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Research Article

Integrating Machine Learning Algorithms for Performance Enhancement and Thermal Efficiency Optimization in Finned Heat Transfer Systems

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ABSTRACT

Persuasive thermal control is essential for optimizing device adaptation, prolonging product span, preserving energy, conserving the ambient and evading thermal issues. The information over demonstrates the worth of analyzing methods that promote energy transfer, like pin fins. A common amiable cooling approach that can be used to enrich the effectiveness of energy transfer in a variety of applications is pin fins. These consist of turbine cooling, microchannel cooling, and SAH ducting. Pin-fins have been demonstrated to significantly reduce pressure and transfer heat in these systems, highlighting their efficacy. Improving flow structure, pressure drop reduction, and heat transfer mechanisms all depend on pin-fin designs and combinations being optimized. This paper focuses to severely assess the form of survey on pin fins and examine their thermic interpretation in compensating heat transmission, energy utilization, and apparatus effectiveness with respect to different pin-fin forms and configurations. The current study will examine the impingement of distinct pin-fin shapes on the collective system interpretation in order to assist the research community in creating cooling systems that are more effective and efficient. Moreover, this paper proceeds beyond a simple summary by closely interrogating the advantages and disadvantages of diverse pin-fin designs and their implications on distinct flow types and energy-transfer techniques. Using AI techniques to optimize ducting, random forest showed optimum duct length of 207.69 mm, width of 67.12 mm and height of duct 17.26mm with accuracy of 81.86%,57.12% and 86.37% respectively. This work improves the development of thermic operation tactics for acceptable and sustainable energy sources by critically analyzing the existing literature and identifying areas that need more research.

Keywords: Heat Transfer, Fins, Thermal performance, Machine learning.

INTRODUCTION

Equipment for high-performance heat transfer is required for advanced technologies. Active and passive methods are two categories in which techniques for increasing the rate of heat transmission are divided. From a design perspective, proactive techniques need more power, which makes them complicated. The input needed to enrich the energy transfer rate and make the appropriate flow adjustments limits the applications. Conversely, passive approaches require the addition of more devices and surface or geometric changes to the flow path. Furthermore, this technique promotes better heat transfer coefficients through changing or interfering with the current flow behaviour (apart from the expanded surfaces), which also causes the pressure drop to rise. An object's capacity to transmit heat is indicated by its radiation, convection, and conduction rates. The rate of energy transfer increased as the temperature raised. either by boosting the body's surface area, optimizing the contrast between the object and its surrounding, or raising the convective energy transmission coefficient. Sometimes it doesn't alter the first two choices, which are either reasonable or economical. Nevertheless, adding a fin to a absorber improves its contact area, which in some circumstances is a economical solution to problems with heat transmission. Two passive methods that are often employed in different industrial applications to improve energy transmission between the major heat sink and the surrounding fluid are fins and expanded surfaces. The expansion of heavy industries has led to a sharp increase in energy need. It is essential to have easy access to energy, and the conventional method of obtaining this energy through the burning of fossil fuels has severely damaged the environment. Furthermore, a serious threat to civilization is the exhaustion of finite energy supplies and rapid climate change. Finding sustainable and renewable alternatives is essential to address these issues because it may lessen our dependency on fossil fuels and lessen the associated adverse effects on the environment [1]. Several nations across the world have implemented different policies and plans to mitigate the consequences of atmospheric change. Australia is among the country that release the most greenhouse gases per person worldwide as a result of the harsh consequences of atmosphere change, and extreme atmospheric conditions. This dedication is essential for defending the economy, society, and environment, as well as for assisting international works to slow global warming [2]. Achieving optimal heat transfer enhancement capabilities through the evolution of incredibly efficient heat exchanger technology might be beneficial for fulfilling the requirements of contemporary energy systems. For example, the application of channel-based cooling systems has resulted in a terrific raise in heat dissipation. Energy efficacy and thermal control, research has found a major new focus in channel-based cooling methods [3].

