elevated operational costs become the unintended consequences, compelling industries to seek innovative solutions that not only mitigate the impact of scale formation but also elevate the overall performance of heat exchangers.

This research embarks on a comprehensive review of advanced methodologies aimed at addressing the intricate challenge of energy loss in heat exchangers.

The journey begins with an examination of geometric enhancements, specifically the utilization of microchannels and fins. These innovations promise optimized heat transfer, disrupting the conventional limitations imposed by scale formation.

The examination of leading-edge technologies like 3D printing and topology optimization will be undertaken to assess their impact on transforming the design framework of heat exchangers. Beyond that, we will unravel the promises held by micro and nano texturing, evaluating their efficacy in minimizing scale formation and enhancing overall heat transfer efficiency.

By navigating the terrain of cutting-edge surface geometry, coatings, and transformative design techniques, this review seeks to offer an all-encompassing comprehension of the cutting-edge tactics at the disposal of researchers and engineers. By illuminating these pathways, we aim to contribute to the collective knowledge that propels the evolution of heat exchanger technologies, fostering a future where energy losses are minimized, and efficiency is maximized.

II. LITERATURE REVIEW

The literature review section of our research paper delves into a comprehensive analysis of existing studies aimed at enhancing the efficiency of heat exchangers. This critical review encompasses a range of research papers exploring diverse avenues for improvement, including investigations into geometry optimization, such as microchannels, innovative fin designs, advancements in 3D printing techniques, and surface texturing methodologies.

The use of microchannel heat exchangers has been shown to significantly enhance the performance of thermally activated cooling systems, with Wang et al. [1] reporting improved heat transfer effectiveness and overall system efficiency. However, the selection of microchannel geometry is crucial, as improper selection can lead to various losses B. Dash et al. [2]. Wilson et al. [3] discussion of modifying a ceramic heat exchanger’s microchannel characteristic to boost thermal performance while preserving minimal pressure drops emphasizes this point even further. Chandratilleke et al. [4] introduces a novel technique using pulsating cross-flow synthetic jets for thermal enhancement in microchannels, which significantly increases heat dissipation without increasing flow pressure drop. These studies collectively highlight the potential of microchannel heat exchangers in enhancing heat transfer performance.

The use of fins in heat exchangers for performance enhancement has been extensively studied. Huisseune et al. [5] found that the addition of delta winglet vortex generators to louvered fins can significantly improve heat transfer, despite increasing core pressure drop. Zoman et al. [6] and Maji et al. [7] both reviewed the use of perforated and other types of fins, respectively, for heat transfer enhancement, with both studies highlighting the potential for improved performance. Dandotiya et al. [8] focused on the design of a PCM-based multitube heat exchanger, emphasizing the importance of fin placement for optimal performance. These studies collectively demonstrate the potential of fins in enhancing heat exchanger performance.

The application of coatings to improve heat exchanger efficiency has been the subject of numerous investigations. Bonanno et al. [9] and Elagina et al. [10] both found that nanostructured and capillary-porous coatings, respectively, can improve heat transfer and emission efficiency. Mironov et al. [11] specifically focuses on aircraft heat exchangers, proposing the use of dimpled heat exchange surfaces to improve efficiency. These studies collectively highlight the potential of coatings to enhance heat exchanger performance. Caprì et al. [12] reviewed the use of innovative adsorbent coatings to increase the achievable heating/cooling power density in adsorption heat pumps. These studies collectively highlight the potential of coatings to improve the efficiency of heat exchangers in various applications.

The use of 3D printing in heat exchangers has been shown to enhance their performance. Fontana et al. [13] found that 3D printed polymeric heat exchangers, particularly those made with Grafylon filament, demonstrated improved thermal performance. Similarly, Rastan et al. [14] reported that 3D printed mini channel heat exchangers with longitudinal vortex generators exhibited enhanced convective heat transfer. These findings were further supported by Felber et al. [15], who designed and tested an air-cooled heat exchanger with 3D printed air channels and pin fins, and found that the performance matched the model's predictions. These studies collectively highlight the potential of 3D printing in improving the thermal performance of heat exchangers.

