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Review

A Review on Application of Pin-Fins in Enhancing Heat Transfer

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Abstract: The pin-fin is one of the main technologies in enhancing heat transfer. The accelerated flow and vortex structures are produced, which can disrupt the development of the flow boundary layer. The configuration of the pin-fin is obvious for heat transfer and flow characteristics, including its shape, size, and arrangement in the cooling channel. This work provides a detailed introduction to the application of pin-fins in enhancing heat transfer and reducing flow resistance, including the conventional shapes, improved shapes based on circular pin-fins and irregular shapes. At the same time, the influence of the diameter, height and density of pin-fins on heat transfer and flow performance is studied, and the influence mechanism is analyzed from the perspective of boundary layers. In addition, some applications that combine pin-fins with other cooling methods to further improve performance are analyzed. In terms of the optimization technology, the structure optimization for pin-fin shape and the layout optimization for pin-fin array are summarized. Therefore, this review provides a wide range of literature for the design of internal cooling channel pin-fins.

Keywords: pin-fin; heat-transfer enhancement; flow field; optimization

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1. Introduction

A range of methods, such as pin-fins, surfaces with dimples, surfaces with protrusions, vortex generators and surface roughness, are employed to enhance the convective cooling efficiency in channels. The role of all these devices is to enhance mixing effects by increasing secondary flow and turbulence levels [1]. The pin-fin group's disruptive impact on the flowing medium increases the convective cooling effect, which is why it is regarded as an effective cooling technique. On the one hand, the cooling area is expanded. This is due to the fact that the fluid will accelerate flow through the pin-fin, create a wake region that is severely disrupted behind the pin-fin, interact with the end wall to create a horseshoe vortex and generate erratic vortex shedding. Therefore, it is widely used in gas turbine trailing edges to reduce blade surface temperature. In addition, since the two surfaces can be connected through the pin-fins, it also increases the integrity of the structure and provides a higher structural strength [2].

Ligrani et al. [1,3] have made a detailed summary of heat-transfer characteristic in gas turbine channels, which are equipped with pin-fin group. The results show that the cooling effectiveness (η) can be increased by 3.5 times after adding the pin-fins. However, as the application environment is becoming worse and worse, it is necessary to further strengthen the cooling effect. Therefore, a lot of research has been carried out to enhance the heat transfer in the pin-fin channel. The cooling performance through the pin-fin can be improved due to three vortex structures induced by the pin-fin, including the horseshoe vortex at the leading edge of the pin-fin, the Karman vortex street in the wake area of the pin-fin, and the passage vortex [4,5]. Among them, the horseshoe vortex and the passage vortex are caused by the end wall effect and have a great influence on the cooling effect.

In order to provide design reference for the cooling structure of the channel in high-temperature environments, this paper summarizes and analyzes different pin-fin structures used to enhance heat-transfer effects in the pin-fin channel from two aspects of the pin-fin shapes and optimization technologies, including regular pin-fins, improved circular pin-fin and irregular pin-fin, geometric parameters and arrangement of pin-fin, the combination of pin-fin with other cooling methods, structural optimization, and layout optimization for pin-fin groups. The channel-cooling structure equipped with the pin-fins studied in this paper can be used in cooling of the high thermal load environments, including heat sink, cooling of electronic devices, various battery packs, electronic chips, etc., and even gas turbine combustion chambers and turbine blades.

2. Research on the Shape of Pin-Fins

2.1. Regular Pin-Fins

In order to meet the cooling requirements, the flow and heat-transfer characteristics of the different shapes of the pin-fin were studied, so as to provide a reference for finding the appropriate structure of the pin-fin, as shown in Figure 1. Ambreen et al. [6,7] analyzed the comprehensive influence of four types of pin-fins (square, circular, hexagonal and triangular) on the heat-transfer characteristic of micro heat sinks. They found that under the same flow conditions, circular pin-fins have the best thermal performance, followed by hexagonal and square pin-fins, and triangular pin-fin behaved the worst. Moreover, the upstream row of pin-fins played a major role in flow distribution and thermal characteristics. Jin et al. [8,9] conducted a comparative study on six types of pin-fins (circular, elliptic, oblong, drop-shaped, NACA, and lancet) in order to explore the geometry of the pin-fins with an excellent heat-transfer effect and small friction coefficient. They found that the elliptical pin-fin has the best heat-transfer-enhancement effect, but the channel friction coefficient is also large, while the NACA pin-fin has the lowest friction coefficient and the cooling effect is second only to the oblong. Meanwhile, they noticed that all six types of pin-fins had a “U-shaped” strong cooling zone at the leading edge. Xu et al. [10] explored the influence of six types of pin-fins on the heat transfer and resistance characteristics of the channel by experiment. They also draw a conclusion that the elliptical pin-fin had the best heat-transfer characteristic. Siw et al. [2,11] experimentally studied the flow and cooling characteristics of staggered array groups of triangular, semi-circular, and circular pin-fins. The results showed that the triangular pin-fin array best enhanced the heat-transfer effect, and the semi-circular is the worst. That is because each triangular pin-fin generates more wake flow and turbulence, resulting in more mixing. At the same time, the shape resistance of triangular pin-fin is the largest, resulting in the greatest pressure loss, and the pressure loss of circular pin-fin is the least. Ilyushin and Novozhilov [12] (https://doi.org/10.1109/SCM.2017.7970519, accessed on 7 December 2014) verified this conclusion by a mathematical method. Wang et al. [13] studied the flow and cooling characteristics of three different pin-fins (circular, elliptical, and drop-shaped, with the same cross-sectional area) in a rectangular channel. The results showed that the streamlined drop-shaped pin-fin can better delay the flow separation, which reduced the aerodynamic loss compared with the circular pin-fin, but its enhanced cooling effect is smaller than that of the circular one. Liu et al. [14] studied the flow and cooling characteristics of channels equipped with circular, elliptical, and diamond-shaped pin-fins by experiment. They found that elliptical pin-fin had the best streamline and cooling effects. The results showed that the flow resistance is larger at low Reynolds number (*Re*) because of the end wall effect and the large density of the pin-fins. At the same time, the endwall effect decreased with the increase in *Re*. However, due to the emergence of eddy resistance, the flow resistance still increases, and the flow disturbance changes from laminar flow to turbulent flow, thus enhancing the heat-transfer effect. Zhao et al. [15] studied the flow-resistance characteristics of five types of pin-fins rectangular channels at the same height and transverse spacing. The results also showed that the elliptic pin-fin has the best streamline and the smallest flow resistance, while the triangular pin-fin has the largest flow resistance. Corbett et al. [16] studied the effect of the pin-fin array spacing on flow and cooling performance. The experimental data showed that the diamond-shaped pin-fin array has the best heat-transfer performance, while the triangular pin-fin array possesses the lowest pressure drop. The friction coefficient is not affected by increasing the density of the pin-fin, but the heat-transfer effect will increase. Soleymani et al. [17] studied the influence of geometric characteristics of a heat sink composed of 20 microchannels and 143 pin-fins on heat dissipation performance. The results showed that the oblong pin-fin has better thermal performance than the NACA. In addition, increasing the NACA airfoil angle can increases its heat-transfer effect. Ho et al. [18] conducted an experimental study on the staggered NACA airfoil pin-fin and compared it with the regular circular and oblong pin-fins. They observed that the streamlined geometry of the NACA airfoil pin-fin has less resistance, thereby improving the thermal performance. At the same time, the Nusselt Number (*Nu*) of oblong pin-fins is higher than those of other airfoil profiles. Moon et al. [19] compared the flow and heat-transfer characteristics of circular, oblong, and fan-shaped pin-fins. They found that the fan-shaped pin-fin generates a larger and longer horseshoe vortex around the pin-fin compared with the circular pin-fin. For the fan-shaped pin-fin, the horseshoe vortex is stronger than the counter-rotating lateral vortex on the surface downstream near the pin-fin, but the opposite trend is found in the case of the circular pin-fin. Phase change materials used to further improve the thermal performance is the future development trend [20,21].

