CHAPTER 2

LITERATURE REVIEW

The main emphasis of this research work is on the heat transfer enhancement on surface treated heat sinks for energy efficient heating and cooling applications. Hence, a detailed literature review is made on numerous studies carried out by researchers, for further understanding of thermal management of electronic cooling, for gaining information to increase the heat transfer characteristics and for reducing the size of the heat sink with low manufacturing cost. The present survey also pertains to the study of the technological importance and recent growth in cooling systems for electronic devices for enhancement of their performance by increasing surface roughness through use of various surface modification techniques. The initial sections present findings from literature about the thermal management on electronic cooling, natural and forced convection studies on heat sinks through experimental and numerical investigations. In the later part of the chapter, findings relating to literatures about the surface treatment on the heat sinks with surface coating and also by surface modification through grit blasting are presented. This chapter also presents the various surface characterization techniques reported by the researchers.

2.1 NATURAL CONVECTION IN HEAT SINKS

Natural convection and radiation are the preferred modes of cooling due to their ease and simplicity. Cooling of the low-power electronic devices is done through natural convection and radiation. Natural convection has been one of the popular research topics in heat transfer. Natural convection up to 5W of power helps cooling the heat generated in the circuit boards effectively. Natural convection cooling is desired since it does not involve any fans, blower etc., which may lead to break down during operation. In
consumer electronics, components or Printed Circuit Boards (PCBs) placed in the enclosures like Radio, Television, VCR, etc., are cooled by natural convection there by creating adequate number of vents on the casing to allow the cold air to enter inside and the hot air to leave without any restrictions. The medium of fluid is normally air (Yunus 2003). Numerous microelectronic applications employ natural convection cooling due to its reliability and easy maintenance.

Heat sink is a heat exchanger which transfers the heat produced by an electronic device to a fluid medium of coolant liquid or air that enhances heat dissipation from a hot surface. In electronic cooling, plate and pin fins heat sinks are extensively used for getting increased cooling. Normally, the design of heat sink geometric variables is meant to provide increased surface area for getting enhanced thermal performance. Soni (2016) compared three different types of heat sinks of plate, pin, and elliptical fins with vertical base plate under natural convection conditions. Ravi kumar et al. (2017) have made comparison between compared circular pin-fin and plate fins of aluminum heat sinks to control the CPU processor. They optimized the geometric parameters of the heat sinks to improve thermal performance and achieved reduction in cost in all aspects. Reviews on analytical, experimental and numerical analysis with thermal performance and overall convective heat transfer coefficient studies on heat sinks has been reported.

2.1.1 Experimental Studies on Heat Sinks under Natural Convection

Many researchers have made experimental investigation of the thermal performance of the heat sinks under natural convection by modifying their geometric design, orientation, optimum spacing and operating parameters using various fin configurations to enhance the rate of heat transfer.
Bouknadel et al. (2014) have considered taken four heat sinks having different fin configurations for various materials like Aluminum, copper material and compared with Graphite-metal. The design and shape of the sink with suitable orientation plays an important role to carry the heat from the bottom to the top of the heat sink. Guvenc & Yuncu (2001) have investigated the heat transfer performance in rectangular fin arrays attached on a vertical base for fifteen various configurations. The effects due to variations in geometric fin height, length and thickness, spacing between the fins, and ambient-to-base temperature difference were carried out. The heat transfer rate of the fin was maximized for the optimum value of spacing. The rectangular fins mounted on the vertical oriented base were found preferable to the horizontal oriented base for the similar geometry of fin arrays.

Yang et al. (2017) have experimentally investigated pin-fin heat sinks and compared with various design methods of the heat transfer competences. The structural and operating parameters are the main essential factor to consider the total thermal resistance. To reduce the total thermal resistance of the pin fin, various optimum combination of pin fin width, height, pressure drop and input heat source were adopted and compared with other designs. A regression model was built with statistical analysis of experimental data and the optimal control parameters are determined. Uniform design method is used for alternative design to optimize the structural parameters to improve the performance of the product. Zografos & Sunderland (1990) have made experimental studies of the heat transfer coefficient of the aluminum pin-fin arrays. Circular pin-fins with different fin diameters were arranged in a staggered and inline under various spacing between the fin center ratios for different heat inputs and inclinations. An array of pin fins was developed for empirical model that envisaged the performance for the wide range of geometries and Rayleigh number. The conclusion was that the staggered pin fin array provided improved
performance compared to plate fins with the ability to transfer more energy under the same uniform heating conditions. The better performance was seen when the pin fin diameter center to center ratio was 1/3. Welling & Wooldridge (1965) have experimentally studied the effect on free convection heat transfer for various vertical rectangular fin geometries. They varied the height of the fin and distance between the fins for the given temperature. The increase in fin height-to-channel width ratio, the free-heat transfer convection increases. A proportionate increase in the fin conductance also increases proportionally with increase in fin height to channel width ratio was seen.