The optimization of topology has been investigated as a way to improve heat exchanger efficiency. The application of this technique was examined by Papazoglou et al. [16] and Feppon et al. [17], wherein Feppon concentrated on fluid-to-fluid heat exchangers and Papazoglou on a two-flow heat exchanger. Both studies found that topology optimization can lead to improved heat transfer and reduced pressure drop. Pan et al. [18] developed an optimization method for retrofitting large-scale heat exchanger networks, which could potentially incorporate topology optimization. Topology optimization was used in the design of air-cooled

heat exchangers by Haertel et al. [19], indicating its potential to improve performance in certain applications. These studies collectively suggest that topology optimization can be a valuable tool for increasing the efficiency of heat exchangers.
Heat exchanger efficiency can be greatly increased by texturing, according to research. The use of improved types of discrete roughness and irregular grid sizes, respectively, to increase heat transfer surface area and improve heat transfer is covered by Fugmann et al. [20] and Olimpiev et al. [21]. Charate et al. [22] provides a comprehensive review of various methods for enhancing heat transfer in heat exchangers, including the use of augmented surfaces and enhanced heat transfer. These studies collectively highlight the potential of texturing in improving the performance of heat exchangers.

III. Methodologies implemented by various researchers

(1) Verification by 3D Printing Technology:

A thorough analysis of the effectiveness of using 3D printing technology to optimize heat flow dynamics was provided by Rubeis et al. [23]. By means of thorough investigation and testing, their study demonstrated a significant improvement in thermal efficiency.

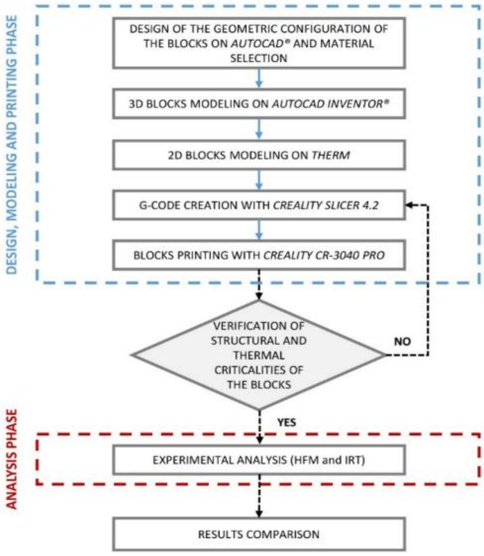

Figure 1. Methodology flowchart representing the various work phases.

The study's two major objectives are to: (i) investigate the potential of 3D printing technology to produce ever-more complex forms; and (ii) examine the effects of various internal geometries on heat transmission mechanisms by analyzing 3D-printed blocks.

Block design, modelling, and production represent the initial stage. Initially, the blocks were created with the printer's size limitations in mind, with dimensions of 300 × 300 × 400 mm. The dimensions (width × height × depth) of the three 3D CAD models, which were made with AutoCAD Inventor ®, were the same at 250 × 250 × 100 mm. Then, three distinct interior structures with air chambers were drawn: a multi-row structure, a square structure, and a honeycomb structure.

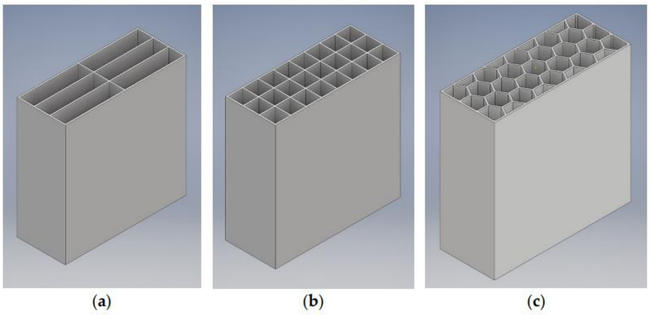

Figure 2. 3D Models of the block (a) Mult-row structure. (b) Square structure. (c) Honeycomb structure.

