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REVIEW OF ENHANCEMENT OF HEAT TRANSFER FROM RECTANGULAR FIN ARRAYS

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Abstract

Heat transfer removal rate from surfaces is great importance in many engineering applications. For many industrial applications like automotive, air conditioning, electronic cooling, spacecraft and aircraft applications, internal heat generation can cause overheating problems that may result in system failure, short machine life, need of maintenance and low system reliability. To solve such problems passive cooling techniques are widely used. This article summarizes an extensive literature review of rectangular fin structures that is much-used heat transfer enhancement technique with a high efficiency rate and a low cost. Moreover, in this study not only solid rectangular fin structures are studied but also inclined, perforated and staggered type rectangular fin studies are summarized. To increase the heat transfer rates and Nusselt number distributions, designers should optimize the parameters such as fin number, fin shape, fin height, fin diameter and inter-fin distance ratio for all of the fin types. In the optimization process of those components, designers should have experience with the fin design procedure; without the necessary experience and knowledge, instead of increasing the heat transfer rates, fin surfaces can resist and block the incoming air flow which will affect heat transfer rate adversely. This review is a guideline for designers presenting how rectangular fin arrays are used to enhance heat transfer rates.

Keywords: Rectangular fins, perforated fin, inclined fin, interrupted fin, convective heat transfer

DİKDÖRTGEN KESİTLİ KANATÇIKLARIN ISI TRANSFERİNE OLAN ETKİSİ: DERLEME MAKALESİ

Öz

Birçok mühendislik probleminde ısı transferi oranları önemli bir etkiye sahiptir. Otomotiv, havalandırma, elektronik soğutma, hava aracı gibi birçok endüstriyel uygulama alanında ısı artımı, ekipmanlarda fazla ısınmaya neden olarak sistem hatalarına, kısa makine ömrüne, güvenilirliğin düşmesine ve bakım ihtiyacının artmasına neden olmaktadır. Bu tip problemlerin önüne geçilmesinde pasif soğutma teknikleri sıklıkla kullanılmaktadır. Bu derleme makalesinde yüksek verim ve düşük maliyet ile ısı transferi iyileştirmesi sağlayan pasif soğutma tekniklerinden olan dikdörtgen kanatçıklar araştırılmıştır. Ayrıca dikdörtgen kanatçıkların eğimli, delikli, aralıklı, hizalı ve kaydırılmış olarak kullanılmasının ısı transferine olan etkilerinin araştırıldığı birçok makale de özetlenmiştir. Kanatçıklı yapılar ile ısı transferini arttırmak için tasarımcılar, kanatçık uzunluğu, kanatçık şekli, kanatçık genişliği, kanatçık sayısı, kanatçıklar arası mesafeler gibi birçok parametreyi optimize etmek mecburiyetindedir. Bu optimizasyon sürecinde deneyim sahibi olmayan bir tasarımcı, ısı transferini arttırmak yerine, tasarladığı kanatçıklı yapı ile gelen havanın ısınan hava ile karışmasını engelleyip ısı transferi üzerinde tam tersi etki yaratabilmektedir. Bu derleme makalesi ıs transferiini dikdörtgen kanatçık kullanarak maksimize etmek isteyen tasarımcılar için bir rehber niteliğindedir ve literatürde bu konu ile yapılmış geniş bir spektrumu taramaktadır.

Anahtar Kelimeler: Dikdörtgen kanatçık, delikli kanatçık, eğimli kanatçık, ısı transferi

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1. Introduction

For many industrial applications, internal heat generation can cause overheating problems, which may result in system failure, short machine life, need of maintenance and low system reliability. To handle overheating problems, active and passive methods are defined.

(a)Active Methods: In the active methods some external power output is needed, like stirring the fluid; vibrating the surface; use of magnetic fields and jet impingement.

(b)Passive Methods: Geometrical or surface modifications are mostly performed in the existing material or additional devices like extended surfaces and rough surfaces are added to the system, which does not need extra energy. Passive solutions are preferred widely as they have proved to be cost effective, noiseless and trouble free solutions [1,2].

Extended surfaces, one of the passive methods, are widely used in the engineering disciplines, which are concerned with energy transitions requiring heat movement. Installing a fin in a heating surface increases the convective heat transfer coefficient or increases the heat transfer area of the surface, which causes enhancement in the heat dissipation performance, protecting the reliability and durability of the devices. As they are easy to manufacture, cheap and have proved efficient, fin arrays are commonly used in heat exchangers, cooling of gas turbine blades, cooling of electronic devices and other application areas that require high heat flux removal rates [3-5].

Basic modes of the heat transfer are convection, conduction and radiation. Convection is a widely used cooling technique. If convection occurs naturally without any external forces, it is known as natural convection. Forced convection and mixed convection are better choices when compared with natural convection as they provide higher heat transfer rates and higher Prandtl numbers. In forced convection, adding a fan or a pump to the system is the most common method. Air is forced to move with the help of the fan. Mixed convection occurs when both natural and forced convection mechanisms act together in the heat transfer process and flow is driven by buoyancy forces [6-9].

In every new design, thermal losses of power electronic devices are increasing while sizes are decreasing therefore several types of fin geometries like rectangular, cylindrical, annular, pin fins and square have been used in order to strengthen the heat transfer area of the surface. Rectangular fins are the most popular fin type due to their low cost, high thermal efficiencies and easy manufacturing procedure. In Figure 1, types of the rectangular fins, which are used to increase heat transfer in the literature, are given. Standard type rectangular fins are well studied in the literature since 1960's. Inclined, perforated and staggered type rectangular fins are types of the new cooling techniques and have been studied for 20 years. Studies are performed experimentally, numerically and analytically in order to develop theoretical expressions, graphical correlations and empirical correlations to represent the coefficients for natural convection heat transfer from vertical and horizontal plates.