Deshpande & Taji (2014) have done a comparative experimental study on plain rectangular horizontal fin and perforated fin. They measured the average heat transfer and base heat transfer coefficient under natural convection conditions by keeping the geometric parameters and array constant and made variations in heat input and fin spacing. An enhancement of 15% for the perforated fin compared to plain fins and 10 mm spacing was found to be optimum in this case. Deshpande & Taji (2015) have also experimentally investigated the heat transfer performance of the horizontal perforated rectangular fins under mixed convection conditions. The studies were carried out for a constant fin height, width, and length of fin array by varying the input heat, fin spacing and fluid flow velocity. The experimental results were correlated using dimensionless parameters. They reported the significant on heat transfer from fins as a result of variations in fluid flow velocity on fin spacing and also the need for a small amount of fan energy input for increasing the average heat transfer coefficient. Bakale et al. (2016) made a study of the heat transfer coefficient of horizontal rectangular aluminum fins on the aluminum block. They used different heat inputs for the various fin spacing and notch sizes for optimizing the notch size and maximizing heat transfer. They concluded that the average coefficient of heat transfer increases as the notch size increases and decreases after specific notch
size. Hegana & Kulkarni (2016) conducted experiments on the heat transfer characteristics of the horizontal rectangular aluminum fin arrays. Variations in fin distance were done by addition of aluminum spacers of different thickness between the fins and removal of less effective portion of rectangular fin with semicircular profile notch, with the objective of improving performance. Increase in the average coefficient of heat transfer for notched fin array increases by 30 to 50% than the un-notched fin arrays was observed.

Jones & Smith (1970) made experimental studies on the heat transfer coefficient over a range of isothermal fin arrays on horizontal surfaces. They arrived at the optimum fin spacing, fin height for the maximum heat transfer per unit base surface area and also suggested the preliminary design method which included temperature differences considering the fin weight.

Huang et al. (2008) have carried out experiments on a flat plate and seven different square pin fin heat sinks with various fin arrangements and different orientations were tested under controlled environmental conditions. Depending on the fin structure the performance of the sink with upward and sideward orientation of the fins showed a competitive result. The fins facing downward orientation provided the lowest heat transfer coefficient. The porosity of the heat sink was around 0.83 and 0.91 in fins facing up-ward arrangement and side-ward arrangement respectively.

Bejan et al. (1995) performed analytical, numerical and experimentally investigations for selecting select the optimum spacing between the arrays of horizontal cylinders under natural convection conditions to maximize the total overall heat transfer. There were variations in the array of spacing between the cylinders for the fixed geometric parameters like cylinder height, width, length, and volume. They identified the optimal
cylinder spacing as relatively insensitive irrespective of the cylinder with uniform heat flux.

Starner & McManus (1963) have experimentally investigated the heat transfer coefficient for four rectangular fin arrays, base orientated vertically, horizontally and in the angle of 45 degrees with various fin configurations. The heat transfer rate for horizontal orientation proved more favorable than others showing a strong dependence on end-flow conditions.

Yazicioglu & Yuncu (2007) have experimentally investigated the free convective heat transfer to evaluate the effect of aluminum rectangular vertical fins on a rectangular base plate. Heat sinks were tested for thirty different fin configurations towards optimizing fin spacing, length, and height of the fin parameters. Ambient to base temperature variations were measured for various heat input. The results were compared with the those of the previous work to evaluate the optimal fin spacing and the maximum convective heat transfer rate for the same fin length and ambient to base temperature difference. For rectangular fin arrays on vertical base plate, the experimental results showed better and greater heat transfer rate enhancement than the horizontal based vertical fins.

Sparrow & Vemuri (b) (1986) did heat transfer analysis on the pin-fin heat sink with three different orientations under a combined mode of heat transfer. The radiation components were analytically determined. The fins were mounted on a base plate in an equilateral triangular array. For the fixed values of fin parameters with an increase in number of fins, the rate of heat transfer initially increases and attain maximum and then drops defining optimum fin population. They concluded the heat transfer is 15% and 20% less when the fins are horizontal and downward facing respectively than was when they are faced vertically up-ward.
Sparrow & Vemuri (a) (1985) did experiments on circular rod like pin fins in the combined mode of natural convection/radiation to govern the heat transfer performance. In the study, the base plate was oriented vertically and pin-fins axes were attached horizontally. The investigations were done by varying the heat sink parameters like fin length and diameter. The temperature differences between the base plate surfaces to ambient were also varied. The longer fins were highly efficient and yield six-fold enhancement in heat transfer. Finning was found to be more than the un-finned convection-radiating base plate. The heat transfer increased initially and attained maximum, and then decreased for the stable values of the geometric and thermal parameters. The heat transfer rate decreased when the shrouds were positioned in close proximity to the fin array.