The growth in technologies for extremely small heat transfer devices [7–9] and improved heat degradation (as illustrated in Fig. 1) [4-6] have both been made possible by the employ of narrow channels for energy transfer in convective mode. Applications include electronic cooling systems, gas turbines, and solar-air heaters. When employing zero-carbon fuels to stabilize the electrical system, gas turbines are essential. Evolved of high temperatures, however, lead to failure of material and necessitate effective cooling of the blades and vanes, especially when hydrogen fuel is used [13]. Efficient thermal control of blade-cooling mechanisms and energy transfer breakthrough system is necessary for well-functioning, as showed in Fig. 1(a) [14]. Solar energy is becoming increasingly important and can be used in many applications. The use of solar radiation to heat liquids is a practical and affordable solution for flat-plate solar collectors. SAH are suitable for applications that need typical temperatures, like crop drying, room heating, commercial HVAC systems, and the fabric industry [15]. According to Fig. 1. (b), SAH are appropriate for a variety of applications that need moderate temperatures, including chamber heating, crop drying, commercial HVAC systems, and the fabric industry. They have a straightforward channel strategy with a duct design that transforms solar irradiation [15]. To modify solar radiation into thermal energy, air heaters include a common channel design with a collector (Fig. 1). (b). Typical SAH, which have minimum thermal efficacy due to limited convective energy transmission, can have their heat transfer coefficient raised by roughened surfaces [16]. Energy efficacy and preservation have been the basis of numerous studies; miniaturization is an innovative way to elaborating efficacious systems [17]. This technique has had a unique influence on heat exchanger technology by employing microscopic channels for energy transfer by convection, which has made it extremely compact and efficient, especially in cooling applications like electronic devices (see Fig. 1. (c)). The development of technology for electrical equipment's has made the optimization of these channels using energy transfer enhancement devices a significant area of study [18]. Pin fins have accumulated a lot of awareness in the past couple of decades [19, 20]. By expanding the energy surface area and generating vortices on the heated surface, pin fins essentially increase the total efficiency of heat transmission. However, there is often a warning that the usage of pin fins may result in an accelerating pressure drop across the apparatus or system, which indicates a raised operational energy consumption. Therefore, in earlier research, researchers have tried to maximize pin fins to transfer heat quickly while lowering pressure as little as possible [21–23]. Furthermore, micro-channels frequently operate at low Reynolds numbers (1900–2000), whereas blades of turbine and, generally speaking, SAH perform at high Reynolds Number. This page offers a thorough summary of current studies that have employed pin fins in a variety of applications, including cooling of gas turbine, SAH ducts, and cooling for microchannel. To give a comprehensive evaluation of the potential of pin-fins, a significant assessment of the thermohydraulic properties of several pin-fin configurations is presented. This study's goal is to furnish useful information about the probable effects that the different pin fin characteristics might have, understand how those effects might affect interpretation, and ultimately boost researchers in developing channel shapes appropriate for a particular specialized application. This paper was the first of its kind, as far as the author is aware, and it will help advance a thorough knowledge of pins-fins in the area of thermal control for applications in renewable and sustainable energy sources.

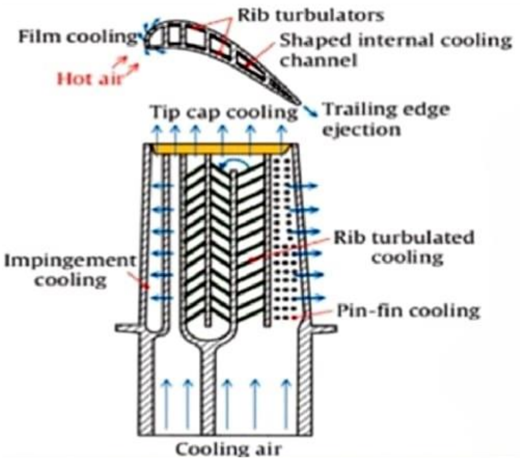

Figure 1. a) Gas Turbine cooling

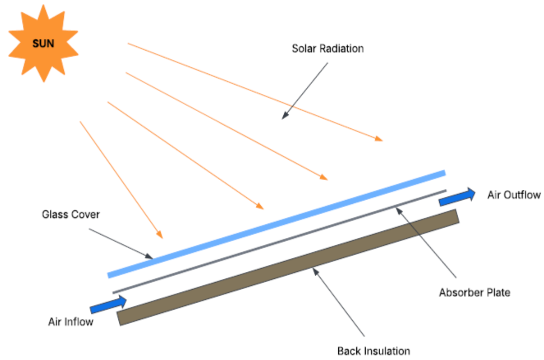

Figure 1. b) Solar Air Heater

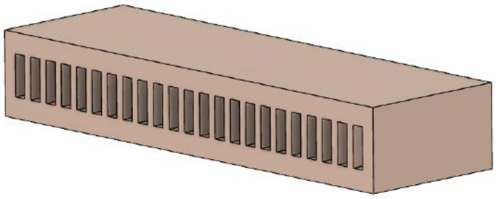

Figure 1. c) Electronic cooling system

II. PROBLEM DESCRIPTION

The intention of this study is to examine and improve fin design factors in order to augment heat transfer efficiency. The main emphasis will be on the fins' surface treatments, material characteristics, and geometric arrangement. Because sub-laminar layers grow over the surface, limited convection in smooth channels is usually linked to insufficient thermal performance. Heat transport is impeded by this layer's thermal resistance. Heat transfer is enhanced when various inserts are integrated into the smooth channel walls because they cause local turbulence, which disrupts the sub-laminar layer. Previous study has extensively explored a variety of inserts, such as protrusions, ribs, dimples, pin fins, or their combination [24, 25]. This technology, which is categorised as passive cooling, raises turbulence levels and secondary flows to promote mixing and improve heat transmission. In particular, pin fins are often utilized to improve heat transmission by expanding the absorber area available for efficient energy exchange. Evolved decrease in pressure and friction factor are major drawbacks of this technology, despite its benefits in terms of better energy transfer. Increased energy consumption and power requirements for pumping could arise from this, which are undesirable consequences that require attention [26]. A channel's pattern of flow, energy transfer, friction properties, and widespread performance are greatly influenced by a number of pin-fin roughness factors, including as the pin's relative area, height when attached and detached, and pin-fin arrangement. Furthermore, determining the flow type that most considerably affects energy transfer, friction factor, and the overall performance of the channel is crucial. Anticipated results include a set of fin design rules that widespread energy transfer efficiency. a comparison of several fin geometries and materials. Surface treatment suggestions that can improve thermal performance. An established theoretical framework for creating effective fins for a range of engineering uses.