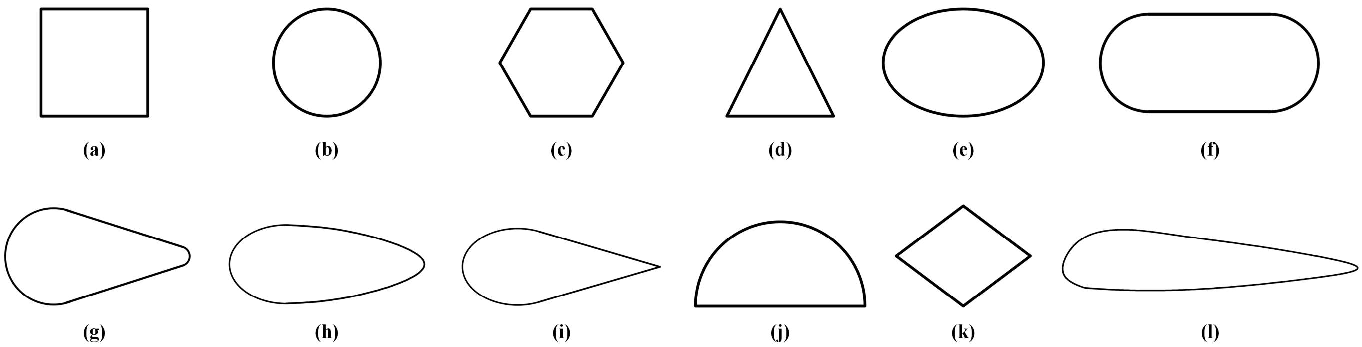

Figure 1. Regular pin-fin shapes. (**a**) Square, (**b**) circular, (**c**) hexagonal, (**d**) triangular, (**e**) elliptic, (**f**) oblong, (**g**) drop-shaped, (**h**) NACA, (**i**) lancet, (**j**) semi-circular, (**k**) diamond-shaped, (**l**) airfoil.

2.2. Improved Circular Pin-Fin and Irregular Pin-Fin

Numerous studies have shown that pin-fins not only enhance cooling effectiveness but also increase flow resistance. However, by designing the geometric shape of a pin-fin reasonably, special-shaped pin-fins with better performance than conventional pin-fins can be obtained. After continuous research on the cooling mechanism of pin-fins, the cross-sectional shape of the pin-fin has evolved from the initial circular shape to various shapes, as shown in Figure 2. Luo et al. [22] designed a new type of curved pin-fin to improve the cooling effect on the basis of the circular one. The numerical calculation results showed that the curved pin-fin with smaller inclined angle and shorter vertical segment has lower friction coefficient and better thermal performance. Compared with the conventional circular pin-fin, the average Nusselt number (*Nu*) decreased by 2.4%, the friction factor (f) decreased by 22.1%, and the comprehensive performance factor (P_f) increased by 6.1%. Zeng et al. [23] proposed a unique open-ring pin-fin, which has an internal cavity and two inner small and outside large rings. The results showed that this structure can cause periodic flow separation and convergence, leading to continuous flow mixing, periodic interruption, and redevelopment of the boundary layer. The *Nu* increased by 77~260% compared with conventional rectangular smooth channels. Zhu et al. [24] analyzed the enhanced heat-transfer mechanism of vertical and inclined circular pin-fins. They found that compared to vertical ones, inclined pin-fins can weaken the closed vortices in the middle section and optimize the flow in the channel. The *Nu* can be increased by 37.9% compared with vertical pin-fins. Moon et al. [19] proposed a fan-shaped pin-fin to improve heat transfer and reduce pressure drop in the cooling channel. They found that due to the smaller area behind the fan-shaped pin-fin compared to the circular one, the downstream lower *Nu* area became smaller, providing higher overall cooling performance. The *Nu* increased by 22.8% at *Re* = 80,000 compared with conventional circular pin-fins. Zhao et al. [25] designed a conical pin-fin to induce the transverse vortex, and compared it with the longitudinal vortex induced by the delta-winglet. The results showed that the cooling effect of the conical pin-fin is not as good as that of the delta-winglet, but it is more beneficial to improve the cooling uniformity, and the *Nu* can be increased by 35% compared with conventional circular pin-fins. For the detached pin-fin, the research results showed that it can significantly reduce pressure loss compared to the full-length pin-fin [2]. In order to investigate the effect of detached pin-fins on enhancing heat transfer and reducing pressure loss, Liang et al. [26] conducted a comparative study on rectangular channels equipped with full-length and detached pin-fins. The numerical results showed that compared to the full-length pin-fin, the detached pin-fin channel can reduce the friction factor by 31.9% and increases the total heat transfer by 16.9%. This is due to the additional transverse vortices generated by the fluid in the trailing edge area of the detached pin-fins, which greatly enhances the cooling of the downstream end wall. Hosseinirad et al. [27] designed a composite pin-fin that combines a square pin-fin and a thin straight plate to weaken flow separation and reduce pressure drop. They also found that composite pin-fins with arched and forward arrangements have the highest heat-transfer coefficient.

