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A Detailed Review on Pin Fin Heat Sink

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***Abstract*—**Heat sinks are being considered in many advanced heat transfer applications including automotive and stationary fuel cells as well as cooling of electronic devices. However, there are innumerable fundamental issues in the fields of heat transfer and fluid mechanics perspectives which remains unresolved. The present review emphasizes on the progress of research in the field of pin fin heat sinks, while understanding the fluid dynamics and heat transfer characteristics with a detailed and sophisticated prediction of the temperature distribution, high heat flux removal and by minimizing thermal resistance. Lot of research work carried out across the globe to address this challenge and trying to come up with an economically viable and user friendly solution. The high activities for future pin fin heat sinks research and development to meet the current issue is recorded in this article.

***Keywords*—**Heat sinks, heat transfer, heat flux, thermal resistance, electronic devices.

I.INTRODUCTION

HEAT sink is a device which is used to dissipate the unwanted heat to ambient and are used in a wide range of applications wherever efficient heat dissipation is required, major examples include refrigeration, heat engines, cooling electronic devices and lasers.

Heat sink performance (including free convection, forced convection, liquid cooled, and any combination thereof) is a function of material, geometry, and overall surface heat transfer coefficient. Generally, in forced convection heat sinks thermal performance is improved by increasing the thermal conductivity of the heat sink materials, increasing the surface area (usually by adding extended surfaces, such as fins or foam metal) and by increasing the overall area heat transfer coefficient (usually by increase fluid velocity, such as adding fans, pumps, etc.).

II.REVIEW PRESENTATION

With the rapid usage of electronical devices, thermal management issues are considered as crucial matters. Therefore, a lot of efforts have been made to understand heat flow methods in such devices. The heat sinks have a large surface area to dissipate the generated heat and reducing the thermal resistance. In fact, the foremost goal in designing the heat sinks is to reduce the thermal resistance. However, due to the space limitation in electronics packages, heat sinks often occupy more space and cause leads to the weight and cost of the finished product. Generally speaking, the performance of a heat sinks depends on so many factors including thermal resistance, geometry of cooling channels mostly fins, location, and concentration of heat sources, and airflow bypass [1]. The efficiency of a heat sink was measured both traditionally as well as experimentally, and the results were available in the form of design graphs in heat sink catalogs [2]. In addition, due to the vicinity of heat sinks with the ICs, ignoring the effect of emitted radiations is inevitable. The radiated noise from an electronically device may disturb the functioning of other electronic packages. Hence, one should take care of radiation effects from the bottom of the heat sink [3], [4]. Shah et al. [5] reported a numerical analysis for the performance of an impingement heat sink. Also they attained an optimal heat sink shape having lower operating temperature and pressure gradient.

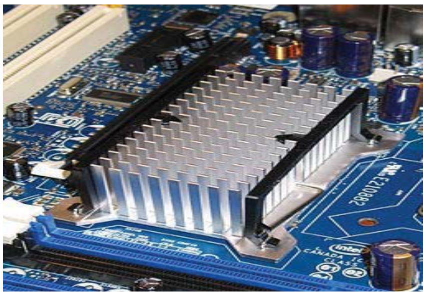

Fig. 1 Pin fin heat sink

Forced convection mode cooling techniques have been adopted to conventional electronics cooling devices with heat sink which shows superiority in terms of unit price, weight and reliability. To design a practical heat sink, some criteria such as a large heat transfer rate, a low pressure drop, and a simple structure should be considered. Regardless of fluid flow direction, the pin-fin heat sink rendours high heat transfer rate without losing its performance [6], [7]. Initial stage studies for pin–fin arrays were performed by Sparrow et al. [8] and Van Fossen [9]. They experimentally studied staggered and in-line pin–fin arrays installed in an internal cooling channel. Metzger et al. [10] investigated the effects of stream wise and span wise distances between pin–fins. They discovered that the area-averaged heat transfer coefficient on the heated surface depends on the streamwise and spanwise distances between pin fins for both staggered and in-line arrays. Chyu et al. [11] conducted an experiment to evaluate the heat transfer performance of staggered and in-line pin–fin arrays in a cooling channel. The heat transfer rate was enhanced by at least a factor of two by introducing one of the pin–fin arrays in the smooth channel, and the staggered pin–fin arrays showed higher heat transfer performance than the in-