III. PIN FIN CROSS-SECTION

The flow system and energy transfer which create vortex in the flow for different pin-fins cross sectional aspect effects on this. In channels, numerous pin-fin designs have been examined; The several pin-fin profiles examined in earlier research are displayed in Fig. 2. A common technique to promote energy transfer is the employment of pin fins with a circular cross-section [31–33].

However, researchers have also looked into other pin-fin forms and conception to produce improved or comparable energy transfer results with less pressure failure. Numerous experiments have been carried out to comprehend the effects of pin-fin forms at high Reynolds numbers, which may find application in solar air heater ducting and gas turbine cooling. The wake flow field, energy transfer, and maximum pressure loss were compared between staggered elliptical and circular pin-fin arrays [34].

It was identified that the elliptical fins considerably moderate pressure loss even though they did not transmit heat as well as the circular fins. Applying the Reynolds analogy, the thermohydraulic interpretation of pin-fin arrays was evaluated; elliptical pin fins exceeded circular pin fins by a slight margin. Circular, diamond and cubic pin fins studied by Chyu et al. for evaluated the effects on energy transmission and pressure loss [35]. Energy transfer improved significantly for diamond and cubic fins with pressure loss. Circular pin fin offers the best thermohydraulic interpretation. Kirsch et al. looked at the interpretation of oblong and cylindrical pin fins [36]. It was detected that the oblong pin surface had an area-averaged heat transmission of 30 to 35. Drop-shaped pin fins affected the flow and energy transfer in rectangular channel investigated by Wang et al. [37]. The testing detections showed that by successfully delaying or avoiding flow separation, the streamlined drop-shaped pin fins reduced pressure drop more than the circular pin fin design. Furthermore, it was valid that the primary element affecting the occurrence of horseshoe and wake vortices as well as vortical structures was the dealings between the main flow and the pin fins. The vortex has little influence on pressure drop in comparison to wake vortices. Because of its much weaker flow separation and hence reduced pressure loss, the drop-shaped pin fin is a more practical option than circular pin fin designs. Visualizations of the vorticity distribution supported the study's findings, which imply that drop-shaped pin fins might overcome circular ones.

Liang et al. [38] The interpretation of streamlined teardrop-shaped guiding pin fins and circular pin-fin arrays in channels has been analyzed and compared. They validated the use of teardrop pin fins to enhance heat transfer and direct channel flow. When compared to circular arrays, the teardrop pin fins' unique shape dramatically reduced the pressure drop, as seen by the area associated with the pressure drop in the channel being much lower. Additionally, the teardrop pin fins exhibited considerably greater average heat transmission beneath the bottom wall than the circular pin fin. These conclusions suggest that teardrop can greatly improve channel heat transfer and may be a more efficient structure for flow directing than circular designs.

Furthermore, Jin et al. [39] explored how energy transfer and flow in different rectangular channels were affected by elliptic, circular, oblong, lancet, teardrop, and NACA shapes. The results exhibited that NACA and teardrop pin fins exceeded the other pin fins. It was discovered that vortices have developed near the pin fins, indicating that the flow blending there has improved. Interestingly, the trailing edge of each pin fin produced wake vortices. The circular pin fin's wake vortex area was initiate to be substantially major than the NACA and teardrop fins. The information above implies that profiles related to circular pin fins may resultant in a lower pressure drop, which could significantly affect the design of heat-transfer devices given the close collaboration between vortices and pressure drop.

Liang et al. [40] examined the thermo-fluid behaviour of a BCC lattice array, a Kagome lattice array, and a stable red pin-fin array in a channel have rectangular shape. The study found that the circular pin, pin-fins array with end wall averaged Nusselt values between 26 and 41 performed much worse than the BCC array and the Kagome array.

Triangular and cylindrical grooved pin fins studied by Gokhan Eren et al. [41] for factors affected by various shape of pin fin in rectangular channel. According to their decisions, the most crucial friction factor characteristic was an optimized pin-fin form. However, the Triangular grooved pin fins showed the maximum thermal interpretation factor, with an optimal value of 2.81.

Moon and Kim [42] conducted an experiment in which they examined the efficiency of heat transmission between a circular and a fan-shaped pin fin in a rectangular channel. The findings demonstrated that the fan-shaped generated a much higher average Nusselt number over the Reynolds number range when compared to the circular. This advancement is caused by the vortex that surrounds the fan-shaped pin fin, which is longer and larger than the circular pin fin.