Important dimensionless numbers that are used in the correlations are Reynolds number (Re), Nusselt Number (Nu), Prandtl Number (Pr) and Rayleigh Number (Ra). Reynolds number is the ratio of inertial forces to viscous forces. Reynolds number definition based on hydraulic diameter is given below.

$$\mathrm{Re} = \frac{u_\infty D_h}{v} \tag{1}$$

The Nusselt number is the ratio of convection heat transfer rate to the conduction heat transfer rate.

$$Nu = \frac{hL}{k} \tag{2}$$

Prandtl number is defined in equation (3).

$$\mathrm{Pr} = \frac{\mu C_p}{k} \tag{3}$$

At higher Reynolds number values, inertia forces dominate the flow instead of viscous forces therefore, boundary layer becomes smaller. When the Prandtl number is high, inertia forces govern the flow and the region that thermal diffusion is important in, which is known as the thermal boundary layer, becomes smaller. The Rayleigh number (Ra) for a fluid is a dimensionless number associated with buoyancy driven flow, which is defined in equation (4).

$$Ra^* = \frac{g\beta\Delta T x^3}{vk} = Gr\,\mathrm{Pr} \tag{4}$$

Using the data obtained from experiments or numeric studies; temperature, velocity, voltage drop and electric current is obtained. Using these data, Re, Nu, Pr and Ra number distributions are measured in the studies [10-12].In accordance to rise the heat transfer rate, designers should optimize the parameters like fin number, fin shape, fin height, fin diameter and inter-fin distance ratio for all fin types. In the optimization process of those components, designers should have an experience about the procedure; otherwise, instead of increasing the heat transfer rates, fin surfaces can resist and block the incoming airflow, which will affect heat transfer rate adversely.

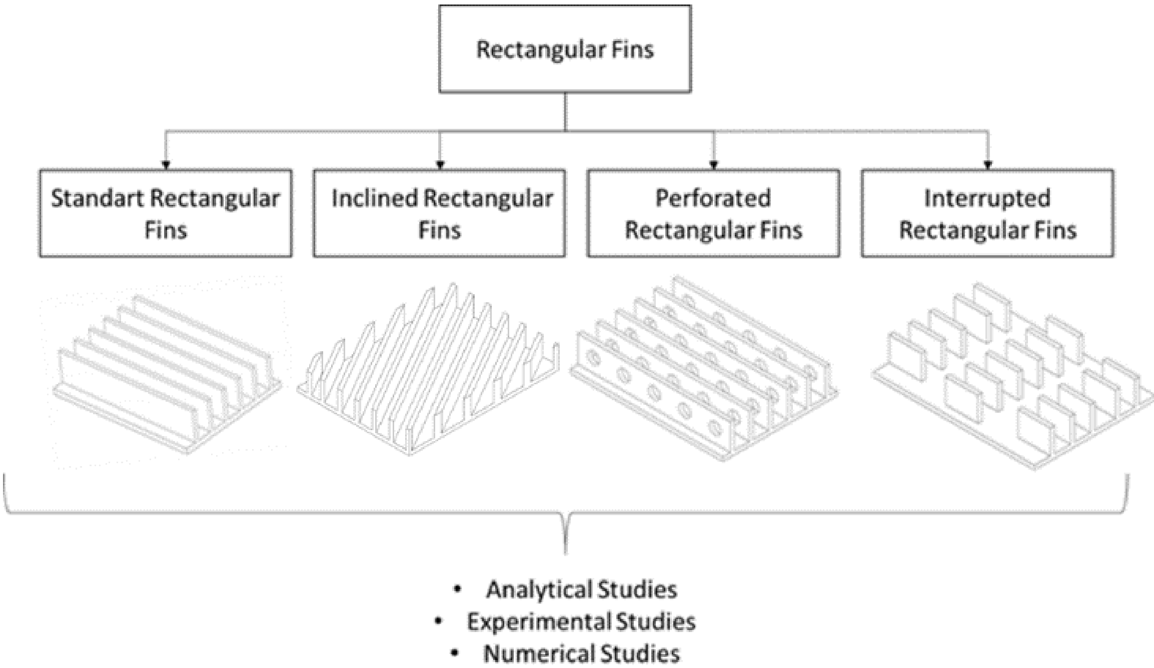

Figure 1. Different rectangular fin types and schematic view of the fin arrays

2. Studies on Standard Rectangular Fins

The ability to heat loss rapidly via natural or forced convection through a vertical or horizontal base is a function of rectangular fin array geometry, i.e. fin length, fin separations (inter-in distance), fin thickness and also fin number and fin material. To see the effect of those parameters to heat transfer and pressure drop, several researches performed since 1960s. In Figure 2, geometrical parameters that effect the fin performance and fin array configuration is shown schematically. Some of the important results of those researches are summarized in this section of the paper.