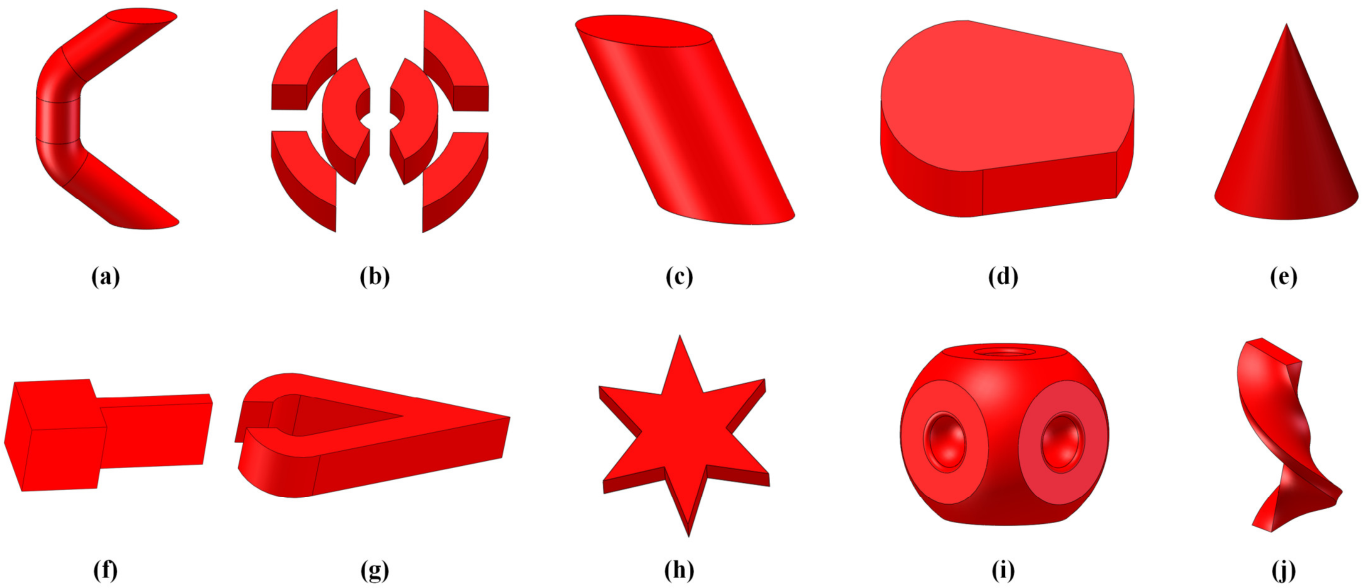

Figure 2. Improved pin-fin shapes. (**a**) Curved [22], (**b**) open−ring [23], (**c**) inclined [24], (**d**) fan-shaped [19], (**e**) conical [25], (**f**) composite [27], (**g**) piranha-shaped [28], (**h**) star-shaped [29,30], (**i**) dimpled spherical [29,30], (**j**) twisted [31].

Due to the development of additive manufacturing, it is possible to develop unique shaped pin-fins to improve the performance of conventional pin-fin arrays. Yu et al. [28] designed a piranha-shaped pin-fin, similar in shape to a drop-shaped pin-fin with a groove at the tail. Due to the appearance of an inner groove, it provided an additional area for thermal diffusion. The experimental and simulation results indicated that piranha-shaped pin-fins disrupt the velocity field, and separation and mixing further enhance heat transfer. The *Nu* can be increased by 86% at *Re* = 2114 compared with conventional rectangular smooth channels. Ferster et al. [29,30] proposed star-shaped and dimpled spherical pin-fins and experimentally studied the pressure loss and heat-transfer characteristics inside the channels. They found that the spacing, the number of pin-fins, and the geometric shape have an impact on pressure loss and cooling effect. Haque et al. [31] designed an innovative twisted pin-fin with a rectangular cross-section with different holes in the pin-fin to improve the cooling effect. Research results showed that this twisted pin-fin can trap more air on the surface of the pin-fin, enhance the mixing, and thus increase the heat-transfer performance. The average Nu increased by 32%, the pressure drop decreased by 15%, and the P_f increased by 27% compared with conventional circular pin-fins. El Said et al. [32] conducted experimental studies on twisted pin-fins with four different torsion angles (0°, 30°, 60°, and 90°) with square and hexagonal cross-sections. The research results showed that the friction coefficient and pressure drop decrease with the increase in torsion angle. Table 1 gives the comparison of different pin-fin structures. From the table, we can conclude that different improved circular pin-fins and irregular pin-fins behaved better compared with initial circular pin-fins, especially the inclined ones.

Table 1. Comparison of different pin-fin structures.