Elshafei (2010) conducted experiments on pin fin heat sinks with circular sections for various parameters of fin geometry, orientation, and heat flux to determine the natural convection heat transfer. There was an increase in the average coefficient of heat transfer with the increase in the diameter ratio for the circular solid pin fin heat sink. For the hollow pin fin heat sinks, the Nusselt number was higher in the sideward orientation than upward. But in the solid pin fin heat sink, the Nusselt number was maximum for the fins facing sideward and upward orientation. For the same heat input, the temperature difference was less in hollow heat sink than that of solid heat sink and one of its value decreases with increasing diameter ratio.

2.1.2 Numerical Studies on Heat Sinks under Natural Convection

Computational methods for analysis of flow and related transport phenomena have attained a level of maturity, whereby they can be used to obtain accurate prediction of heat transfer and complex flow process. These methods are effectively used for the analysis of heat transfer and cooling in electronic systems. An engineer can evaluate the heat transfer process and
flow in much faster time and make appropriate design changes. The design and optimization duration can be reduced substantially by analyzing it using the modern high-speed computers.

Joo & Kim (2015) have studied and compared experimental values with numerical results and validated the thermal performance of the optimized plate fin and circular pin fins with base plate vertically oriented aluminum heat sinks in natural convection. The aim was to optimize the heat dissipation per unit mass and total heat dissipation for the given ambient-to-base temperature difference. For a given volume of the heat sinks, plate fin dissipated the maximum heat than pin fin heat sinks. Pin fin sinks dissipate more amount of heat per unit mass compared to the optimized plate fin sinks when the mass of the heat sink was considered.

Sahiti et al. (2007) have made numerical study to increase the convective heat transfer by optimizing the pin fin heat sinks. The work exhibits the selection of the appropriate best pin-fin cross-section. The performances of the pin-fin were studied with respect to two operating parameters; namely power input and the rate of heat transfer per unit for the same base surface area. The optimization of the cross-section was optioned through the commercial optimization software FRONTIER and Pareto surface modeling solutions are validated through Star-CD. Pareto-frontier solution was obtained and found that the elliptical cross-section to be the best.

Cho & Wong (2015) made numerical studies of the effect of chassis perforations in the horizontal rectangular aluminum fin heat sinks under natural convection conditions. The results showed that the flow venting is smooth and faster resulting in faster was seen as effective cooling. The coefficient of heat transfer will be three times higher, as there was no perforation on the upper chassis wall. The thermal performance was governed by the length and the size of the perforations. When the perforation length
was seen insufficient, the rising heated air was blocked to some extent and the thermal performance would be dropped. Shen et al. (2016) did numerical study of the heat transfer enhancement on the vertical cylinder with longitudinal fins under natural convection used in the electric devices. Heat transfer models were built on the basis of CFD technique. Thermal boundaries along with air flow pattern were discussed. The Nusselt numbers on the surface of the cylinder were independent for the fin height for the cases of low density. Distribution of local Nusselt number on both the cylinder and fin surfaces were analysed and the Nusselt number through the length of the fin was found proportional to the exponential function in vertical direction. The correlation was achieved within a deviation of ±10% by new the finned ratio.

Kim et al. (1991) made a study of the free convective heat transfer in channels formed between a series of vertically sited parallel heat plates. The existing experimental data results for single channels were validated with numerical solutions while calculations were performed for the range of independent parameters like wall thickness to channel width, modified Grashof number and ratio of thermal conductivity of solid surface to air (t/B, Gr*, and k). Occurrence of the maximum hot and cold surfaces temperature at the channel exit was observed. The surface heat flux was uniform for low values of k. The Nusselt number decreases with k for the hot surface and the average cold surfaces, Nusselt number increased with k and reached maximum when k=1. For higher values of k, the heat dissipation was split between the adjacent channels.

Hamady et al. (1994) performed experimental and numerical studies on the heat transfer performance in air-filled heated enclosure. The heated enclosure with the cross-sectional aspect ratio one was rotated about its horizontal axis. Natural convection heat transfer enhancement study of a
rotating enclosure was performed when the flow was driven by gravitational buoyancy forces and the heat transfer was found to be improved. Stability of the flow and heat transfer increased with increase in rotational speed.