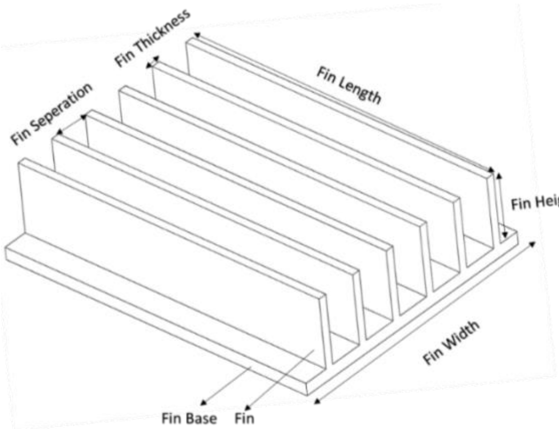

Figure 2. Geometrical fin parameters

2.1. Experimental Studies for Standard Rectangular Fins

Elenbaas [13] presented the first problem of natural convection of parallel plates. Many new studies have been carried out since Elenbaas, both numerically and experimentally. In 1963, Starner and McManus [14] carried out an experimental study with four sets of rectangular fins. Number of fins in the array was changed between fourteen and seventeen and fin height and spacing was altered. With this research it is observed that fin spacing and fin height has a direct impact on heat transfer rates, and also that insufficient applications of fins to a surface can cause lower heat transfer rates when compared to cases without a fin. In light of the acquired knowledge it was concluded that to reach maximum heat transfer rates, narrow fin spacing should be provided in the surface.

For four fin separations and three fin heights on vertical rectangular fin surfaces for free convection heat transfer, experimental investigation is performed by Welling and Wooldridge [15]. Closed spaced fins have a smaller temperature difference in boundary layer when it is compared to widely spaced fins. Widely spaced fins behave like flat plates, and higher heat transfer coefficients are observed. Welling and Wooldridge [15] confirmed the research results of Starner and McManus [14].

Harahap and McManus [16], conducted an experimental study to see the effect of fin spacing, fin height and fin number on natural convection heat transfer. Chimney type flow pattern is observed for all of the cases. As tall fin channels are able to aspirate higher amounts of incoming fresh air and due to this mass flow rate effect, single chimney broke into chimney strips with a decrease in fin height. As single chimney flow is favorable for higher heat transfer coefficients, researchers suggest choosing proper ratio of fin height to fin height to avoid sliding chimney strip flow. A correlation is proposed as it is given in Equation (5) for the available data of the researchers.

$$(Nu)_L = C\left[(Gr)_L(\Pr)\left(\frac{nS}{H}\right)\right]^a\left(\frac{S}{L}\right)^b\left(\frac{H}{L}\right)^c$$

$$\begin{cases} 10^6 < \left[(\mathrm{Gr})_L(\Pr)\left(\frac{nS}{H}\right)\right] \le 2.5\times10^7 \\ C = 5.22\times10^{-8}, a = 0.57, b = 0.412, c = 0.656 \end{cases} \quad (5)$$

$$\begin{cases} 2.5\times10^7 < \left[(\mathrm{Gr})_L(\Pr)\left(\frac{nS}{H}\right)\right] \le 1.5\times10^8 \\ C = 2.787\times10^{-8}, a = 0.745, b = 0.412, c = 0.656 \end{cases}$$

Jones and Smith [17] presented some experimental results to optimize the arrangement of rectangular fins for free convection heat transfer. Average heat transfer coefficients and spacing effects are reported in [14] and [16] are in agreement with the data of this research. Correlation that was obtained by Harahap and McManus [16] (given in Eq. 6), is compared with their data. Data correlations suggest that, correlation parameters of ref [16] are questionable.

Leung et al. [18] compared the heat transfer characteristics of vertical and horizontal rectangular fin arrays. Smoke is introduced to the experimental test rig for different fin separations (10 mm, 20 mm and 40 mm). Although, for all of the fin separations two circulating zone is generated, with the increase of the fin separation distance vortex structures strengthened and more flow enters the inter fin separation.

In another research, Leung et al. [19], study the effect of increasing the fin length to the heat loss experimentally. In the small fin separation distances, increase of the fin length causes large reduction in the heat loss, also the correlation generated by Harahap and McManus [16], promoted this conclusion. Leung and Probert [21,22], conducted an experiment to measure the effect of varying the fin thickness on heat loss for free convection conditions from a vertical rectangular base and from a horizontal rectangular base. To keep the base area same, when fin thickness is reduced, number of fins are increased so the heat transfer area is also increased, on the other hand, for a thinner fin, temperature drop occurs rapidly which causes lower local rate of heat loss. Also when the fin separation is shortened, more inhibited convection occurs. Due to this confliction situation, authors claimed that there should be a critical fin thickness, which corresponds to a maximum heat transfer rate. Bar and Cohen [23, 24] predicted this critical value theoretically for free convection conditions. Non-dimensional correlations are generated for both vertically and horizontally based vertical-finned systems they are given above [24-26]. For the vertically-based vertical finned system:

$$\begin{cases} (Nu)_L = 0.135(\mathrm{Gr'Pr})^{0.5} & when\, Gr'\Pr \le 250 \\ (Nu)_L = 0.423(\mathrm{Gr'Pr})^{1/3} & when\ 250 \le Gr'\Pr \le 10^6 \end{cases} \quad (6)$$

For the horizontally-based vertical finned system:

$$\begin{cases} (Nu)_L = 0.116(\mathrm{Gr'Pr})^{0.5} & when\, Gr'\Pr \le 500 \\ (Nu)_L = 0.457(\mathrm{Gr'Pr})^{1/3} & when\ 500 \le Gr'\Pr \le 10^6 \end{cases} \quad (7)$$