Authors	Pin-Fin Structures	Performance Specifications	References
Luo et al. [22]	Curved	The average Nu decreased by 2.4%, the f decreased by 22.1%, and the P_f increased by 6.1%.	Conventional circular pin-fin
Zeng et al. [23]	Open-ring	The Nu increased by 77~260%.	Conventional smooth channels
Zhu et al. [24]	Inclined	The Nu increased by 37.9%.	Conventional circular pin-fin
Moon et al. [19]	Fan-shaped	The Nu increased by 22.8%.	Conventional circular pin-fin
Zhao et al. [25]	Conical	The Nu increased by 35%.	Conventional circular pin-fin
Liang et al. [26]	Detached	The average Nu increased by 16.9%, the f decreased by 31.9%, and the P_f increased by 29.1%.	Conventional circular pin-fin
Yu et al. [28]	Piranha-shaped	The Nu increased by 86%.	Conventional smooth channels
Haque et al. [31]	Twisted	The average Nu increased by 32%, the ΔP decreased by 15%, and the P_f increased by 27%.	Conventional circular pin-fin

2.3. Geometric Parameters and Arrangement of Pin-Fin

In terms of geometric parameters of the pin-fin, height has also attracted the attention of many scholars as an important factor affecting the flow and heat-transfer characteristics. Pandit et al. [33] studied the effect of the relative height (the ratio of pin-fin height to channel height) of four types of pin-fins on cooling performance. They found that at lower relative height, most of the channels would be blocked, and the cooling effect was best. Chi et al. [34] studied the effect of five different relative heights of circular pin-fins on the flow and cooling characteristics in rectangular channels. It was found that the higher the relative height, the higher the hysteresis loss and heat transfer. When the relative height is 1/2, the ratio of total heat transfer to total loss is the smallest. Hua et al. [35] studied the effects of different sizes of pin-fins on pressure drop and friction coefficients through flow-resistance experiments. The experimental results indicated that the greater the height to diameter ratio of the pin-fins, the higher the pressure drop. Chyu et al. [36] studied the flow and heat-transfer characteristics of the pin-fin array with a height to diameter ratio of 2~4 through experiments. They found that the overall average cooling effect increases with the increase in the ratio, but at the same time, it leads to greater pressure loss. Bhandari and Prajapati [37] conducted a numerical study on the effects of different square pin-fin heights (0.5~2.0 mm, increments of 0.25 mm) on the flow and heat-transfer characteristics. The research results indicated that increasing the height can increase the heat-transfer coefficient, but it only lasts until 1.5 mm. After exceeding this height, the heat-transfer effect will decrease. Li et al. [38] studied the effects of height, width, and spacing of elliptical pin-fin on flow and cooling performance through numerical methods. Research results showed that the higher the height, the better the cooling performance, but the pressure drop also increases sharply. Meanwhile, as the width, lateral spacing, and longitudinal spacing of the pin-fins increase, the pressure drop will increase. Chen et al. [39] conducted a simulation study on the arrangement direction of the triangular prism pin-fin. They noticed that the pin-fin arranged backwards has the strongest disturbance effect, the thinnest boundary layer, and the best cooling effect and comprehensive cooling performance.

In addition to the height of the pin-fin, research has also focused on the pin-fin diameter. Jaseliūnaitė and Šeporaitis [40] studied the different diameters of circular and elliptical pin-fins. They found that the larger the diameter, the more stable the flow and the lower the pressure drop (ΔP).

When the fluid flows through the pin-fins, the turbulence intensity of the fluid will be increased, and the fluid microclusters in the turbulent flow constantly pulsate and mix irregularly. This mixing can effectively destroy the stability of the boundary layer and reduce its thickness or even completely destroy it. At the same time, around the pin-fins, the velocity of the fluid will increase due to obstruction, forming a local high-speed zone. The change of velocity distribution will also break the original boundary layer structure [1]. Due to the direct influence of the thickness of the flow boundary layer on the thickness of the thermal boundary layer, the thinner the flow boundary layer, the thinner the thermal boundary layer, and therefore it has a higher convective heat-transfer effect. In order to achieve higher convective heat-transfer coefficients, it is common to disrupt the development of the flow boundary layer and generate new thinner flow boundary layers on subsequent surfaces. The horseshoe vortex induced by the pin-fin is related to the secondary flow and the enhanced heat-transfer effect, so researchers have conducted extensive research on horseshoe vortices. Ireland and Jones [41] observed the horseshoe vortex near the pin-fin in fully developed pipeline flow, which led to enhanced heat transfer. They believed that the horseshoe vortex plays an important role in promoting the cooling of the pin-fins and the end wall. Won et al. [42] measured the heat-transfer coefficient distribution in a cooling channel with eight rows of pin-fins. The results indicated that the heat transfer on the heated surface is influenced by the strength of the horseshoe vortex. In addition, they also reported that the horseshoe vortex structure becomes more complex and intense with the increase in *Re*. Wang et al. [5] conducted a visual analysis of the horseshoe vortex of the pin-fin at the end wall. They found that installing diagonal bars upstream of the pin-fin can eliminate horseshoe vortices on the windward side and reduce the wake flow. Kirsch et al. [43] experimentally studied the heat transfer and boundary layer characteristics on the surface of an oblong pin-fin, and compared it with a circular one. The results indicated that the stagnation position and the transition point of the boundary layer from laminar flow to turbulent flow have higher cooling effects.