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line arrays. Ames et al. [12] experimentally measured the pressure, temperature, velocity, and turbulence intensity in a channel with pin–fins. and, they reported that the pressure coefficient had its maximum value at the first row, and decreased downstream toward the channel exit. Experimental investigations of heat transfer and pressure drop in a rectangular channel with and without pin–fins were performed by Chang et al. [13] at Reynolds numbers of 10,000 to 30,000. This study revealed that the area-averaged Nusselt numbers on the heated surface increased as the gap between the pins and the end wall decreased. The flow and heat transfer through three different heat sink configurations was numerically simulated using the standard k-E turbulence model. The accuracy of the model was calibrated against numerical experiments and reported excellent results for the range of Reynolds number greater than 11,000. The maximum heat transfer dissipated from a heat sink is obtained when the heat sink geometry produces the turbulent flow conditions that simultaneously generates the highest heat transfer coefficient, has the maximum convective surface area and minimum internal thermal resistance [14]. In this study, they have proposed the case of increasing fin height, it was shown that an increase in the heat transfer coefficient can be achieved without an increase in pressure drop when compared at equal mean fin height [15]. Analytical models were developed for determining heat transfer from in-line and staggered pin-fin heat sinks used in electronic packaging applications. The heat transfer coefficient for the heat sink and the average temperature of the fluid inside the heat sink are obtained from an energy balance over a control volume [16].

Pin-fin heat sinks possess complicated fluid flow and heat transfer characteristics due to flow separation. Even though various types of empirical correlations based on experimental data have been presented for pin-fin heat sinks, there exists no closed-form analytical model for accurately estimating the friction factor and the heat transfer coefficient. Most of the studies on pin-fin heat sinks have dealt with circular-shaped [17], [18] or unshrouded pin-fin heat sinks [19], [20]. Ryu et al. [21] and Dogruoz et al. [22]-[24] studied fluid flow and thermal characteristics of shrouded inline square pin-fin heat sinks experimentally. Kim et al. [25] developed a compact modeling method for thermal analysis of inline square pin-fin heat sinks based on the porous medium approach. However, their approach involves numerical simulations for determining unknown coefficients included in the model. Experimental investigation of a heat sink for cooling of electronic devices is performed. The objective is to keep the operating temperature at a relatively low level of about 323–333 K, using a dielectric liquid that boils at a lower temperature, while reducing the undesired temperature variation in the both stream wise and transverse directions. The experimental study is based on systematic measurements of temperature, flow and pressure, infrared radiometry and high-speed digital video imaging [26]. A comparison of various heat sink geometries has been attempted. These were simplified by assuming periodically developed two-dimensional flow and isothermal heat transfer surfaces. In general, it is found that rounded geometries outperform similar sharp-edged fin shapes. In all cases, staggered geometries perform better than inline. At lower values of pressure drop and pumping power, elliptical fins work best. At higher values, round pin fins offer highest performance [27].

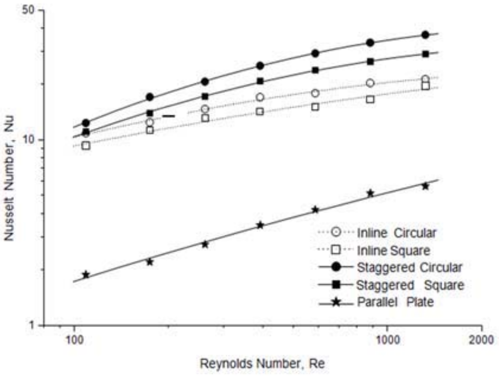

Fig. 2 Nusselt number versus Reynolds number for various fin geometry [27]

For high heat flux cooling, the forced convection is the conventional choice and had been reported by many researchers using pin fin array configuration. Babus'Haq et al. [28] investigated experimentally the steady-state forced convective cooling of a horizontally based pin-fin assembly with circular pin-fins protruded vertically upward from a horizontal base plate. Tahat et al. [29] had experimentally investigated steady-state heat-transfers from pin fin arrays in staggered and in-line arrangements, which were orthogonal to the mean air- flow. For the applied conditions, the optimal spacing of the fins in the span-wise and stream wise directions have been determined. Kim et al. [30] described a novel compact modeling method based on the volume-averaging technique to analyze fluid flow and heat transfer in pin fin heat sinks. The pin fin heat sink was modeled as a porous medium. Peles et al. [31] investigated heat transfer and pressure drop phenomena over a bank of micro pin fins resulting into simplified expression for the total thermal resistance. Su-Ho et al. [32] investigated the pressure drop and heat transfer characteristics of a single-phase micro pin-fin heat sink experimentally by fabricating an array of staggered square micro pin fins of copper. Naphon [33] had presented the experimental and numerical results of the heat transfer characteristics of the inline and staggered taper pin fin heat sink under constant heat flux conditions. Jeng et al. [34] carried out the experimental investigation for pressure drop and heat transfer characteristic on square pin fin heat sink in inline and staggered layout. Khan et al. [35] analytically modeled the circular pin fin heat sink for electronic applications. Selvarasu et al. [36] investigated the effect of pin density on performance by performing steady/time-dependent calculations to investigate the effect of pin density on friction and heat transfer at low Reynolds number. Yang et al. [37] numerically studied the forced convective heat transfer in three-dimensional porous pin fin channels. The Forchheimer–Brinkman extended Darcy model and two-equation energy model are adopted to describe the flow and heat transfer in porous media. Kang et al. [38] optimized the pin fin heat sink with variable base thickness.