Caliskan et al. [43] interrogated the effects of hexagonal and cylindrical pin fins on friction factor, energy transfer, and Nusselt number in a rectangular channel. The effects indicated that HPFs had the best thermohydraulic interpretation among the various pin-fin shapes that were studied; this implies that utilizing HPFs may be more beneficial than using CPFs.The application of curved winglet vortex generator inserts (CWVGs) to enhance forced convection heat transfer in a rectangular channel has been studied by Berber et al. [44]. The results showed that, in comparison to channels without the inserts, the usage of CWVGs considerably raised the Nusselt number. Additionally, it was shown that the use of CWVGs increased the friction factor. Chang et al. [45,46] alleged new pin-fin designs to improve energy transfer in channel flows. Even though the array of pins improved heat transfer, there was a noticeable increase in pressure loss. The twisted-tape pin fins produced several vortices that enhanced heat transfer efficiency and aided in fluid mixing by making the air stream trip over each of the pin fin's curved surfaces. The front and back walls experienced near-wall crossflow due to the unique twist orientation of each twisted-tape pin fin. This enhanced heat transfer and caused variations in the Nusselt number throughout the span. The region in back of each pin fin adept an increase in turbulence intensity and vorticity due to the emergence of shear layers among the limitations of many flow cells, which resulted in increased heat transfer efficiency. Because of the aforementioned, there were more turbulence and frictional drags in the channel.

Yan et al. [47] and Luo et al. [48] investigated the impact of curved pin fins on heat transfer and pressure reduction in a channel. The results validated that the curved pin fin produced velocity components that travelled through the inclined segments and towards the end wall, as well as incoming airflow that impinged on the fin's leading edge. As a result, more airflow was

confined around the foremost end of the pin fin, forming a jet-like flow that was moving counter-rotatingly toward the end walls. As the jet-like flow struck the end walls, the separation regions expanded spanwise. It was demonstrated that a smaller inclination angle and a shorter vertical segment improved the curved pin fin's performance, resulting in a lower friction factor and better thermal interpretation.

A few earlier investigations examined the energy transfer and flow field of inclined pin arrays in a rectangular channel [30,49]. These investigations' findings establish that pin arrays with α= 120° and 135° improved absorber heat transmission as compared to usual right-angle pins. Furthermore, these inclined-pin arrays substantially improved the pressure drop and thermal interpretation. A counter rotating vortex pair with prominent velocity (CRH) was found to form downstream of a pin at α = 120° and 135° in the investigation. Consequently, spawned airflow attachment occurred on the heat transfer surface.

Additionally, the study exhibited that the angle of the inclined pin array significantly affected the structure in back of each pin and might lower the pressure drop in the flow. With potential applications in SAH, more study has been conducted to investigate how pin fin form affects heat interpretation and pressure drop at high Reynolds numbers. Manjunath et al. [50] seemed at how pin-fin arrays affected the instant thermal and effective efficacy of flat plate SAH under different flow rate conditions. The study identified that the pin fins can increase fluid turbulence and energy transfer area till 53.8. Additionally, the pin-fin array considerably improved efficiency, particularly at lower flow rates. Spring-shaped fins were placed beneath the absorber plate in a study by Arunkumar et al. [51] to examine a solar air heater's performance. The results showed that adding spring fins reduced flow resistance while increasing turbulence inside the absorber duct. It was shown that for helicoidal springs with a diameter ratio of 0.06 and for lower Re values, the thermohydraulic enhancement factor was much larger, reaching 1.268.

The thermo-hydraulic performance of a solar air heater with a staggered design including several C-shaped finned absorber panels with a combination of perforated and non-perforated plates was assessed in a study by A. Saravanan et al. [52]. According to the findings, employing a C-shaped finned absorber plate may raise the heat transfer rate by 2.67 and the friction factor by 5.94 when compared to a smooth absorber plate. However, the maximum thermo-hydraulic performance of the perforated fins was only 1.6.

For the purpose of to assess the thermohydraulic efficiency parameter, Antony et al. [53] carried out a numerical study of the thermal performance augmentation of a flat plate solar air heater utilizing stepped cylindrical turbulators attached beneath the absorber plate. By producing a highly turbulent flow, the study found that employing cylindrical stepped turbulators improved system performance. The flow separation around the stepped generators also had an impact on this. The study's findings show that the highest thermohydraulic performance metric, 1.49, is linked to this particular design.

The impact of spherical turbulence generators on a SAH thermohydraulic efficiency was examined by Manjunath et al. [54]. The findings showed that spherical ball turbulators significantly raised the Nusselt number, surpassing the basic model by up to 2.5 times. By making the air flow turbulence-prone, the spherical ball turbulators produced swirl motion in the boundary layer underneath the absorber plate. Better thermohydraulic performance resulted from the turbulent mixing of air particles surrounding the spherical ball turbulator, which increased heat transmission from the absorber plate to the air passing through the duct. To learn more about how pin form affects heat transmission and pressure drop at low Reynolds numbers, more research has been done.

Microchannel cooling may be affected by these discoveries. Liu et al.'s work [55] investigated the deionized water's flow resistance and heat transfer characteristics in a rectangular channel with a staggered array of micro pin-fin groups in the shapes of ellipses, diamonds, and circles. The results showed that of the different pin fin groups examined, the diamond-shaped pin fins created the least amount of disruption and were linked to the least efficient improvement in heat transfer, but the circular and elliptical pin fins were more likely to disrupt flow. Another study used a short channel with a rectangular cross-section to explore six pin-fin shapes: the hexagon, diamond, triangle, ellipse, square, and circle [56].