In recent years, researchers have also studied the influence of the arrangement of pin-fins (in-line and staggered arrangements) on the heat transfer and flow characteristics of channels with pin-fins, and proposed a non-uniform arrangement method. Xu et al. [44] studied the flow characteristic of in-line and staggered arrangements in microchannels, and for the first time analyzed the effect of the arrangement of pin-fins on flow transition. They found that at the critical *Re*, the in-line arrangement channel transformed from a stable double vortex wake to an unsteady vortex shedding wake, causing strong flow disturbances and significant additional pressure drop in the lateral direction, ultimately leading to a flow transition in the in-line channel. Bianchini et al. [45] proposed a novel pentagonal arrangement to investigate the influence of the arrangement of circular pin-fin array, and compared it with the staggered arrangement. They found that the pentagonal arrangement showed uneven distribution of cooling effect, with local enhancement and weakening at specific radial positions. After analyzing the conventional configuration of in-line and staggered pin-fins, Abuşka and Çorumlu [46] created a novel configuration by rearranging the staggered pin-fins' positions. The experimental results showed that the improved staggered conical design has good pressure loss and manufacturing cost value. Guo et al. [47] developed a battery thermal management system with circular pin-fins and studied the effects of the arrangement and layout direction of the pin-fins on the temperature, temperature distribution, and pressure drop of the battery pack. They found that compared to vertically arranged pin-fins, horizontally arranged layouts have higher heat-transfer enhancement effects and more significant pressure losses. Kewalramani et al. [48] studied the influence of geometric features on the hydrodynamic and thermal characteristics of elliptical pin-fin heat sinks. Research has found that through the analysis of local Nu, it is found that after the fifth row of pin-fins starting from the inlet, local Nu has repeated changes.

In addition, many scholars have also studied the pin-fin density on this basis. Bahiraei et al. [49] studied the effect of pin-fin density on cooling characteristics by changing the elliptical pin-fin number. The research results indicated that, under higher pin-fin density, more and narrower channels were created, which accelerated the flow velocity of the fluid, induced the generation of vortices and secondary flow, and also had a higher heat-transfer area. When the pin-fin density increased from 0.036 to 0.168, the cooling effectiveness increased by about 49.6%. Ostaneka et al. [50] designed a group of pin-fin arrays with non-uniform arrangement and compared them with a uniform layout. The results indicated that at low *Re*, the performance of non-uniform arrays is lower than that of equally spaced arrays. At high *Re*, non-uniform arrays cover a flow direction distance of 16.8% more than uniformly spaced arrays, which can bring higher cooling. Polat and Cadirci [51] conducted parametric analysis on geometric variables such as angle and longitudinal to radial ratio of diamond-shaped pin-fins. The results indicated that angle is the main factor affecting the flow and cooling performance, and it contributed the most to the flow structure and circulation area behind the pin-fin. Reducing the longitudinal pitch can enhance cooling performance and reduce flow performance.

The above research results show that when the heat-transfer effect is increased by increasing the diameter, height and density of the pin-fins, the flow resistance will also increase. This is because the flow area decreases when flowing through the pin-fins, and the obstruction effect on the fluid increases. Therefore, when designing the pin-fins, the trade-offs for heat-transfer effect and flow resistance should be considered.

2.4. Research on the Combination of Pin-Fin with Other Cooling Methods

In recent years, some scholars have attempted to combine pin-fins with other enhanced cooling methods and have made certain progress. For example, dimples can cause shedding vortices, resulting in enhanced cooling near the downstream edge of each dimple [52]. To further improve the cooling effect of the pin-fin, researchers have added dimple/protrusion to the pin-fin array. Xie et al. [53,54] conducted a detailed study on the effects of structural parameters on dimple/pin-fin combination and protrusion/pin-fin combination. They found that increasing the pin-fin diameter can increase the scale and intensity of the wake flow, which can enhance the cooling effect. Increasing the dimple depth can induce stronger flow separation, and enhance heat transfer between the near wall and central region, and thus improve overall thermal performance. Compared with conventional smooth channels, the average Nu increased by 31.2~72.1% and 87.4~127.3% when combining with dimple and protrusion structure, respectively. Karami et al. [55] studied the effect of baffles on heat transfer by changing the type and size of baffles. The results indicated that the heat-transfer rate increased by 47.37%, and the pressure drop increased by 77% compared with the channel without baffle. Researchers have also attempted to combine delta winglet with pin-fins. Syaiful et al. [56,57] indicated that delta winglet has a significant impact on fluid mixing, especially in the wake region with weak heat transfer. In addition, compared to the structure with only pin-fins, the configuration of three pairs of delta winglets increased the convective cooling coefficient (h) by 53.58%, but at the same time, the pressure drop increased by 69.69%. Another successful technique widely used to improve the heat-transfer effect is to create perforations on the pin-fin, as perforations can cause stronger turbulence in the wake area, thereby increasing the transfer of cooling. Huang et al. [58] designed a perforated structure for circular pin-fins and studied the optimal shape and perforation diameter under fixed volume constraints. The numerical results showed that the designed perforated circular pin-fin structure can increase the average Nu by 35.8%. Gupta et al. [59,60] investigated the effects of perforation numbers (1, 2, and 3) and perforation shapes (circular and square) on square shaped pin-fins. They found that compared to initial square pin-fins, perforation increases the convective surface area, resulting in higher Nu. The performance increased by 30% from one perforation to two perforations, and by 28% from two to three perforations. Simultaneously increasing the number of holes can reduce the degree of blockage, thereby reducing the pressure drop. Al Damook et al. [61] used numerical simulation methods to study the effect of using circular, square, and elliptical perforations on the heat-transfer effect on circular pin-fins. Simulation analysis showed that elliptical perforations can minimize pressure drop, while circular holes can provide the greatest heat-transfer effect. Table 2 gives a comparison of combinations of pin-fins with other cooling methods. From the table, we can conclude that the heat-transfer performance of all structures is improved compared with initial pin-fins, and the protrusion cooling method behaved the best.

Table 2. Comparison of different combination objects.