Bejan and Morega [39] reported the optimal geometry of an array of fins that minimizes the thermal resistance between the substrate and the forced flow through the fins. They modeled pin-fin arrays as the Darcy-flow porous medium and expressed the local thermal conductance in dimensionless form. Jubran et al. [40] performed an experimental investigation on the effects of inter fin spacing, shroud clearance, and missing pins on the heat transfer from cylindrical pin fins arranged in staggered and in-line arrays. They found that the optimum inter fin spacing in both span wise and stream wise directions is 2.5D regardless of the type of array and shroud clearance used. They also found the effect of missing fin to be negligible for the in-line array but more significant for the staggered arrays. Bejan [41] extended the previous work of Jubran et al. and proved the existence of an optimal spacing between the cylinders. He showed that this optimal spacing increases with the length of the bundle and decreases with the applied pressure difference and the Prandtl number. Tahat et al. [42] studied the effects of varying the geometrical configurations of the pin-fins and found the optimal pin-fin separation in both streamwise as well as spanwise directions to achieve maximum heat transfer rate. They established a general empirical correlation for the average Nusselt number which can be used for both in-line and staggered arrangements. After 6 years Tahat et al. [43] repeated previous experiments for a wider range of Reynolds number, ST/W, and SL/L to give separate correlations for the in-line and staggered arrangements. Azar and Mandrone [44] investigated the effect of pin-fin density on thermal performance ofunshrouded pin-fin heat sinks. They found an optimal number of pin fins beyond which thermal resistance actually increased. They also found that thermal resistance was a function of the approach velocity and the governing flow pattern. Further, pin-fin heat sinks with a small number of pins had the best performance at low and moderate forced convection cooling. Minakami and Iwasaki [45] conducted experiments to investigate the pressure loss characteristics and heat transfer performance of pin-fin heat sinks exposed to air flow in a cross-flow direction, varying the pin pitch as a parameter. They found that as the longitudinal pitch increased, the heat transfer coefficient increased and the pressure loss also increased. Further, as the transverse pitch decreased, the heat transfer coefficient increased, but the pressure loss increased drastically compared to the NuD. Babus'Haq et al. [46] investigated experimentally the thermal performance of a shrouded vertical Duralumin pin-fin assembly in the in-line and staggered configurations. They found that under similar flow conditions and for an equal number of pin-fins, the staggered configuration yields a higher steady-state rate of heat transfer than the in-line configuration. They studied the effect of changing the thermal conductivity of the pin-fin material and found that the optimal separation between the pin-fins in the stream wise direction increased with the thermal conductivity of the pin-fin material, whereas the optimal separations in the spanwise direction remained invariant. Jonsson and Palm [47] performed experiments to compare the thermal performance of the heat sinks with different fin designs including straight fins and pin fins with circular, quadratic and elliptical cross sections. They evaluated the thermal performance by comparing the thermal resistance of the heat sinks at equal average velocity and equal pressure drop. They recommended elliptical pin-fin heat sinks at high velocities and circular pin-fin heat sinks at mid-range velocities. Stanescu et al. [48] performed an experimental, numerical and analytical study of the optimal spacing between cylinders in cross flow forced convection. They determined optimal cylinder-to-cylinder spacing by maximizing the overall thermal conductance between all the cylinders and the free stream. They found that the optimal spacing decreases as the ReD increases, and as the flow length of the array L decreases. Wirtz et al. [49] reported experimental results on the thermal performance of model pin-fin fan-sink assemblies. They used cylindrical, square, and diamond shape cross section pin-fins and found that cylindrical pin-fins give the best overall fan-sink performance. Furthermore, the overall heat sink thermal resistance decreases with an increase in either applied pressure rise or fan power and fin height. Zapach [50] verified experimentally a model for the optimization of pin-fin heat sinks. This model was based on Zukauskas [51] correlations of flow resistance and heat transfer from studies of tube bank heat exchangers. With some minor modification to the heat transfer correlation, he presented a model that can be used to optimize interpin spacing based on a constant fluid velocity or a fan curve. Kondo et al. [52] presented a semi-empirical zonal approach for the design and optimization of pin-fin heat sinks cooled by impingement. They calculated the thermal resistance and pressure drop for an air cooled heat sink and performed experiments and flow visualization to validate the model's predictions. The benefits of using pin fin heat sinks with multiple perforations are investigated using complementary experimental and Computational Fluid Dynamics (CFD) methods. An experimental heat sink with multiple perforations is designed and fabricated and parameter studies of the effect of perforated pin fin design on heat transfer and pressure drops across the heat sinks undertaken. Experimental data is found to agree well with predictions from a CFD model for the conjugate heat transfer into the cooling air stream. The validated CFD model is used to carry out a parametric study of the influence of the number and positioning of circular perforations, which shows that the Nusselt number increases monotonically with the number of pin perforations, while the pressure drop and fan power required to overcome the pressure drop all reduce monotonically. Pins with five perforations are shown to have a 11% larger *Nu* than for corresponding solid pin cases. These benefits arise due to not only the increased surface area but also heat transfer enhancement near perforations through the formation of localised air jets. In contrast, the locations of the pin perforations are much less influential. When examined in the context of CPU cooling, a conjugate heat transfer analysis shows that improved heat transfer with pin perforations translates into significantly reduced processor case temperatures with the additional benefit of a reduction in the weight of the heat sink's pins. To achieve these benefits care must be taken to ensure that pin perforations are aligned with the dominant flow direction and manufactured with a good quality surface finish [53].