Heat transport simulation models were run using THERM software to do a theoretical analysis of the blocks. In particular, the finite element method was used to concentrate on the two-dimensional heat transmission via building components. The results of the THERM simulations are as follows:

Table 1. Results obtained from THERM simulations

Block Type	Transmittance [W/m^{2}K]
Multi-row block	1.52
Square structure block	1.29
Honeycomb structure block	1.23

After that, all printing properties were specified through the creation of G-codes using the Creality Slicer 4.2 program. Because of its exceptional qualities, biodegradability, affordability, and compatibility with the FDM printing process, polylactic acid (PLA) was selected as the printing material. The material (PLA) utilized for printing has a filament diameter of 1.75 mm and a printing temperature of 200–225 ◦C.

The examination of the blocks' thermal performance is the main emphasis of the second stage. Using the infrared thermography (IRT) methodology and the heat flux meter (HFM) approach, an experimental investigation was carried out. He created the blocks. Since PLA was chosen for block printing and its thermophysical qualities were not included in the software library, PLA's thermal characteristics had to be manually entered.

The table provides a summary of the findings from each block's HFM experimental campaigns.

Table 2. Results of the HFM experiment where conductance (Λ), and transmittance (U)

Block Type	Test 1		Test 2		Test 3	
	Λ	U	Λ	U	Λ	U
Multi-row	1.94 ± 0.05	1.46 ± 0.05	1.89 ± 0.05	1.43 ± 0.05	1.89 ± 0.05	1.43 ± 0.05
Square structure	1.66 ± 0.04	1.30 ± 0.04	1.58 ± 0.04	1.25 ± 0.04	1.58 ± 0.04	1.25 ± 0.04
Honeycomb structure	1.55 ± 0.04	1.22 ± 0.04	1.54 ± 0.04	1.22 ± 0.04	1.53 ± 0.04	1.22 ± 0.04

The primary conclusions demonstrated a correlation between higher internal geometric complexity of the blocks and better thermal performance. As a matter of fact, the honeycomb structure block performed the best, attaining a thermal transmittance of 1.22 W/m^{2}K, 14.7% less than the simpler multi-row block. The honeycomb construction block fared better still when it came to thermal stratification, which was measured using the IRT technique on the outside of the blocks.

Innovative technology like 3D printing gives designers a great deal of creative freedom. Through the incorporation of biomimetic architecture concepts into sustainable designs, complex geometric structures that would be impossible to construct using traditional means can now be achieved. The potential for investigating ways to enhance building thermal performance is extremely fascinating due to the versatility of forms that can be produced through 3D printing. The disadvantages of utilizing 3D printing to make thermal insulation blocks must be understood, though; these primarily have to do with printing time and size constraints.

(2) Verification by Topology Optimization:

The goal of Høghøj et al. research study [24] is to suggest a technique for optimizing the topology of heat exchangers with two fluids using density-based methods. The goal is to transfer as much heat as possible between the fluids while respecting the maximum pressure drop limitations for each fluid flow. The methodology uses a stabilized finite element discretization to solve the governing equations, a single design variable to model the physical fields, and erosion-dilation identification procedures to guarantee well-separated fluids and a minimum wall thickness between them. This method is utilized in two numerical instances: a two-dimensional counter-flow heat exchanger and a three-dimensional shell-and-tube heat exchanger, showcasing and validating the methodology.

In the scenario of a two-dimensional counter-flow, the optimization findings indicated that as the permissible pressure drop was raised, the channels narrowed, resulting in a rise in the heat transfer coefficient. The optimized configurations for both original designs exhibited enhanced heat transfer performance in contrast to the baseline designs, achieving improvements of up to 113% while maintaining the same pressure drop. With a heat transfer improvement of up to 113%, the optimized designs in the three-dimensional shell-and-tube heat exchanger example showed notable improvements over the baseline designs. The optimized designs featured complex geometrical elements that improved the surface area and the heat transfer. The results showed that the original design and the flow field in the early design iterations had a significant impact on the final design.

It is possible to conclude that the use of topology optimization improved the heat exchangers' performance based on the data in the research report. The optimized designs demonstrated significant improvements in heat transfer compared to the baseline designs in both the two-dimensional counter-flow example and the three-dimensional shell-and-tube heat exchanger example. The heat exchanger's performance was enhanced by up to 113% in the optimized designs when pressure drops were the same, confirming the efficacy of the suggested topology optimization methods.