Authors	Combination Objects	Performance Specifications	References
Xie et al. [53,54]	Dimple	The average Nu increased by 31.2~72.1%.	Conventional smooth channels
Xie et al. [53,54]	Protrusion	The average Nu increased by 87.4~127.3%.	Conventional smooth channels
Karami et al. [55]	Baffle	The heat-transfer rate increased by 47.37%, the ΔP increased by 77%.	Conventional circular pin-fin
Syaiful et al. [56,57]	Winglet	The h increased by 53.58%, the ΔP increased by 69.69%.	Conventional circular pin-fin
Huang et al. [58]	Perforation	The average Nu increased by 35.8%.	Conventional circular pin-fin
Gupta et al. [59,60]	Perforation	The average Nu increased by 53.5~187.3%, the ΔP decreased by 20.7~39.1%.	Conventional square pin-fin

3. Optimization Technology of the Pin-Fin

Due to the rapid development of optimization techniques combined with computational fluid dynamics in recent decades, numerical optimization methods are considered a universal design tool and provide many advantages, including automated design capabilities, various constraints, and multidisciplinary applications. Among various optimization algorithms, approximate model technology has been widely used in engineering applications due to its inherent advantages, and a typical goal of optimizing the pin-fin in cooling channels is to maximize heat-transfer performance. Due to the high complexity of fluid thermal structure interactions, gradient-free methods are commonly used to optimize cooling systems. The research status of this section is mainly divided into research of structural optimization and layout optimization.

3.1. Structural Optimization

Structural optimization can be divided into size optimization, shape optimization, and topology optimization. When changing the geometric size of the pin-fin, apart from increasing or decreasing exponentially, most optimized structures simultaneously change the geometric shape. For example, Ahmadian Elmi et al. [62] optimized all geometric parameters that affect the performance of a circular pin-fin group, including the number, height, diameter, and lateral pitch. The results indicated that by optimizing these parameters, the overall performance gradually improves, and the final optimized shape is conical. Therefore, there is no obvious difference between size optimization and shape optimization, and they are not distinguished here.

Moon and Kim [19] used a multi-objective algorithm based on a radial basis function neural network approximation model to optimize the fan-shaped pin-fin, with the goal of maximizing heat transfer and minimizing friction loss. The Pareto optimal solution showed that compared to the circular pin-fin, the Nu increased by 22.82%, and friction loss increased by 22.82%. Li and Kim [63] used the NSGA-II algorithm to perform multi-objective optimization on an elliptical pin-fin group. The optimization objectives were to maximize Nu and minimize the friction factor (f). The results showed that the Nu increased by 87.8% and the f increased by 38.7% compared with the reference shape. Ghosh et al. [64] used a Bayesian optimization method based on approximate modeling to optimize the thermal performance of a four row pin-fin array, with the optimization goal of maximizing Nu while maintaining f as a constraint. The optimization results indicated that the Nu increased by 0.4% and the ΔP increased by 33.2%. Horiuchi et al. [65] established a multi-objective optimization algorithm based on experimental results, which combines the multi-objective genetic algorithm (MOGA) and Kriging approximation model. The optimized variables include the diameter, height, flow direction, and spanwise pitch, with the optimization objective of minimizing thermal resistance (R_{th}) and pressure drop. The result showed that the thermal resistance decreased by 1.24% and the ΔP decreased by 35.3%. Radmark et al. [66] used the full factor experimental design method (FFD) to optimize a group of rectangular pin-fin arrays. The optimization is completed in two parts. In the first part, to minimize the thermal resistance and pressure drop of the cooling device, Horiuchi used the traditional weighted method, iterative JAYA algorithm, and NSGA-II to optimize the shape of the cross-section and spacing of the pin-fin. The second part utilized an artificial neural network (ANN) combined with NSGA-II to optimize the height of the pin-fin. The optimization results indicated that the ΔP decreased by 37% without scarifying the R_{th} compared with the initial rectangular pin-fin. Sahel et al. [67] optimized the geometry of a semi-spherical pin-fin, with the goal of improving the thermal performance of the radiator while reducing its occupied volume and mass. The optimization results showed that compared with initial pin-fin, the cooling coefficient can be increased by 122.94%, the hydrothermal performance coefficient can be improved by 1.98%, and the volume occupied can be reduced by 76%. However, the optimization of pin-fins mentioned above is based on the geometric dimensions of conventional ones, and there has been no significant change in the shape. Duan et al. [68] optimized cylindrical pin-fins considering energy dissipation and the average temperature and obtained oval-shaped pin-fins by the Globally Convergent Method of Moving Asymptotes (GCMMA). The results showed that the ΔP decreased by 27.9%, and the average η increased by 26.76% compared to the initial ones. Nguyen et al. [69] optimized the shape of the pin-fin in the cooling channel using genetic algorithms and machine learning models, which can automatically search for the shape. They obtained a funnel-shaped pin-fin, which increased its heat-transfer coefficient (h) by about 20% compared to the initial circular one, while the pressure drop loss did not increase significantly. Yang et al. [70] reduced thermal resistance by studying the optimal combination of circular pin-fin height, heat sink width, pressure drop, and heat source power. The results showed that the optimal structure can improve the total thermal performance by more than 10%. Li et al. [71] applied a fast optimization method combining an intelligent algorithm based on 3D geometric reconstruction, spatial discretization, and simulation to optimize a microchannel heat sink. The optimization results showed that b temperature uniformity of the optimized model has been effectively improved, and P_f increased by 210%. Ismayilov et al. [72] used the multi-objective genetic algorithm (MOGA) to optimize the size and angle of attack of the wing-shaped pin-fin, and aimed at achieving the maximum cooling coefficient and minimum pressure drop. The optimization result is a novel bird-shaped pin-fin with a cooling coefficient increased by 11.9% compared to the initial wing-shaped one, and the pressure drop only increased by 7.3%. Berber et al. [73] studied the effect of angle of attack of winglet on heat convection using an Artificial Neural Network (ANN). The results showed that the Nu increased by 146.4~211.5% compared with a NACA-type winglet without curves. Table 3 gives the comparison of different structural optimizations. From the table, it can be observed that most of the optimization processes are two-objective optimization, which includes maximizing heat transfer and minimizing flow resistance. With optimization, the whole comprehensive performance is improved.

Table 3. Comparison of different structural optimizations.