An experimental study of a pin fin heat sink was carried out in support of the development of heat sink optimization methods requiring more detailed measurements be made. Measurements of heat flux and temperature are used to separately determine heat transfer coefficients for the pins and the base region between the pins. Three pitch to diameter ratios (distance from pin center to pin center measured diagonally) were studied: P/d = 3/1, 9/4, 3/2. Heat generation was accomplished using cartridge heaters inserted into a copper block. The high thermal conductivity of the copper ensured that the surface beneath the heat sink would be at a constant temperature. The cooling fluid was air and the experiments were conducted with a Reynolds numbers based on a porous media type hydraulic diameter ranging from 500 to 25000. The channel had a shroud that touches the fin tips, eliminating any flow bypass. The base region heat transfer coefficients were, surprisngly, larger than the pin values [54]. This paper presents the effects of heat dissipation performance of pin fins with different heat sink structures. The heat dissipation performance of two types of pin fin arrays heat sink are compared through measuring their heat resistance and the average Nusselt number in different cooling water flow. The temperature of cpu chip is monitored to determine the temperature is in the normal range of working temperature. The cooling water flow is in the range of 0.02L/s to 0.15L/s. It’s found that the increase of pin fins in the corner region effectively reduce the temperature of heat sink and cpu chip. The new type of pin fin arrays increases convection heat transfer coefficient and reduce heat resistance of heat sink [55]. The heat sink of pin-fin array structure is widely applied in the cooling enhancement of current electronic equipment because of the advantage of non-sensitive to airflow direction and large surface area per given volume. In this study, a systematic experimental design based on the response surface methodology (RSM) is used to identify the effects of design parameters of the pin-fin heat sink (PFHS) on the thermal performance. Various design parameters, such as the height and diameter of pin-fin and the width of pitch between fins, are explored in the experiment. The thermal resistance R_{th} and pressure drop ΔP are adopted as the thermal performance characteristics. A standard RSM design called a central composite design (CCD) is applied in this experimental plan. The results distinguish the significant influential factors for minimizing the thermal resistance R_{th} and pressure drop Δp. An effective procedure of RSM has been established for predicting and optimizing the thermal resistance R_{th} and the pressure drop ΔP of PFHS with the design constraints. The experimental results also indicate that the model proposed in this study is reasonable and accurate and can be used for describing the thermal resistance R_{th} and pressure drop ΔP with the limitations of the factors studied [56]. This study performs an experimental study of PFHS having circular, elliptic, and square cross-section. A total of twelve PFHS with inline and staggered arrangements were made and tested. The effect of fin density on the heat transfer performance is examined. For an inline arrangement, the circular pin fin shows an appreciable influence of fin density whereas no effect of fin density is seen for square fin geometry. This is associated with the unique deflection flow pattern accompanied with the inline circular fin configuration. For the staggered arrangement, the heat transfer coefficient increases with the rise of fin density for all the three configurations. The elliptic pin fin shows the lowest pressure drops. For the same surface area at a fixed pumping power, the elliptic pin fin possesses the smallest thermal resistance for the staggered arrangement [57]. Bar-Cohen and his coworkers [58]-[63] studied optimal numerical design of forced convection heat sinks of various plane fin or pin fin geometries. They focused on sustainability and considered energy use at all stages including manufacturing of the heat sink, to arrive “least energy optimization”. Steady-state heat-transfers from pin-fin arrays have been investigated experimentally for staggered and in-line arrangements of the pin fins, which were orthogonal to the mean air-flow. For the applied conditions, the optimal spacings of the fins in the span-wise and stream-wise directions have been determined. The dependences of the Nusselt number upon the Reynolds number and pin-fin pitch (in both directions) have been deduced [64].