Modified Grashof number (Gr') is given as:

$$Gr' = \left[\frac{g\beta s^3}{v^2}\right]\left[\exp\left(-\frac{kb}{k_f\delta}\right)\right]\left[\frac{s}{(Lb)^{0.5}}\right] \quad (8)$$

Experiments are performed to investigate the effect of fin material to the free convective cooling by Ko et al. [27]. For materials, duralumin with a thermal conductivity of 160 W/mK and stainless steel with a thermal conductivity of 14 W/mK is used. Results suggest that the stainless-steel fin arrays have a little lower heat transfer performances than duralumin fin arrays with similar geometries. Fin separation is found as almost independent of fin material. Due to the research of Babus'Haget al. [28], thermal conductivity of the material of the fins had only a small effect on the heat transfer rate. Also, they confirmed that fin material has no effect on fin spacing.

Harahap and Setio [29] review the correlation that was generated in their previous work [16] and with using more extensive data, which was collected with this work; they introduced corrections to their previous correlation. The experimental data of this research presents a range of W/L values, the effect of W/L (Width of the fin array/ Length of the fins) is also taken account and Equation 5 was revised to the following form.

$$(Nu)_L = C\left[(Gr)_L(\Pr)\left(\frac{nS}{H}\right)\right]^a\left(\frac{S}{L}\right)^b\left(\frac{H}{L}\right)^c\left(\frac{L}{w}\right)^d$$

$$\begin{cases} 2\times10^6 < \left[(\mathrm{Gr})_L(\Pr)\left(\frac{nS}{H}\right)\right] \le 2\times10^7 \\ C = 1.86\times10^{-4}, a = 0.576, b = 1.812, c = 0.656, d = 0.755 \end{cases} \quad (9)$$

$$\begin{cases} 2\times10^7 < \left[(\mathrm{Gr})_L(\Pr)\left(\frac{nS}{H}\right)\right] \le 2\times10^8 \\ C = 1.15\times10^{-3}, a = 0.875, b = 0.812, c = 0.656, d = 0.755 \end{cases}$$

Effect of different fin spacing, fin length and fin thickness ranges to the heat transfer rate was studied by Yazicioglu and Yüncü [30,31]. They performed experiments for different heat inputs (25, 50, 75, 100, 125 W) for all of the geometrical configurations. Maximum heat transfer and fin spacing is correlated as it is given in Equation 10 and 11.

$$\frac{S_{opt}}{L} = 3.94Ra_L^{-1/4} \quad (10)$$

$$\dot{Q}_{c,\max} = (\mathrm{Q}_c) + 0.124\,\mathrm{Ra}_L^{0.5}\,kH\Delta t\left(\frac{W}{L}\right) \quad (11)$$

Dogan and Sivrioglu [32,33], designed an experimental set-up to observe the effect of fin spacing, fin height and magnitude of heat flux on heat transfer for both mixed and natural convection dominated flow regimes. In their first research Dogan and Sivrioglu [32], Reynolds number was 250 and Richardson number was between 600 and 15000. Results suggest that, increasing the fin height causes rise in the heat transfer rates. Up to the critical fin spacing value heat transfer coefficient rises and then it decreases with the increase of fin spacing. Therefore, researchers define an optimum fin space interval. When fin spacing is reduced below the optimum fin space value, developed boundary layers on fin surfaces intersects and this intersection blocks cold fluid entrance between the fins.

In their second study Dogan and Sivrioglu [33], Reynolds number is around 1500 and Richardson number is between 0.4 and 5, which corresponds to mixed convection flow regime. In this study, Nusselt number correlation is attained which is the function of Re, Gr and fin geometrical parameters.

Hong and Chung [34] carried out numerical and experimental analysis of open channel natural convection heat transfer of a finned plate. Three different fin spacing are examined to observe the effect of fin spacing in natural convection heat transfer. Researchers observed that there is an optimal fin spacing range and in the outside of this range heat transfer is impaired.

Ayli et al. [35] studied forced convection heat transfer from longitudinal fins in a square channel experimentally and numerically for turbulent fully developed flow and a correlation is developed and compared with experimental results. The correlation which is given in Equation (13) is applicable for $9.17 \times 10^7 < Re < 2.47 \times 10^8, 0.089 < \frac{d}{w} < 0.0625, \quad 0.24875 < \frac{t}{L} < 0.729$ range. d and t are defined as the fin separation and inter fin distance respectively.

$$Nu = 4.69822 \times 10^{-7} \, \mathrm{Re}^{1.11986} \left(\frac{d}{w}\right)^{-0.215} \left(\frac{t}{L}\right)^{-0.207} \qquad (12)$$

2.2. Numerical Studies for Standard Rectangular Fins

One of the first numerical studies about heat transfer from rectangular fin arrays had been performed by Sana and Sukhatme [36], they employed three-dimensional approach to analyze single chimney flow patterns and they obtained an agreement with the experimental data.

Vollara et al. [37] conducted a model to calculate the heat transfer of vertical finned surfaces in natural convection. Heat flux can be changed by 20 % by reduction of the optimal fin spacing. Effect of fin length and fin spacing are investigated for copper fins in the research of Arquis and Rady [38]. For increasing the heat transfer rates, the fin spacing for low values of fin height should be carefully chosen as a function of Rayleigh number.