Authors	Initial Structures	Optimization Objects	Optimization Algorithm	Optimal Results	References
Moon and Kim [19]	Fan-shaped	Maximize the Nu and minimize the friction loss	Radial basis neural network method	The Nu increased by 22.82%, and friction loss increased by 22.82%.	Conventional circular pin-fin
Li and Kim [63]	Elliptical	Maximize the Nu and minimize the f	NSGA-II	The Nu increased by 87.8% and the f increased by 38.7%.	Initial elliptical pin-fin
Ghosh et al. [64]	Circular	Maximize the Nu and minimize the ΔP	Bayesian	The Nu increased by 0.4% and the ΔP increased by 33.2%.	Initial circular pin-fin
Horiuchi et al. [65]	Circular	Minimize the R_{th} and minimize the ΔP	MOGA	The R_{th} decreased by 1.24% and the ΔP decreased by 35.3%.	Initial circular pin-fin
Radmark et al. [66]	Rectangular	Minimize the R_{th} and minimize the ΔP	ANN combined with NSGA-II	The ΔP decreased by 37% without scarifying the R_{th}.	Initial rectangular pin-fin
Sahel et al. [67]	Semi-spherical	Maximize the Nu and minimize the volume and mass	/	The Nu increased by 122.94%, and volume decreased by 76%.	Initial semi-spherical pin-fin
Duan et al. [68]	Circular	Minimize the flow energy dissipation and the average T	GCMMA	The ΔP decreased by 27.9%, and the average η increased by 26.76%.	Initial circular pin-fin
Nguyen et al. [69]	Circular	Minimize the T and ΔP	GA	The h increased by 20%.	Initial circular pin-fin
Yang et al. [70]	Circular	Minimize the R_{th}	Regression model	The R_{th} decreased by more than 1.24%.	Initial circular pin-fin
Li et al. [71]	dual split-cylinder	Maximize the P_f	Generalized pattern search (GPS)	The P_f increased by 210%.	Initial dual split-cylinder pin-fin
Ismayilov et al. [72]	Wing-shaped	Minimize the h and minimize the ΔP	MOGA	The h increased by 11.9%, and ΔP increased by 7.3%.	Initial wing-shaped pin-fin
Berber et al. [73]	Curved winglet	Maximize the Nu	ANN	The Nu increased by 146.4%~211.5%.	NACA type winglet without curves

However, size or shape optimization can only achieve the objective function by adjusting the structural points or boundaries, without changing the topological structure. With the rapid development of additive manufacturing (AM), the limitations of generating complex geometric shapes have been overcome, which also means that size and shape optimization cannot fully tap into the outstanding potential of additive manufacturing [74]. Meanwhile, topology optimization, as a promising design method, can find the optimal size or shape of the model and optimize the topology structure. This method automatically generates free form and efficient structures, meeting the requirements of additive manufacturing solutions. Therefore, topology optimization has higher design degrees of freedom and is more popular than size- and shape-optimization methods [75]. In recent years, topology optimization has been introduced into the field of thermal fluid structure design. The main idea of this method is to unify the fluid and solid through a design variable and interpolate the properties of the material. By optimizing the design variable field, liquid and solid distributions can be obtained. The ability to generate free shapes has aroused great interest among researchers.

The above optimization processes are based on the basic pin-fin as the initial blueprint, and through optimization algorithms, irregular geometric shapes are obtained. However, some researchers have developed a new optimization method that does not have initial pin-fin geometry. During the optimization process, the design domain is represented by a density field, and its properties continuously change from solid to fluid. The optimization of irregular topological structures in fluid systems began with the treatment of Stokes flow by Borvall and Peterson [76]. They provided mathematical proofs of the existence of optimal solutions and the convergence of discrete solutions in the article, and concluded that regularization is not required. Yeranee et al. [77] aimed to minimize pressure loss and improved the thermal performance of cooling channels by utilizing density based on topology optimization considering turbulent flow. The optimization results showed that under the constrained volume, the optimized model had a larger heat-transfer area and higher surface temperature uniformity. Compared with circular, diamond, and triangular pin-fins, the heat transfer is improved by 31.6%, 28.5%, and 34.9%, respectively. Haertel et al. [78] adopted a topology-optimization algorithm based on density to optimize the pin-fin in the radiator, with the objective of minimizing heat-transfer resistance. They found that topology optimization can reduce thermal resistance by 13.6% through parameterization research. Hu et al. [79] used topology-optimization techniques to generate adaptive pin-fin shapes and arrangements in microchannels, and achieved good heat-transfer results. They suggested that topologically optimizing the shape and arrangement of the pin-fins promotes fluid mixing and reduces low-velocity regions. The results showed that the average T can decrease 30.1%, and ΔP decreased by 17% compared with circular pin-fins. Alexander et al. [80] proposed a density-based topology-optimization method to optimize the pin-fin of a three-dimensional heat sink with natural convection cooling. The results indicated that the obtained topological structure validates the previous conclusions about the length/thickness ratio and Biot number (Bi), and also indicates that the irregular geometric structure generated by topological optimization can significantly improve the cooling performance. Xie et al. [81] adopted a topology-optimization process based on the variable density method, with minimum pressure drop as the optimization objective and heat-transfer performance as constraints. They replaced the traditional three-dimensional model with a two-dimensional model to optimize the design of the convective air radiator structure. The average temperature of the optimized radiator decreased by 5.76% and the Nu decreased by 42.9%. Huang et al. [82] studied the topology-optimization problem of variable density microchannel heat sinks and analyzed the essence of the appearance of gray elements from the perspective of the working mechanism of variable density by Sequential quadratic optimization (SNOPT). They compared the results with traditional linear microchannels and found that the T decreased 9.3 °C. Gilmore et al. [83] applied topology optimization to a three-dimensional conjugate heat-transfer model to generate a novel microchannel heat sink structure for high heat flux cooling, minimizing both temperature and pressure drop during the optimization process. The optimization results showed that the structure reduced the pressure drop by 17% and the R_{th} by 22.4%. Table 4 gives the comparison of different structural optimization. From the table, it can be observed that most of the optimization processes are two-objective optimization, which includes maximizing heat transfer and minimizing flow resistance. With optimization, all the comprehensive performance is improved.