The steady-state forced-convective cooling of a horizontally based pin-fin assembly has been investigated experimentally. The circular pin-fins protruded vertically upward from a horizontal base plate. For each in-line or staggered combination of specified pin-fins and air-flow rate, the optimal spacing-to-diameter ratios corresponding to the maximum rate of heat dissipation from the array have been deduced. The effect of changing the thermal conductivity of the pin-fin material has been studied. Designers should aim to have a spacing-to-diameter ratio of 1.04, in the span-wise direction, for all pin-fin systems; whereas, the ratio for the pin-fins in the stream-wise direction will depend upon what fin material is used and whether or not the pin-fins are staggered or aligned [65]. This is an experimental, numerical and analytical study of the optimal spacing between cylinders in cross-flow forced convection. The cylinder array occupies a fixed volume and is exposed to a free stream of given velocity and temperature. The optimal cylinder-to-cylinder spacing is determined by maximizing the overall thermal conductance between all the cylinders and the free stream. In the first part, the optimal spacing and corresponding maximum thermal conductance are determined based on experiments with forced air for H/D= 6.2 and in the Re_D range 50–4000, where Re_D is based on the free-stream approach velocity and cylinder diameter D, and H is the array length in the flow direction. In the concluding section, the experimental and numerical results for optimal spacing and maximum thermal conductance are explained and correlated analytically by intersecting the small-spacing and large-spacing asymptotes of the thermal conductance function [66]. In this paper, they extend the constructal optimization method to cylindrical assemblies of pin fins. The assembly is arranged as a tree with one stem and many radial branches. The optimization consists of maximizing the global conductance subject to fixed total volume and amount of fin material. The length scale of the spacing between adjacent elemental fins is selected based on earlier results regarding the forced convection of compact electronic packages. The optimized features of the tree construct are the external shape (height/diameter) and the internal ratio between the stem diameter and the diameter of the elemental fins. The paper provided how the geometric optimum responds to changes in the remaining parameters of the design: the volume fraction occupied by fin material, the free stream velocity, and the Prandtl number. The optimized geometry is relatively robust. [67]. This paper presented a numerical investigation on geometric optimization of PCM-based PFHS. Paraffin RT44HC is used as PCM while the fins and heat sink base is made of aluminum. The fins act as thermal conductivity enhancers (TCEs). The main goal of the study is to obtain the configurations that maximize the heat sink operational time. An approach which couples Taguchi method with numerical simulations is utilized for this purpose. Number of fins, fins height, fins thickness and the base thickness are parameters which are studied for optimization. In this study natural convection and PCM volume variation during melting process are considered in the simulations. Optimization is performed for different critical temperatures of 50 °C, 60 °C, 70 °C and 80 °C. Results show that a complex relation exists between PCM and TCE volume percentages. The optimal case strongly depends on the fins' number, fins' height and thickness and also the critical temperature. The optimum PCM percentages are found to be 60.61% (corresponds to 100 PFHS with 4 mm thick fins) for critical temperature of 50 °C and 82.65% (corresponds to 100 PFHS with 2 mm thick fins) for other critical temperatures [68]. A three-dimensional inverse design problem is examined using a general purpose commercial code CFD-ACE+ and the Levenberg–Marquardt Method (LMM) to estimate the optimal perforation diameters of perforated pin fin array based on the desired temperature difference between base plate averaged temperature and ambient temperature (ΔT) and system pressure drop (ΔP). The analysis consists of three cases. In design 1, five design variables are used to estimate the optimal perforation diameters and the objective is to minimize ΔT and ΔP of the pin fin array. In design 2, four design variables are considered to determine the optimal perforation diameters based on the minimization of ΔT and ΔP. In design 3, all the perforation diameters are assumed identical and use only one parameter to determine the optimal perforation diameter based on the minimization of ΔT and ΔP. The numerical design results showed that, for all six designs considered here, the designed optimum heat sinks always have the lowest average base plate temperature, it can decrease from 6.3% to 7.3% when compared with the solid pin fin array [69].