According to the study's findings, the triangle fin has the highest Nu number, even though the fin designs produced Nusselt (Nu) numbers at high Reynolds numbers that were quite close to one another (within 37). The fluid mechanics of deionized water flowing over tiny pin fins of different forms, such as square, diamond, triangle, circular, and elliptical, was investigated by Zhao et al. [57].

The tiny pin fins were staggered with different pin density values but same height and transverse spacing in a rectangular channel. The study found that the channel with the highest density elliptical pin fins had the highest friction factor (f) value, while the channel with the lowest density triangle fins for laminar flow had the lowest f value. In contrast, the elliptical and triangle pin fins were associated with the lowest and largest f values for turbulent flow, respectively.

Yan et al. [58] investigated a new pin-fin heat sink design with SMFAP, SMFCP, and SMFBP pin-fin geometries. According to the results, the various pin-fin configurations altered the flow's dissolution point, which in turn altered the size of the vortex rear the cylinder. The staggered micro fin-shaped is the most common of the three types. The results of the study exhibited that the pin fin (SMFAP) had the best hydrothermal performance.

Using Piranha Pin Fins (PPFs), Yu et al. [59] investigated convective energy transport in microchannels. The study's findings demonstrated that PPFs improved heat transmission in microchannels, perhaps due to a variety of reasons. Initially, PPFs increased the surface area that could be used for energy dispersion and integrating with cold liquids. Moreover, the velocity field was disrupted by the extruded PPFs., which promoted mixing and separation and ultimately enhanced heat transmission. Furthermore, the Nusselt number was greatly increased by eliminating fluids, which reduced pressure loss. It's critical to take the differences into account in each channel, even if methods for enhancing heat transfer can be applied to a range of industries and channels. The interpretations in the essential geometrical, thermal, and hydraulic operating parameters for three different channel types are shown in Table 1 based on the reviewed literature. Because of its thermal, hydraulic, and geometrical requirements, researchers wish to believe these elements when designing channels for specific uses.

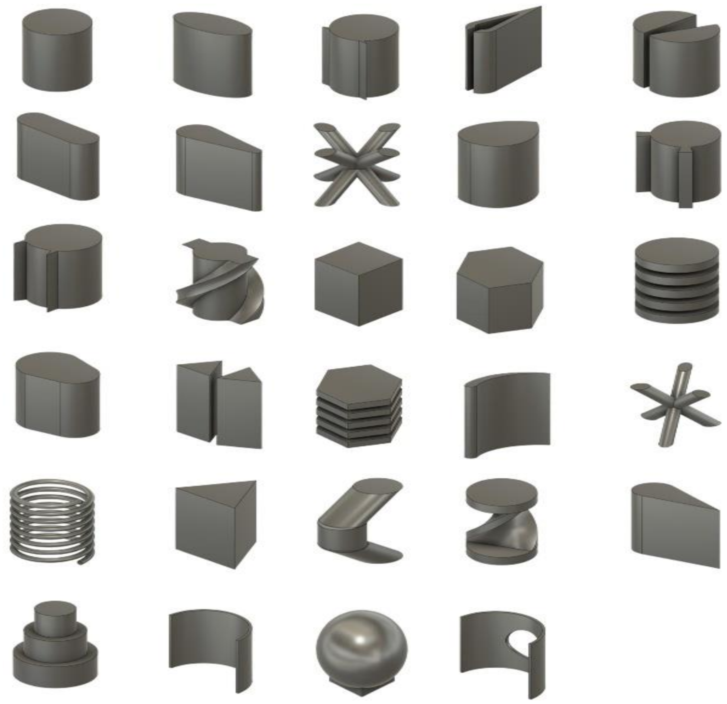

Figure 2. A brief summary of several pin-fin forms from earlier research

Table: -1 Optimise geometrical parameters for various duct size.

References	Year	Method	Roughness	L	W	H	W/H	L/Dh	Fluid	Reynolds No.	Best Case	Result
Uzol and Cengiz [34]	2005	Exp	elliptical and circular pin fins	1270	366.7	76	4.825	10.08	Air	18000-86000	Elliptical pin fins	ηmax = 0.52
Chyu et al. [35]	2007	Exp	circular, cubic, and diamond pin fins	304.8	95.3	6.4	14.89	25.41	Air	12000-19000	Circular pin fins	ηmax = 1.86