(3) Verification by Surface Texturing:

The study by Ghahramani et al. [25] aimed to investigate the impact of laser texturing on the efficiency of a heat exchanger in both laminar and turbulent flow regimes. The researchers used a combination of surface imaging, laser machining, and calculations of heat exchanger parameters to assess the influence of the textured surface on heat transfer characteristics. To compare the heat transfer efficiency, two plate-type heat exchangers were manufactured with identical dimensions, one with smooth plates and the other with textured plates. The heat exchangers were tested in two separate days at two flow rates to obtain accurate results due to possible environmental effects.

The results indicated that the surface texture created by laser ablation slightly deteriorated the mean temperature efficiency and heat transfer coefficient for laminar flow due to the increase in roughness of the plates. In turbulent flow, a small improvement in the mean temperature efficiency and heat transfer coefficient was observed for the textured heat exchanger, but the improvement was not significant. The researchers also found that the laser ablation process caused oxidation of the plates and distortion of the metal, which may have influenced the results.

The performance comparison before and after laser texturing of the heat exchanger showed that the surface texture had a limited impact on the heat transfer efficiency. In laminar flow conditions, the surface texture resulted in a slight degradation of the heat transfer rate, whereas in turbulent flow, only a marginal enhancement in the heat transfer rate was noted.

Overall, the study did not demonstrate a substantial improvement in the efficiency of the heat exchanger as a result of laser texturing. The study concluded that further refinement of the surface condition and geometry is necessary to determine if significantly higher heat transfer efficiencies can be achieved through laser texturing. Therefore, based on the results provided in the document, the laser texturing did not significantly improve the efficiency of the heat exchanger.

(4) Verification by Micro Channeling:

Xia et al. study [26] investigates the improved heat transmission phenomenon in micro-scale channels. Examining and documenting the improved heat transfer impact in micro-sized channels is the aim of this research article. The work specifically attempts to develop a computational fluid dynamics (CFD) simulation model to investigate the heat transfer effect in micro channels. The study also suggests a better heat exchanger design based on the micro-effects noted.

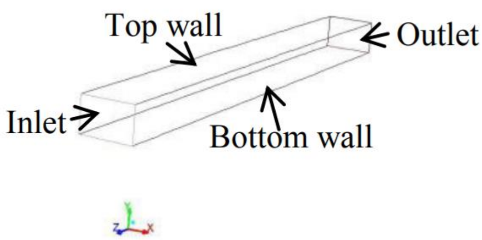

Figure 3. Geometry set-up of the channel

The investigators developed a simulation model for examining the heat transfer effect in micro-sized channels using computational fluid dynamics (CFD). Using ANSYS Fluent's Design Modeler, they generated a geometric model of the micro channel and set boundary conditions for the channel walls, inlet, and outflow. In the simulation, momentum transport was modelled using the conventional k-ε model and the continuity, momentum, and energy conservation equations were solved. Next, in order to investigate the impact of size on heat transfer, the researchers changed the microchannel's cross-sectional area. In order to comprehend how the intake area affects heat transfer and pressure loss, the results were examined, and a new heat exchanger design using micro-channel bundles was suggested in light of the findings.

Table 3. Changes in the cross-sectional area of the microchannel

No.	Length (μm)	Width (μm)	Area (μm^2)	Ratio of heat transfer area to volume (μm^{-1})
1	3	2	6	0.5
2	6	4	24	0.25
3	12	8	96	0.125
4	18	12	216	0.0833
5	24	16	384	0.0625
6	30	20	600	0.05

The study findings suggest that as channel inlet area decreases, the temperature of the air flowing through the microchannel decreases at a faster rate. This suggests that the heat transfer ability is stronger in micro-sized channels with smaller inlet areas. Additionally, the study showed that the heat transfer rate per unit effective heat transfer area improves as the inlet area reduces, suggesting that smaller inlet areas improve heat transfer efficiency.