III. MICRO PFHS

Micro PFHS, characterized by low thermal resistance, compact structure and uniform temperature distribution along the flow direction, is effective and valuable for thermal management of electronic devices. To enhance the cooling performance of the micro square PFHS, a geometry optimizing method changing pin-fin porosity and pin-fin located angle is presented. The flow and heat transfer characteristics were studied numerically and the geometry of the micro square PFHS was optimized. To reveal the characteristics and advantages of the micro square PFHS, the comparison between the square pin-fin and the column pin-fin was made. Numerical results indicate that both the pin-fin porosity and located angle are important for the cooling capacity and thermal performance of the micro square PFHS; the optimal porosity and located angle for thermal performance are 0.75 and 30° respectively. Furthermore, micro heat sinks with the optimized square pin-fin present better thermal performance than micro column PFHS, which implies that there is great potential to employ micro square PFHS for thermal management on electronic devices with high energy density [70]. Micro PFHS with variable fin density were analyzed numerically in order to dissipate the high heat fluxes expected from the 2016s IC chips with low pressure drops and uniform junction temperatures. The results showed that the fin shape plays an important role in the pressure drop rather than the heat dissipation which was mainly affected by the heat transfer area to fluid volume ratio γ. The best performance was obtained when flat-shaped fins were used. The 100-µm fin length made the system more desirable (good heat dissipation with a reasonable pressure drop) and according to Fig. 3, considering a constant heat flux, a constant junction temperature is achieved [71].

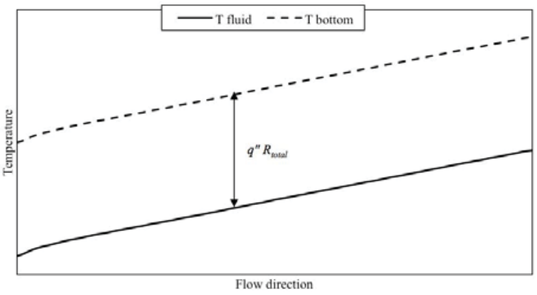

Fig. 3 Sketch of temperature variation in internal flow systems subject to constant heat flux and thermal resistance [71]

Effect of micro pin-fin shapes on cooling of high heat flux electronic chips with a single hot spot was investigated numerically. Hydrothermal performances of different micro pin-fin shapes were evaluated. Circular shape, hydrofoil shape, modified hydrofoil shape, and symmetric convex shape were the cross section shapes used for micro pin-fins. All cooling configurations had the same staggered arrangements for micro pin-fins. An electronic chip with a 2.45 × 2.45 mm footprint having a hot spot of 0.5 × 0.5 mm at its centre was used for simulations. Uniform heat flux of 2000 W cm^{-2} was applied at the hot spot. The rest of the chip was exposed to 1000 W cm^{-2} uniform heat load. The cross section area of the circular shape and hydrofoil shape micro pin-fins was kept the same to have a fair comparison. Convex and hydrofoil shape designs showed significant reduction in the required pumping power as well as the maximum required pressure. In the last case, the height of micro pin-fins was increased from 200 µm to 400 µm to remove 100% of the total heat load *via* convection, and at the same time keep the maximum temperatures within an acceptable range [72]. This paper focuses on studying the effect of thermal resistance and pressure drop of micro heat sinks when subjected to various factors such as pitch distance in axial and transverse directions, aspect ratio of the pin-fin, hydraulic diameters of the pin-fin, and the liquid flow rate through the device. A figure of merit (FOM) involving both the thermal resistance and pressure drop across the heat sink is introduced in the paper and the performance is evaluated on the basis of this FOM. The heat sinks are subjected to uniform heat flux at the bottom of the heat sink and the characteristic study is based on constant Reynolds number of liquid flow at the entrance of the channel. Water is used as the fluid in this study. The study is conducted over the Reynolds number range of 50–500. The characteristic study is carried out with the help of simulations developed using commercially available computational fluid dynamics software CoventorWare™. The characteristic study carried out in this paper is divided into four cases. In the first case the axial pitch distance is varied between 350 µm and 650 µm by keeping the aspect ratio of the pin-fin structure constant at 0.5. For the second case the transverse pitch distance is varied between 150 µm and 300 µm and the aspect ratio is kept the same as in the first case. Third case studies the effect of varying the aspect ratio (between 0.33 and 1) of the pin-fin structures by keeping both pitches constant. Case four studies the variation in the performance of the heat sink with the change in the hydraulic diameter of the pin-fins. The study conducted in this paper reveals the importance of considering the pressure drop along with the thermal resistance in evaluating the overall performance of the micro PFHS. At low Reynolds number (below 300) the heat sinks with circular pin-fins shows better performance compared with heat sinks with square pin-fins and vice versa at high Reynolds number (above 300). FOM varies considerably with the change in the parameters like axial pitch distance, transverse pitch distance, aspect ratio and hydraulic diameter of the pin-fins [73].