Baskaya et al. [39] investigate the effects of fin spacing, fin height, fin length, fin temperature difference between fin and surroundings on the free convection heat transfer from horizontal fin arrays numerically. For fin surface symmetry condition and for other boundaries open boundary condition was used. After grid independency studies, researchers compare their data with the experimental study of Harahap and McManus [16]. According to comparison between computational fluid dynamics (CFD) results and experimental results, maximum difference is found as 8 %. After reaching the accurate results, a parametric study was conducted with changing the fin length, fin spacing, fin height, temperature difference between fin and surrounding. Due to their results, heat transfer coefficient reduces with fin length, shorter fins produce single chimney flow while longer fins produce multiple chimneys where single chimneys has better heat removal characteristics than multiple chimney flows.

For different fin spacing and fin height, steady state, laminar natural convection heat transfer in three dimensional horizontal rectangular enclosures was studied by Pathak et al. [40]. They concluded that Nusselt number rises by increasing the number of fins, which means decreasing S/H ratio, after critical S/H value, increasing the fin number results with the decrease in the Nusselt number. S is defined as fin thickness and H is defined as fin height in the paper. In Figure 3, comparison of the several experimental data and analytical models in the literature for vertical rectangular fins with natural convection heat transfer rate is shown.

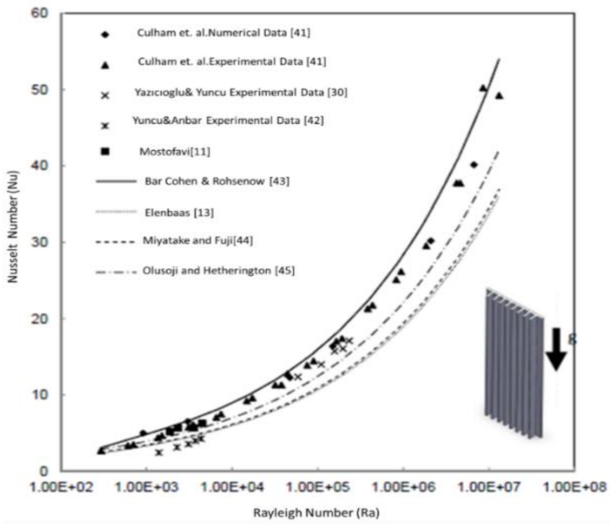

Figure 3. Comparison of some experimental and analytical models in literature (courtesy of Mostofavi [11])

3. Studies on Interrupted Rectangular Fins

In time, to improve the heat transfer rate in finned structures new geometrical improvements were implemented to the finned surfaces. For several decades, the primary approach to increase the heat transfer and efficiency was creating gaps on solid continuous fins (Figure 1). The flow area that is created in this gap, also interruption length, fin length, fin-separation distance has a direct effect on heat transfer rate. In this part of the research, several researches about natural and forced convection heat transfer from interrupted vertical and horizontal rectangular fins are summarized.

In continuous fin surfaces, rate of heat transfer decreases as flow becomes fully developed after critical length. On the other hand, interrupted fins disturb the thermal boundary layer and reset the boundary layer growth in each fin leading edge corner by this way a thermally developing flow regime is maintained which leads to higher heat transfer coefficients. Also using interrupted fins provides lower weight and provides cost reduction to the manufacturers [46, 47].

3.1. Experimental Studies for Interrupted Rectangular Fins

Ahmedi et al. [48] performed an experimental and numerical study about natural convection from rectangular interrupted fin arrays. With this research, they focus to determine the optimum values for several geometrical parameters of fin arrays like effects of fin spacing and fin interruption length. Continuous and interrupted fin experiments were carried out to observe the effect of the interruption. Also for five continuous finned plates experimental studies were conducted and compared with the analytical existing model of [32]. Number of interruptions varied between 1 to 4. Results of the study showed that, resetting boundary layer increases the heat transfer rates. When interruptions are added, heat flux from the heat sink rises. Also a correlation is developed to calculate fin interruption as it is given below.

$$\left(\frac{G}{L}\right)_{opt}=11\times\left(\frac{T_w-T_\infty}{T_\infty}\right)^{-2.2} \quad (13)$$

Where, G is the fin interruption length. This correlation is applicable in the range of $10^2 < Ra < 10^6$.

Kharce and Farkade [49] used rectangular notched fins to rise the heat transfer rate. Due to the comparison of experimental studies that performed with notch and without notch fins it was seen that heat transfer coefficient rises at a level of 20%.

Wange and Metkar [49], created a stagnant zone in the bottom of the rectangular fin array. They performed experimental and numerical analysis to compare the results. While the notch area is kept the same, by changing the fin length and fin height, fin surface area is changed. It can be resulted from present studies, geometric parameters of fin like depth of notch has a direct impact on fin performance.

Dixit and Mishra [51], conducted an experimental study to investigate the effect of notch in the heat transfer rate and also find optimum notch dimensions. When notch depth increases heat transfer coefficient also increases.

Shehab [52] investigated the rectangular notch portion effect on free convection heat transfer rate experimentally. In this study fin number and fin spacing effect were investigated for rectangular notched fins. The research illustrates that when the removal area of the fin increases, the average heat transfer coefficient also rises and an increase in heat input causes a peak in the heat transfer coefficient. Rising the fin spacing causes more fresh air entrance between the fins, therefore heat transfer rate goes up.

Bakale et al. [53], performed experiments to observe the effect of different notch sizes on heat transfer coefficient. Four types of fins used as without notch, %10 notch, %20 notch and 30% notch. The study showed that as the notch size increases so does the heat transfer rate.