Table 4. Comparison of different topology optimization.

Authors	Optimization Objects	Optimization Algorithm	Mathematical Solution	Optimal Results	References
Yeranee et al. [77]	Minimize pressure loss	Variable density method	/	The heat transfer increased by 31.6%, 28.5%, and 34.9%.	Circular, diamond, and triangular pin-fins
Haertel et al. [78]	Minimum the ΔP	Variable density method	GCMMA	The R_{th} decreased by 13.6%.	Conventional channels
Hu et al. [79]	Minimum the ΔP, and maximum T as a constraint	Variable density method	MMA	The average T decreased 30.1%, ΔP decreased by 17%.	Circular pin-fins
Alexander et al. [80]	Minimize T	Variable density method	MMA	/	/
Xie et al. [81]	Minimum the ΔP	Variable density method	GCMMA	The Nu decreased by 42.9%	Conventional channels
Huang et al. [82]	Minimize the T	Variable density method	SNOPT	The T decreased 9.3 °C.	Conventional channels
Gilmore et al. [83]	Minimize the T and ΔP	Variable density method	SNOPT	The R_{th} decreased by 22.4%, the ΔP decreased by 17%.	Conventional channels

3.2. Layout Optimization

According to the literature summary in Section 2.3, the arrangement of the pin-fin has a significant impact on the flow and heat-transfer performance. Therefore, many researchers are committed to improving the flow and heat-transfer performance by optimizing the layout. Meng et al. [84] applied NSGA-II and the TOPSIS method to optimize the arrangement of pin-fins in the flow channel, with the position, number, and relative spacing of the pin-fins as optimization variables. The optimization objectives were system output power and pressure drop. The optimization results showed that changing the arrangement can increase the system output power by 22.89% and reduce the pressure drop by 82.98%. Polat et al. [85] applied NSGA-II to optimize the flow and cooling characteristics inside heat sinks with circular-, square-, and diamond-shaped pin-fins under the same hydraulic diameter. The design variables were porosity number and Re, with the optimization objective of maximizing Nu and minimizing pressure drop ratio. The results indicated that in all structures, the diamond shaped one significantly improved cooling efficiency while increasing the pressure-drop ratio. Lee and Kim [86] optimized the density distribution of the pin-fin using a gradient descent method based on the Kriging approximation model. the height of the pin-fin and the size of the bottom plate are fixed in the optimization process, with the objective of minimizing thermal resistance. The optimization results showed that the thermal resistance of the optimized layout is reduced by 11% and the weight is reduced by 30% compared to a uniform distribution.

Some scholars attempted to optimize the structure and layout of the pin-fin as variables simultaneously. Although this optimization method significantly improved the flow and heat-transfer performance, multivariate optimization also brought huge computational pressure. Moon and Kim [87] applied the NSGA-II based on the Kriging approximation model to optimize an array of staggered circular pin-fins. The optimization parameters included the ratio of the diameter to height and the ratio of the downstream spacing to height. The optimization objectives are to achieve optimal heat-transfer effect and minimize friction loss. The optimization results indicated that at some of the most advantageous points of the Pareto front, it not only improved cooling performance but also reduced pressure loss. Fallahtafti et al. [88] adopted an artificial neural network combined with NSGA-II to optimize the thickness and gap of the pin-fins, using a full factor design with the optimization goal of minimizing both thermal and flow resistance. They found that the optimized structure has a smaller thermal resistance and a pressure drop. Zhao et al. [89] proposed a new type of non-uniform pin-fin cooling plate to improve temperature uniformity, power consumption, and weight performance, and used an elliptical basis function (EBF) neural network model combined with a multi-island genetic algorithm (multi-island GA). The numerical simulation results showed that the use of non-uniform turbulence column-optimization design can reduce power consumption by 29.84%, weight by 29.0%, temperature standard deviation by 17.43%, and maximum temperature by 1.04 °C.

4. Conclusions

This work provides a detailed introduction to the application of pin-fins in enhancing heat transfer, including the conventional shape, improved and irregular shape, layout of pin-fin and optimization techniques of pin-fin shapes and layout. It can be seen that with the development of manufacturing technology, irregular pin-fins will become the future development trend due to their better flow and heat-transfer performance. We hope that the above research can have reference value for our colleagues. The authors are certain that pin-fin technology will continue to advance quickly with our joint efforts. The main conclusions of this paper are as follows,

The horseshoe vortices produced by different pin-fins are different, including the strength and size; this is the main reason they affect the heat-transfer effect.

Different improved circular pin-fins and irregular pin-fins behaved better compared with initial circular pin-fins, especially the inclined ones; the Nu can be increased by 37.9% compared with vertical pin-fins. However, the processing cost is higher.

Compared with a single pin-fin, the combination of pin-fin with other cooling methods has obvious effects on enhancing heat-transfer. The heat-transfer performance of all structures is improved compared with initial pin-fins, and the protrusion cooling method behaved the best; the average Nu increased by 87.4~127.3%.

The larger diameter, height and density of the pin-fins will further reduce the flow area when the fluid flows through the pin-fins, resulting in increased flow resistance. But at the same time, the flow velocity and turbulence intensity of the air flow through the pin-fins are further increased, and the heat-transfer effect will be enhanced.

In terms of the shape optimization of the pin-fins, various intelligent optimization algorithms are applied to optimize the structural parameters of the pin-fins, especially MOGA and NSGA-II methods. Since there is no shape limitation in the initial topology optimization, the performance after optimization is better than that of conventional optimization methods, and the variable density method is adopted in all topology-optimization methods. In terms of layout optimization, NSGA-II is the most commonly used.

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