IV. Heat Transfer and Pressure Drop Characteristics

Over the past century, several investigators have explored various heat transfer and pressure drop characteristics for flow across a bank of tubes at the macro scale and a considerable amount of data and correlations for heat transfer coefficients (Nusselt number) and friction factors are readily available in the literature. Explicit correlations for various flow regimes (laminar, transitional, or turbulent), pin fin arrangements (staggered or in-line) and pin geometry including longitudinal/ transverse pitch-to-diameter ratio and pin height-to-diameter ratio (L/D) have been developed. Since cross flow over a long array of tubes is commonly encountered in shell-and tube heat exchangers, early studies have mainly focused on arrays of long cylinders with L/D >8 [74], [75]. Mahmoud et al. [76] investigated the thermal effect of 0.25 to 1.00 mm-high fins on copper heat sinks. In their work, the authors considered an upward facing array, uniformly heated by an electrical mat, with input powers ranging from 0.2 to 1.6 W. Their results showed that the values of convective heat transfer coefficient increased while increasing the fin spacing or decreasing the fin height. In their work, the authors did not take into account the effect of fins thickness on the thermal exchange. The investigations described in this section point to the tremendous possibilities with single-phase water cooling. The effective utilization of advanced micro fabrication technologies, combined with an understanding of the basic heat transfer and fluid flow phenomena, will be able to meet the challenges of dissipating heat loads in excess of 5 to 10 MW/m^2 (0.5 to 1 kW/cm^2) [77]. Heat transfer conditions in the flow channels formed by the rectangular fins of a heat sink have been analysed using analytical, numerical and computational methods of varying complexity. Initially results are presented for idealized fins which are 100% efficient using an expression for mean Nusselt number to describe heat transfer conditions from entry to exit. Next a uniform fin efficiency based on this mean Nusselt number is utilised. More detail is then introduced by allowing both Nusselt number and fin efficiency to vary along the flow passage and by calculating air temperatures using numerical integration. Finally the effects of flow disturbance at entry to the heat sink and axial conduction in the cooling fins are modelled in a CFD study with a finite element treatment of the fins [78]. Heat transfer and pressure drop characteristics of micro pin fin arrays in a narrow rectangular channel with an air through flow are studied with different flow rates ranging from laminar to turbulent flow. Copper micro pin fins 150–400 µm long and 75–700 µm in diameter are fabricated by microfabrication techniques. Performance ratios that compare heat transfer to pressure drop characteristics are evaluated to investigate performance of the micro pin-fin surfaces when both heat transfer and pressure drop are important. The results indicate that fluid dynamic effects generated around micro pin fins take a more dominant role for heat transfer enhancement than the area increase due to micro pin fins. A maximum heat transfer enhancement of 79% over plain surface is achieved due to a micro pin-fin surface with a height of 250 µm and a diameter of 400 µm. It is expected that the micro pin-fin surfaces can be used for improving cooling performance of fan-assisted heat sinks for electronics thermal management [79]. Heat-transfer coefficient and pressure drop measurements are reported for a heat sink comprising pin–fins with a cross section of 1 mm by 1 mm and a height of 1 mm. The pin–fins were manufactured on a 50 mm square base plate in a square, in-line arrangement with a pitch of 2 mm. The data were produced while boiling de-ionized water at atmospheric pressure. The mass flux range was 40–200 kg/m^2 s and the heat flux range was 30–470 kW/m^2. The test section was heated from below by an electrical heating method that is normally associated with a constant heat flux boundary condition [80]. This paper investigates heat transfer and pressure drop phenomena over a bank of micro pin fins. A simplified expression for the total thermal resistance has been derived, discussed and experimentally validated. Geometrical and thermo-hydraulic parameters affecting the total thermal resistance have been discussed. It has been found that very low thermal resistances are achievable using a PFHS. The thermal resistance values are comparable with the data obtained in microchannel convective flows. In many cases, the increase in the flow temperature results in a convection thermal resistance, which is considerably smaller than the total thermal resistance [81]. Analytical equations for temperature distribution and heat transfer rate from a cylindrical pin fin with orthotropic thermal conductivity, encountered in the use of thermally enhanced polymer composites, are derived and validated using detailed finite-element results. The thermal performance of such fins was found to depart from the classical fin solution with increasing radial conductivity-based Biot number. The in depth analysis of developed orthotropic axi-symmetric pin fin temperature and heat transfer rate equation is carried out to better understand the heat flow rate in such fins [82].