L. Kirsch et al. [36]	2014	Exp	oblong pin fins	1220	63.5				Air	10000-30000	circular pins	
Wang et al. [37]	2012	Num and exp	circular, elliptical, and drop-shaped pin fins	130	120	10	12	7.04	Air	4800-8200	Drop-shaped pin fins	
Liang, Ce et al. [38]	2021	Num and exp	Guiding pin fins						Air	20000-80000	Drop-shaped pin fins	Q=12%
W. Jin et al. [39]	2021	Num	Circular, oblong, elliptic, lancet, NACA, and teardrop	222	159	12.7	12.52	9.44	Air	5000-30000	NACA pin fins	η_{max} = 1.43
Liang et al. [40]	2021	Num and exp	Kagome lattice and Body Centered Cubic lattice array	120	80	15	5.33	4.75	Air	5700-17100	Body Centered Cubic lattice	η_{max} = 1.23
Eren and Caliskan [41]	2016	Exp	Cylindrical and triangular grooved pin fins	277	100	25	4	6.92	Air	3188-15146	triangular grooved pin fins	η_{max} = 2.88
Moon and Kim [42]	2014	Num	fan-shaped pin fins	203.2	58.83	28.7	2.05	5.27	Air	5000-10000		η_{max} = 1.11
Caliskan and et al. [43]	2019	Exp	hexagonal and cylindrical pin fins	277	100	25	4	6.92	Air	3188-19531	staggered hexagonal pin fins	η_{max} = 2.28
Berber et al. [44]	2022	Exp	curved winglets	4000	200	50	4	50	Air	6000-20000	$\alpha = 90^0$	η_{max} = 1.88
Chang et al. [45]	2021	Num and exp	twisted-tape pin fins	225	100	25	4	5.62	Air	5500-15000		η_{max} = 1.56
Chang et al. [46]	2021	Num and exp	Pin fins with spiral wings	275	100	25	4	6.87	Air	5500-20000		η_{max} = 1.12
Yan et al. [47]	2021	Num	upright, curved, and inclined pin fins	240	25	35	0.71	8.22	Air	10000-50000	curved pin fins	η_{max} = 1.375
Luo et al. [48]	2022	Num	curved pin fins	240	25	30	0.83	8.8	Air	10000-50000	$\theta = 45^0$	η_{max} = 0.87

Narato et al. [30, 49]	2020-2021	Num and exp	inclined pin fins	500	300	32	9.37	8.64	Air	14000-32680	$\theta = 135^0$	η_{max} = 1.26
Manjunath et al. [50]	2019	Num	circular pin fins	1200	150	30	5	24	Air	4000-24000		
Arunkumar et al. [51]	2020	Num and exp	spring fin wire	1000	200	30	6.66	19.16	Air	3000-24000		η_{max} = 1.19
A. Saravanan et al. [52]	2021	Exp	C shape finned	1430	700	50	14	15.32	Air	3000-27000		η_{max} = 1.6
A. Leander Antony etal. [53]	2020	Num	Stepped cylindrical turbulence generator	100	200	30	6.66	1.92	Air	3000-24000		η_{max} = 1.49
M.S. Manjunath et al. [54]	2017	Num and exp	spherical turbulence generators	1200	150	30	5	24	Air	4000-25000		
Liu et al. [55]	2015	Exp	circular, diamond, and elliptical	60	5.2	0.5	10.4	65.76	Water	8-1000	Elliptical pin fins	
Tullius and et al. [56]	2012	Num	circle, ellipse, diamond, square, hexagon, and triangle pin fins	45	15	1	15	24	Water	100-1500	Triangle, circle and ellipse pin fins	η_{max} = 1.64
Zhao et al. [57]	2016	Exp	circle, ellipse, diamond, square, and triangle pin fins	39.6	5.2	5	10.4	7.76	Water	50-1800	Elliptical pin fins	
Yan et al. [58]	2021	Num	fin-shaped pin fins	10	1	0.2	5	30	Water	200-1200	staggered SMFAP pin fins	η_{max} = 1.39
Yu et al. [59]	2016	Num and exp	micro–Piranha Pin Fins	22.5	2.4	1	2.4	15.93	Water	508-2114		η_{max} = 1.56
Chang et al. [60]	2008	Exp	Staggered detached circular pin fins	270	80	20	4	8.44	Air	10000-30000		η_{max} = 0.61
Siw et al. [61]	2012	Exp	Inline and staggered detached circular pin fins	10Dh	76.2	25.4	3	10	Air	10000-25000	staggered	η_{max} = 1.38

Moores et al. [62]	2009	Exp	Staggered detached circular pin fins	65	54	2	27	16.85	Water	200-20000		
Jadhav and Balaji [63]	2016	Num and exp	detached circular pin fins	150	150	45	3.33	2.17	Air	2200-23000		
Prajapati [64]	2019	Num	detached rectangular pin fins	15	3.5	1	3.5	9.64	Water	100-400		
Kadam et al. [65]	2019	Exp	Detached circular pin fins	100	50	8	6.25	7.25	Water	149-854	Open MCHS	
Bhandari and Prajapati [66]	2021	Num	Inline detached square pin fins	27	9	2	4.5	8.25	Water	100-800		
Chyu et al. [68]	1999	Exp	Staggered and inline circular pin fins	159	25.4	12.5	2.03	9.49	Air	5000-25000	staggered circular pin fins	
Siw et al. [69]	2015	Exp	Staggered and inline circular pin fins	457.2	63.5	12.7	5	21.6	Air	6000-15000	staggered circular pin fins	
Babar et al. [70]	2023	Exp	Staggered and inline airfoil shaped pin fin	68	24	1	24	35.42	Water	600-860	staggered airfoil shaped pin fin	
Lyall et al. [71]	2011	Exp	A single row of circular pin fins	45Dh	610	9.5	64	45	Air	5000-30000		
Lawson et al. [72]	2011	Exp	Staggered circular pin fins	45Dh	610	9.5	64	45	Air	5000-30000		
Kirsch et al. [73]	2015	Exp	Oblong pin	17.2Dh	1220	635	1.92	17.2	Air	40000-60000	Closer streamwise spacing wider spanwise spacing	
Ostanek and Thole [74]	2012	Exp	circular pin fins	5870	1130	635	1.78	7.22	Air	0-20000		
Li et al. [75]	2016	Num	Elliptic pin fin	45	15	1	15	24	Water	700-3500	Hp/Hc = 0.5, Sy/wp = 1.5, Sx/wp = 1.5	