While Wange and Metkar, Dixit et al., Shabab and Bakale et al. [50-53] used aluminum as a fin material Kharce and Farkade [50] used copper for notched fin material instead. They reveal that a copper plate gives a better heat transfer rate than an aluminum one.

3.2. Numerical Studies for Interrupted Rectangular Fins

Singh and Singh [54], studied steady state heat transfer for notched fins for different heat inputs and different notch geometries. They concluded that triangular notched fins give the maximum heat transfer coefficient when compared to circular and trapezoidal notched fins. Furthermore, rectangular notch structure increases the heat transfer rate 50.51 % when it is compared to un-notched rectangular fin.

Kallanavar and Kapale [55] examined parametric effect of notched fin arrays over natural convection heat transfer computationally. Parameters that were investigated were fin spacing, depth of notch cut, percentage cut of notch and shape of notch. As notched fin material both aluminum and copper was used. Taji et al. [56]'s experimental data is used to verify the numerical results. They commented that rectangular notched fin arrays provide greater heat transfer rate than triangular and semicircular notched structures. What's more, they reveal that with the rise of the fin spacing, heat transfer coefficient reaches an optimum value. After reaching the critical value, heat transfer starts to drop.

Heat transfer coefficient of fin with different rectangular notch size for cylinder fins was investigated by Beldar [57] both numerical and experimental. It is observed that increasing notch percentage also increases heat transfer coefficient and Nusselt number.

4. Studies on Perforated Rectangular Fins

Rising the fin surface area, reducing the thermal boundary layer thickness and creating more turbulence has a desirable effect on heat transfer enhancement, pressure drop, Nusselt number and friction factor.

To improve ventilation and to create more turbulence in the fin array holes, cavities, grooves which are generally circular are introduced to the fin surface. Essa et al. [58, 59] and Zan et al. [59] showed that perforations in the fin surface decrease the weight of the fin and material cost while increasing the heat transfer rate. By introducing circular holes, Meng et al. [61] showed an enhancement of 16.7% in the heat transfer rate. Sara et al [62] claims that solid blocks and fins cause a flow separation which originates dead flow zones and for that reason perforated fins have higher heat transfer value.

Several researches are performed experimentally and numerically in order to optimize the perforation diameter, perforation position, perforation number and perforation geometry to maximize the heat transfer coefficient and fin efficiency.

4.1. Experimental Studies for Perforated Rectangular Fins

Ehteshum et al. [63] perform experiments to observe the effect of perforation size and number of perforation on rectangular fin array inside a channel under turbulent flow. Perforation effect on heat transfer rate is compared with unperforated solid fin structures. Their results represents that fins with larger perforations are more efficient than smaller perforations and solid fin structures.

Awasarmol and Pise [64] conducted an experimental investigation of natural convection heat transfer from perforated rectangular fin arrays with different inclinations. Holes are drilled from 4 mm to 12 mm. In the first part of their study they determined the optimum perforation configuration and in the second part they determined the optimum perforation diameter. Due to the results, there is a critical perforation diameter that maximizes the heat transfer rate. Perforation fin with 12 mm hole and 45° angle of orientation creates 31% enhanced heat transfer while decreasing material weight by 30%.

Sahin and Demir [65] performed an experiment to determine the heat transfer and pressure factor characteristics of the perforated fins in the test channel. Due to the perforations, resistance to the flow is smaller which causes lower friction factor.

Ehteshum et al. [66] studied thermal and hydraulic performance of rectangular fin arrays with different perforation size and number experimentally. Results show that fins with larger perforation are more efficient.

Muthuraja et al. [67], carried out experiments for fins with circular perforations to observe the heat transfer enhancement. Due to their experimental results, heat dissipation rate for the perforated fins were dependent strongly on perforation dimensions.

%10, %20 and %30 percentage of circular perforation on rectangular fin was reported in the research of Patil et al. [68]. Both experimental and numerical results are obtained to show that the convection heat transfer rate is influenced by percentage of perforations and base-to-ambient temperature difference.

Ibrahim et al. [69] researched overall heat transfer distribution and effect of perforations under natural convection with experimental studies. Fin diameter effect on temperature distribution is investigated. Increasing the perforation diameter causes a decrease in the thermal resistance that's why increasing the perforation diameter led to temperature drop between the fin top and tip.

Dhanawade et al. [70] also examined the effect of perforation geometry in rectangular finned surfaces and also compared the diameter effect both in circular and square perforations. In their experimental results square fins provide higher Nusselt number when compared to circular perforated fins. Discovered in the research of Prasad et al. [71], heat dissipation for perforated fins depends on parameters like thickness of fin, conductivity of material, shape of the perforation and temperature of the surrounding.

4.2. Numerical Studies for Perforated Rectangular Fins

Huang et al. [72], introduced perforations in the fin base instead of introducing it in the fin surface. This research is one of its kind in the literature for they discuss the perforation length and perforation pattern effect on the heat transfer mechanism due to their numerical study. Shown in their results, fin-base perforations, especially locating in the inner region, improve ventilation and heat transfer characteristics. According to the results of Bassam and Abu [73, 74] increasing the number of permeable fins always increases the Nusselt number and heat transfer unlike solid fins.

Ismail et al. [75], carried out numerical analysis to determine the fin and perforation length effect on turbulent heat convection from rectangular fin arrays. As the fin length is used as the characteristic length for the Reynolds number, Reynolds number effect is also investigated. They compared their numerical results with the experiments of Jonsson and Moshfegh [76]. They found that solid fins have higher Nusselt number than square and circular perforated fins and also solid fins have higher thermal resistances compared with the perforated fins.