Endwall heat transfer and pressure drop characteristics in four rectangular channels with a channel aspect ratio of 4 and the staggered arrays of circular pin-fins with four clearances (C) between pin-tips and the measured endwall of 0, 1/4, 1/2 and 3/4 pin-diameter (d) are examined comparatively at Reynolds numbers (Re) of 10,000, 15,000, 20,000, 25,000 and 30,000 to determine the effects of pin-tip leakages on the endwall heat transfer and on channel inlet-to-exit pressure drops. The accelerated flows through pin-to-endwall clearances modify the protrusion-endwall interactions that affect the horseshoe vortices as well as the downstream wakes and shear layer separations. By way of increasing C/d ratio from 0 to 3/4, the area averaged endwall Nusselt numbers decrease with substantial reductions in channel inlet-to-exit pressure drops. The endwall heat transfer level with detached pin-fins at $C/d = 1/4$ is somewhat less than that with attached pin-fins but the pressure drop coefficient of the former is much lower than that of the later, which leads to the highest thermal performance factor among the four comparative cases in the Re range examined by this study [83]. The heat transfer across the fins is by laminar forced convection bathed by a free-stream that is uniform and isothermal. The optimization is subjected to fixed total volume of fin materials. The dimensions of the optimized configuration are the result of balancing conduction along the fins with convection transversal to the fin. The resulting flow structure has multiple scales that are distributed non-uniformly through the flow structure. Numerical results on the effect of Reynolds number and the thermal conductivity ratio on the optimal configuration are reported. The results predicted based on scale analysis are in good agreement with the numerical results. The results also show that the flow structure performs best when the fin diameters and heights are non-uniform [84]. Considering temperature dependent heat transfer coefficients and heat transfer from the fin tip, the optimum dimensions of rectangular fins and cylindrical pin fins are investigated analytically. In this work, the fin volume is fixed to obtain the aspect ratios of the uniform area cross-section fins with maximum heat transfer rates. The characteristic length that has been determined empirically is taken into consideration in heat transfer coefficient. The analysis shows that an optimum aspect ratio of a fin is not found for a fin with heat transfer from the tip at a large fin volume or a large heat transfer coefficient at the fin base. However, there always exists an optimum aspect ratio for an insulated-tip fin. The optimum aspect ratio of a fin is highest for a fin with an insulated tip and decreases with increasing rate of heat transfer from the tip [85]. The thermal and hydraulic characteristics of forced-convective transfers from arrays of vertical, uniformly spaced, rectangular fins, aligned parallel to an undisturbed air stream, have been investigated experimentally. For a constant temperature of the fins' base, at each air flow rate and shroud clearance gap to fin-height ratio, optimal inter-fin separations, corresponding to the maximum steady-state rate of heat transfer, have been determined. The thermal conductivity of the material of the fins had only a relatively small effect on the rate of heat transfer through the array of fins. So optimal geometrical configurations of even relatively low thermal-conductivity plastic material could be usefully employed as covers for rapidly heat-dissipating enclosures for electronic systems [86]. In this paper, experimental results are reviewed and numerical studies during turbulent air forced convection through extended surfaces are presented. The thermal and hydraulic behavior of a reference trapezoidal finned surface, experimentally evaluated by present authors in an open-circuit wind tunnel, has been compared with numerical simulations carried out by using the commercial CFD software COMSOL Multiphysics. Numerical results about heat transfer and pressure drop, both for plain finned surfaces and for pin fin surfaces, have been compared with empirical correlations from the open literature, and more accurate equations have been developed and proposed. [87].

V. CONCLUSIONS

This paper has been provided an overview of the research performed so far in the field of PFHS. This section will summarize the possible future directions of research that may be followed in order to obtain greater understanding of these heat sinks. Effect of coolant types should be investigated more thoroughly. Liquids seem to provide superior cooling properties when compared to gases, since they offer lower thermal resistance. Water has been the coolant of choice for most experiments because it is readily available and cheap and has a high specific heat capacity. In order to produce better cooling at viable costs, one can opt an alternate analysis as CFD package to simulate various types of coolants.

Experiments may be performed later to validate the simulations results.

The optimization of pin fin or other geometry of heat sink dimensions is still in its primary research. This optimization should ensure low and uniform temperature distribution, as well as low pressure drops. Some of the researchers provided optimization of the heat sinks those models pave the way for upcoming optimization models that will guarantee the maximum performance of future PFHS. Fluid properties are affected by variations in temperature; however, most of the studies cited did not consider this fact. Studies accounting for the temperature-dependent fluid properties will certainly give more accurate and realistic results than constant fluid properties studies, by predicting the real performance of PFHS.

Finally, the growing interest in the PFHS, which is evident by the number of available studies, leads to conclusion that research in this area will give us optimized solution in this decade for cooling of electronic devices.

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