IV. PERFORMANCE EVALUATION OF THE CHANNEL

Previous research has shown that surface roughness can improve convectional heat transmission and raise the friction factor because of flow turbulence. Priority achieves the maximum energy transfer rate with the least amount of pressure loss, to design usually aim to model the most cost-effective and efficient channel design. To help with the design of improved heat transmission methods in channels, a variety of performance metrics have been put forth. A thorough comparison of various outcomes is made possible by these parameters. The following criteria have been established in order to guarantee uniformity and clarity.

The Nusselt number,

This is used to assess heat transmission in a channel and is obtained from the channel hydraulic diameter [27].

$$Nu = \frac{hD_h}{K}$$

Where,

$D_h = 2WH/W + H$

The friction factor

Friction factor by obstruction dur to augmented surface cause the pressure loss and calculated from power supplied from external source. To represent friction factor, non-dimensional form used. The Darcy-Wiesbach equation used to calculate friction factor [28].

$$f = \frac{2\Delta P D_h}{\rho u^2 L}$$

Thermohydraulic functionality

The thermohydraulic interpretation of the channel—which involves evaluating heat transmission and friction considerations—determines the optimum channel design. Lewis [29] created thermohydraulic interpretation (η) as a metric to evaluate the enhanced energy transfer in roughened channels to smooth channels while maintaining the same pumping power and operational conditions. Equation (3) is applied to discover the value of η.

$$\eta = \frac{Nu_p / Nu_s}{\left(f_p / f_s \right)^{1/3}}$$

V. PIN-FIN ENERGY TRANSFER PERFORMANCE PREDICTION BASED ON MACHINE LEARNING

The optimization of energy transfer in fin systems is critical for improving the energy efficiency in thermal management applications. Traditional methods often involve trial and error, but with the rise of computational techniques, optimization methods such as genetic algorithms and differential evolution can be employed to systematically explore the design space. The objective of this article is to maximize the energy transfer coefficient in a fin system while reducing the fin count and surface area. In order to increase the energy transfer coefficient (hmax) while minimizing the fins' surface area (Af) and number (NT), the challenge was posed as a multi-objective optimization issue. Fin width (wf) and fin height (e) were the design variables. One way to state the optimization issue is as

Maximize: h_{max} (Q, A_P, e, T_s, T_a)

Minimize: N_T (A_P, e), A_f (D_h, w_f)

where:

h_{max} is the heat transfer coefficient.

N_T is the number of fins.

A_f is the surface area of the fins.

e is the fin height.

w_f is the fin width.

The design variables (e and w_f) are bounded by:

$1.0 \leq e \leq 10.0$ and $0.5 \leq w_f \leq 5.0$

The objective function

Maximum Heat Transfer Rate

The maximum heat transfer rate is given by:

$$h_{max} = \frac{Q}{(A_p + A_f)(T_s - T_a)N_T}$$

Total Number of Fins

The sum of all fins is determined as:

$$N_T = \frac{A_p}{100e^2}$$

Area of Fins

The area of fins is determined by:

$$A_f = (0.043\, D_h w_f)N_T$$

The objective function is formulated as a weighted sum of the three objectives, combining the increase of the energy transfer coefficient and the decrease of the count of fins and surface area.

The overall objective can be written as:

$$Objective = -w_1 h_{max} + w_2 N_T + w_3 A_f$$

And each aim is given a weight (w1, w2, and w3) that corresponds to its significance in the design process. The values of w_1, w_2, and w_3 can be adjusted to prioritize different objectives based on the design requirements. The experimental dataset included variables such as heat transfer rate (Q), plate area (A_P), fin height (e), surface temperature (T_s), ambient air temperature (T_a), hydraulic diameter (D_h), and fin width (w_f).

Objective Function Equations

The equations derived from the polynomial regression models

for the objectives are presented below.