Shaeri and Yaghoubi [77], numerically compared the perforated rectangular fin performances with different number of circular holes. Ismail et al. [75] and Shaeri and Yaghoubi [77] used the same computational domain for solid and rectangular fins. Represent numerical data is compared with the numerical and experimental results of ref [78] for solid fin structure. After reaching to good agreement between the results of Rouvreau et al. [78] and the data, researchers continue to analyze the perforated fins. According to the results, average friction coefficient has an inverse proportion of the number of perforation and also Nusselt number decreases with the increase of the perforation number.

Shaeri and Jen [79], compare the effect different perforation sizes on heat transfer characteristics numerically. They compared the obtained results with the results of solid fin in [75]. In the obtained results, it was seen that more perforation mean more floors and ceiling which causes higher friction drag. Also, using smaller number of perforations enhance heat transfer rate more efficiently.

Ismail et al. [80] performed a numerical study to find the influence of different perforation geometries of turbulent fluid flow. It is predicted that hexagonal perforated fins have the largest fin effectiveness when it is compared with square, triangular and circular perforated fins.

A numerical investigation has been performed to investigate the thermal performance of square perforated fins with different porosities by Shaeri et al. [81]. They introduce correlations for prediction of Nusselt number of perforated fins for various Reynolds numbers and porosities (ϕ).

$$\begin{cases} \dfrac{Nu_{perforated}}{Nu_{solid}} = 1.296(\mathrm{Re}_D)^{-0.0357}(1-\phi)^{0.269} \\ 2000 \le \mathrm{Re}_D \le 5000, 0.0556 \le \phi \le 0.444 \end{cases} \quad (14)$$

$$\begin{cases} \dfrac{Nu_{perforated}}{Nu_{solid}} = 0.0307(\mathrm{Re}_D)^{0.226} + 0.583(1-\phi)^{0.704} \\ 2000 \le \mathrm{Re}_D \le 5000, 0.25 \le \phi \le 0.694 \end{cases} \quad (15)$$

Vyas et al. [82] numerically investigated the shape of perforation to optimize the heat transfer rate. Perforated fin array with rectangular, circular and elliptical holes using Computational Fluid Dynamics had been carried out. Due to the results rectangular perforated fin arrays provides higher Nusselt number distribution.

5. Studies on Inclined Rectangular Fins

As it is given in Figure 1, another way to increase the heat transfer rate from fin surfaces is tilting the arrays. Also due to the rotation of the some devices or lack of available place in some scenarios, inclined oriented heat sink becomes compulsory to use instead of vertical or horizontal orientations. These possible scenarios motive the studies, which define an inclination to the finned surface.

The inclination angle effect is especially investigated in the literature surveys for inclined fin structures. The stagnation point in the tilted arrays separated flow to two zones which the convective flow shift the reverse directions which affects the heat transfer rate directly, therefore another important parameter that analyzed in the inclined arrays is the stagnation point of the incoming flow [83,84]. This part of the survey indicates that few studies are available on inclined fin arrays.

5.1. Experimental & Numerical Studies for Inclined Rectangular Fins

Mittelman et al. [84] focused on the flow characteristics of the fins with inclination in their experimental and numerical research. They observed both experimentally and numerically that increasing the inclination angles moves the stagnation line in the direction of the bottom edge of the fin. Flow separation triggers the higher heat transfer rates when it is compared to no flow separation along the fin array cases. Researches advices to create inclination greater than 10° in order to enhance heat transfer rates.

Khudheyer and Hasan [85] focused on natural convection heat transfer from rectangular fins with 1 interruption, 4 interruptions, inclination and v-fins for different heat fluxes. Due to their results, interrupted fin surfaces have higher heat transfer coefficient than inclined fins.

Naidu et al [86] conducted an experiment with five different inclinations (0°,30°,45°,60° and 90°) and experimental results has satisfactory orientation with numerical results. It is observed that convective heat transfer rate increases with the rise of the inclination angle for the tested range.

Rocha and Ganzarolli [87] conducted an experiment for inclined rectangular plates with natural convection. A correlation for the local Nusselt number for natural convection is suggested. Rectangular fins under free convection with different tilt angles were investigated numerically and experimentally by Lee et al. [88]. In the research it is observed that, cooling performance of the fin with 60° of tilt angle is 6% higher than solid rectangular fins.

Tari and Mehrtash [89], aimed to obtain a correlation that is applicable to a wide range of angles between vertical and horizontal orientations. They define inclination angle (θ) from vertical orientation as ±0,4,10,20,30,45,60,75,80,85,90°. They compare their numerical average Nusselt numbers with the correlations from the literature [90, 91]. In their results, small inclinations that are defined from the vertical, the inclination does not have a significant effect on heat transfer rate. Between $-60° \leq \theta \leq +80°$ authors suggest Nusselt number correlations as a function of Grashof number, Prandtl number and inclination angle.

6. Conclusions

This article summarizes an extensive literature review about rectangular fin structures which is one of the passive heat transfer enhancement techniques with low costs and high efficiencies. With the studies which are summarized in this paper covers a lot of ground about heat transfer enhancement with rectangular fin arrays. According to the literature survey conducted in this study the most critical observations which are observed from many investigators can be summarized as given.