The advantage of employing micro channeling, which offers better heat transfer rates, is the potential to reduce the overall length of the heat exchanger to 26.8% of its original size.

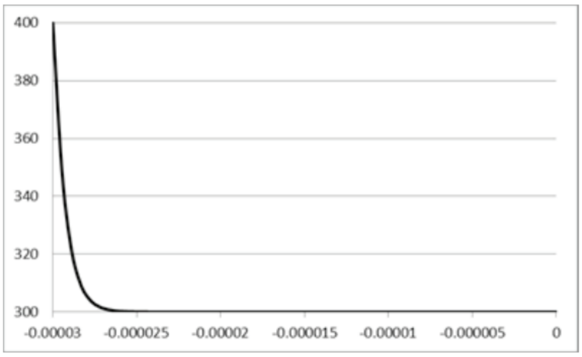

Figure 4. Temperature distribution for inlet area of 3×2 μm^2

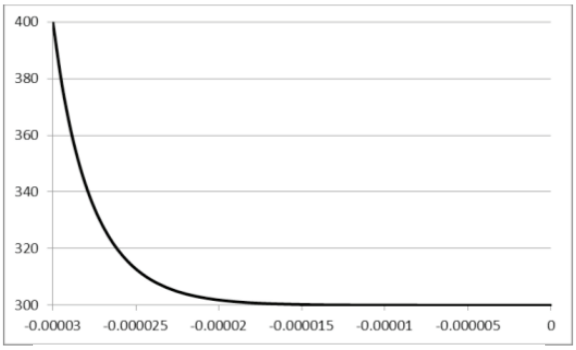

Figure 5. Temperature distribution for inlet area of 12×8 μm^2

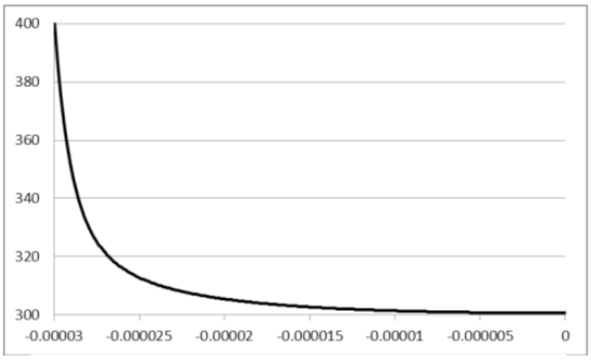

Figure 6. Temperature distribution for inlet area of 30×20 μm²

Based on these results, the researchers proposed a new design for a heat exchanger that embeds micro-sized channels, which is expected to improve efficiency of heat transfer.

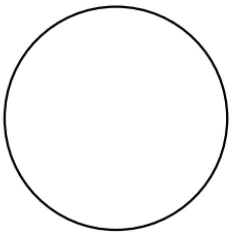

Figure 7. Heat exchanger tube of regular size

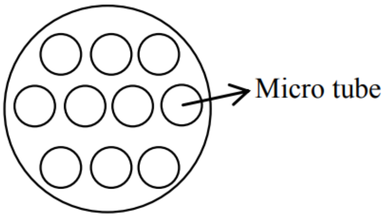

Figure 8. Heat exchanger tube of regular size tube including numerous micro tubes

Overall, the demonstrates the benefits of using micro channels with smaller inlet areas in terms of enhanced heat transfer and reduced pressure loss, and it provides insights for the design of more efficient heat exchangers.

IV. Conclusion

The paper undertakes a critical review of diverse methods aimed at enhancing the efficiency of heat exchangers. Key findings are highlighted below:

1. Geometry optimization, particularly through micro-channeling, emerges as a promising avenue for improving efficiency.
2. Introduction of fins presents another effective method for enhancing heat exchanger performance.
3. Coatings show potential for increasing efficiency by mitigating heat transfer losses.
4. Utilizing 3D printing techniques offers novel possibilities for optimizing heat exchanger design and efficiency.
5. Topology optimization proves to be a valuable approach in maximizing heat exchanger performance.
6. Nano, micro, and laser texturing demonstrate significant potential in enhancing heat transfer characteristics and improving overall efficiency.

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