Heat Transfer Coefficient (h_{max})

$$\begin{aligned} y = 4845.92 &+ (0.00)x_0 + (0.00)x_1 + (0.00)x_2 + (0.00)x_3 + (-0.00)x_4 + (-0.00)x_0^2 + (-0.00)x_0x_1 \\ &+ (-0.00)x_0x_2 + (0.00)x_0x_3 + (0.69)x_0x_4 + (-0.00)x_1^2 + (-0.00)x_1x_2 + (0.00)x_1x_3 \\ &+ (-0.00)x_1x_4 + (-0.00)x_2^2 + (0.00)x_2x_3 + (-0.00)x_2x_4 + (-0.00)x_3^2 + (-0.08)x_3x_4 \\ &+ (-0.06)\, x_4^2 \end{aligned}$$

Number of Fins (N_T)

$$y = -186.05 + (0.01)x_0 + (0.01)x_1 + (0.01)x_0^2 + (-0.02)x_0x_1 + (-0.00)x_1^2$$

Surface Area of Fins (A_f)

$$y = -2.20 + (96.18)x_0 + (96.18)x_1 + (-1034.50)x_0^2 + (-1034.50)x_0x_1 + (-1034.50)x_1^2$$

Fitness Function

The fitness function used for multi-objective optimization is given as:

$$Fitness\ Function = (0.6 \times Heat\ transfer\ coefficient) - (0.2 \times Number\ of\ fins) - (0.2 Surface\ area\ of\ Fins)$$

Optimization Results

Root Mean Square Error (RMSE) and Coefficient of Determination (R^2) were used to assess the effectiveness of the regression models that were used to forecast the goals. As seen below, the outcomes show outstanding predicted accuracy for every model:

- $Heat\ Transfer\ Coefficient\ Model: RMSE = 0.00, R^2 = 1.00$
- $Number\ of\ Fins\ Model: RMSE = 0.00, R^2 = 1.00$
- $Surface\ Area\ of\ Fins\ Model: RMSE = 0.00, R2 = 1.00$

The optimization process yielded the following design variables and corresponding optimized objective values:

Optimized Design Variables:

- $Rib\ height\ (e): 10.00\ mm$
- $Fin\ width\ (wf): 0.50\ mm$

Optimized Objectives:

- $Heat\ transfer\ coefficient\ (h_{max})$: 347.99 W/mm^2K
- $Number\ of\ fins\ (N_T)$: 9.29 ≅ 10
- $Surface\ area\ of\ fins\ (A_f)$: 0.26 mm^2

Optimization of Channel configuration: -

Using literature survey data available related to duct dimension Machine learning model are used to predict the best dimension for increasing heat transfer rate for various Reynolds number.

The optimal outcome for duct size was determined in this paper using ML algorithms such as support vector machines, random forests, and decision trees. The Random Forest Regressor (RFR) demonstrated superior performance with the highest accuracy for length (81.86%) and height (86.37%). Its ensemble nature makes it robust against overfitting and capable of generalizing well across the dataset. Decision Tree Regressor (DTR) performed moderately but suffered from overfitting in certain cases, particularly for the width dimension. Support Vector Machine (SVR) exhibited lower accuracy compared to RFR, particularly for predicting the length dimension. However, its predictions were more consistent across different dimensions. Following is the optimised value for the length, width and Height.

Sr. No	Model	Prediction Accuracy %		
		Length	Width	Height
1	Decision Tree	56.74	78.06	52.26
2	Random Forest	81.86	57.12	86.37
3	Support Vector Machine	57.55	54.34	70.26

Sr. No	Model	Predicted Value		
		Length	Width	Height
1	Decision Tree	226.34	75.33	21.94
2	Random Forest	207.69	67.12	17.26
3	Support Vector Machine	164.36	68.49	17.57

VI. CONCLUSION

This review has addressed the use of pin fins in detail, along with the effects (such as friction and energy transfer characteristics) related to types of flow and pin-fin parameters, including the height of the pin fins (attached and detached), their relative cross-section, and their arrangements. It has also been examined how pin-fin designs provide to heat transmission and their associated thermohydraulic adaptation, as well as the underlying causes of interrupted flow when they are introduced. The following conclusions have been reached and are based on the findings of the evaluated literature:

- **High Predictive Accuracy of Regression Models:** The regression models used for predicting key objectives such as the heat transfer coefficient, number of fins, and surface area of fins demonstrated exceptional accuracy, with RMSE values of 0.00 and R^2 values of 1.00, indicating perfect model performance.
- **Optimized Design Variables Achieved:** The optimization process successfully identified optimal design variables, including a rib height of 10.00 mm and a fin width of 0.50 mm. These parameters resulted in a maximum heat transfer coefficient of 347.99 W/mm^2K, approximately 10 fins, and a surface area of fins equal to 0.26 mm^2.
- **Effectiveness of Machine Learning Algorithms:** Among the machine learning algorithms applied for channel configuration optimization, the Random Forest Regressor (RFR) outperformed others, achieving the highest prediction accuracy for length (81.86%) and height (86.37%). Its ensemble learning capability ensured robustness and minimized overfitting.
- **Optimized Duct Dimensions Identified:** The Random Forest model predicted the most efficient duct dimensions—length of 207.69 mm, width of 67.12 mm, and height of 17.26 mm—making it the most reliable model for enhancing heat transfer rates across varying Reynolds numbers.

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