- In the solid fin arrays, up to the critical fin spacing value heat transfer coefficient rises after then it drops with the increase of fin spacing. So, researchers define an optimum fin space interval. When fin spacing reduced below the optimum fin space value, developed boundary layers on fin surfaces intersects and this intersection blocks cold fluid entrance between the fins.
- Fin structures with notches have a critical fin spacing value like un-notched solid fin structures. Up to this critical fin spacing, heat transfer coefficient increases and after reaching to this value heat transfer coefficient starts to decrease. According to the researchers, this critical value is a function Reynolds number, Rayleigh number, fin geometrical parameters.
- By modulating the notch position in the fin, geometry of the notch, thickness of fins, material composition heat transfer rate can be increased.
- Due to the some researches in the solid fin structures, increasing the fin number after a critical point creates drop in the Nusselt number distribution of the fin, on the other hand in the perforated fins fin number and Nusselt number has direct proportion.
- Perforated fins have higher heat transfer coefficient than solid fins. They also have advantages like being light in weight, saving material and extracting heat quickly from heated surface. Number of perforations has direct proportion with Nusselt number.
- In the perforated fin heat transfer characteristics, most important parameters that affects the cooling effectiveness are Reynolds number and perforation geometry.
- Whether the finned structure is manipulated or not, important parameters that effect the heat transfer

rate are fin geometry, fin length, fin width and fin number.

- In the literature, several theoretical expressions, correlations, empirical equations have been developed to represent the coefficients for atural and forced convection heat transfer from both vertical and horizontal plates.

Table 1. Several researches about heat transfer enhancement techniques with rectangular fin arrays

Author	Type of Investigation	Fin Type	Fluid, Air Flow Regime	Investigated Properties	Observations
Yazicioglu and Yüncü [30]	Experimental	Standard	3.6×10^6<Ra< 2×10^8	Fin Length& Fin Height& Fin Spacing	*Correlation is obtained for maximum heat transfer rate.
Dogan and Sivrioglu [32]	Experimental	Standard	Re=250, 600<Ri<15000 3×10^7<Ra< 6×10^8	Fin Spacing & Fin Height	*To maximize heat transfer rate, fin spacing should be optimized.
Dogan and Sivrioglu [33]	Experimental	Standard	Re=1500, 0.4<Ri<5 3×10^7<Ra< 8×10^8	Fin Spacing & Fin Height	* Nusselt number correlations are obtained
Hong and Chung [34]	Experimental & Numerical	Standard	0.7≤ Pr ≤2000	Fin Spacing & Prandtl Number	*Optimal fin spacing has an inverse proportion with Prandtl number.
Ayli et. al. [35]	Experimental & Numerical	Standard	17×10^7<Re< 2.47×10^8	Fin spacing& Fin Length & Fin Width	*Effects of geometrical fin parameters are investigated & Correlation is obtained
Arquis and Rady[38]	Numerical	Standard	Pr=0.71, 2×10^3<Ra< 3×10^4	Fin Length & Fin Spacing	*Rayleigh number, fin height, fin spacing relationship is defined.
Pathak et. al. [40]	Numerical	Standard	10^4<Ra< 3×10^5	Fin spacing & Fin Height	*Nusselt number, fin thickness and fin height relationship is defined.
Ahmadi et al. [48]	Experimental & Numerical	Interrupted	10^2<Ra< 3×10^6	Fin Interruption Length	*Correlation is obtained for fin interruption length.
Kharce and Farkade [49]	Experimental	Interrupted (Notched)	Fin material: Copper	Fin material & notch effect	*Interrupted fins provide higher heat transfer rates. * heat transfer trate increases when aluminium plate is used instead of copper.
Shehab [52]	Experimental	Interrupted (Notched)	Fin material: aluminum	Fin Spacing& Fin Number	*Heat transfer coefficient is higher in notched one when it is compared with un-notched.
Bakale [53]	Experimental	Interrupted (Notched)	Fin material: aluminum	Notch length	*heat transfer coefficient has direct proportion with the notch size.
Singh and Singh[54]	Numerical & Experimental	Interrupted		Heat Load & Notch Geometry	*Rectangular notched fins provides higher heat transfer rates than other investigated notch geometries.
Kallannavar and Kapale [56]	Numerical	Interrupted		fin spacing & depth of notch cut, shape of notch	*Heat transfer rate depeds to the ciritical fin spacing
Ismail et. al. [75]	Numerical	Perforated	2×10^4<Re< 3.9×10^4, Pr=0.71	Fin and perforation length	*Solid fins have higher Nusselt number distribution than perforated ones.
Shaeri and Yaghoubi [75]	Numerical	Perforated	100<Re<350	Perforation number, fin length	*average friction has inverse proportion with the number of perforation
Ismail et al. [78]	Numerical	Perforated	2000<Re<5000	Perforation geometry	*Heat Transfer Performance Enhancement: Hexagonal>Circular>Square> Triangular
Shaeri et al. [79]	Numerical	Perforated	2000<Re<5000 Pr=0.71	Perforation porosity	*For practical applications, correlations are proposed.
Mittelman [84]	Experimental & Numerical	Inclined		0° to 30° inclination angle	*Authors advice to define inclination angle higher than 10° to enhance heat transfer rate.
Lee [88]	Experimental & Numerical	Inclined	2×10^5<Ra<1.1×10^6	30°,60° 90° inclination angle, number of fins	* Cooling performance of the fin with 60° of tilt angle is 6% higher than solid rectangular fins.

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