Chen et al. (2016) have done Computational Fluid Dynamics (CFD) studies along with experimental data for various flow models in their investigation of the heat transfer and flow characteristics of a circular tube and plate finned-tube heat exchanger for different values of plate fin spacing and tube diameter. The velocity of air between the two fins and temperature was determined numerically for various models and experimental temperature data was used for determination of the fin temperature and heat transfer coefficient of the tube. The numerical fin temperature values at the certain selected locations and the experimental temperature data coincides. For this problem RNG k-ε turbulence model is appropriate than laminar flow model. The results showed that the proposed three novel correlations between the Rayleigh and Nusselt number were in better agreement with the numerical and inverse results obtained.

Qiu et al. (2013) used the three-dimensional computational fluid study to determine the fluid flow and natural convection/ radiation heat transfer enhancement for an externally-finned longitudinal tube placed in a small vertical chamber. The effects of the fin angle and surface emissivity were also examined. The experimental measurement values with numerical model were examined and validated with a proper boundary condition and increase in the mean Nusselt number increases with Rayleigh number was seen for the entire fin angle. The results show the total heat transfer rate as linearly proportional to the fin surface emissivity and it increases with increase in fin angle. The radiation fraction rose with increase in surface emissivity of the fin.
Gherasim et al. (2011) have made comparison of experimentally measured values with numerically predicted results for thermal and hydrodynamic field analysis in a two-channel plate heat exchanger using two extreme flow conditions. The k-ε models along with the non-equilibrium wall function were used for the attainment of the result closest to the experimental data. The flow distributions inside the channel were numerically studied. The study showed that the higher velocity fluid stream along the channel sides exhibiting the regions where two narrow straight smooth passages are located.

Kim (2012) made numerical analysis of the thermal performance of the vertical plate fin under natural convection conditions. Fin thickness was varied in the direction normal to the flow direction. Volume averaging theory was used for optimizing the thickness of the fins. A 10% reduction in thermal resistance was seen when the fin thickness was allowed to increases in the direction normal to the fluid flow. For this optimization, the averaging approach presented in an earlier paper for the case of the heat sinks under forced convection was extended to study the performance of heat sinks under natural convection. However, the difference between the thermal resistances of heat sinks with uniform thickness and the heat sinks with variable thickness decreases as the height decreases and as the heat flux decreases.

Feng et al. (2018) compared conventional plate fin heat sink with cross fin heat sink experimentally to improve natural convective heat transfer. The results were validated with simulated numerically values. In conventional plate fin heat sink the cold fluid can only penetrate to the limited distance inside the heat sink but in the cross fin heat sink the air can pass through heat sink to the entire fin channel which will enhance the heat transfer coefficient.

The trend towards the invention of powerful denser products in the electronic industry is that, a higher level of cooling technique is needed. Further studies should include understanding the exhaustive mechanisms of
fluid dynamic effects that play an important role in heat transfer enhancement of pin-fin surfaces.

2.2 FORCED CONVECTION IN HEAT SINKS

Shrinkage in the size of electronic devices leads to a rise in dissipation of heat per unit area. This necessitates higher volumetric heat densities as more electronic components are packed in a smaller volume. Good thermal design is required for a guarantee of the life of the electronic device and equipment reliability in the field and to minimize the risk of failure. The performance and characteristics of the electronic devices depend on their capability to dissipate the generated heat securely during the operation.

Natural convection electronic cooling is constrained to low-power electronic devices. When cooling is not adequate, it is simply provided with a fan-assisted heat sink by blowing air through the cabinet that houses the electronic devices for cooling the components with high-heat flux. Ebadian & Lin (2011) in their review article, while discussing the conventional cooling techniques, inferred that the microchannel-based forced convection were the most encouraging techniques with a larger capacity for achieving high heat-flux removal rates effectively. Thermally induced buoyancy effects may not be sufficient to cool high-density circuit boards seen currently. Forced convection is employed in such cases.

2.2.1 Experimental Studies on Heat Sinks under Forced Convection

Shende & Mahalle (2013) have elaborated in their review article the aspect of fan selection was very important to maintain the heat source at an acceptable level. In electronic cooling, air can be supplied using one or
several fans. The total volume of air required to flow and the static pressure head of the prime importance to cool the device/system. A fan that is neither undersized nor oversized is selected, since oversized needlessly consume more power and undersize may cause the electronic device to fail due to overheating.

Hamadouche et al. (2016) conducted experiments on open cells rectangular aluminum foam blocks under forced convection. Two different fin heights of aluminum porous blocks and aluminum solid block were investigated for various air velocities between 1 to 5 m/s with constant heat flux of 2 W/cm$^2$. The air entry and exit temperatures and the pressure drop across the foam sample were measured. In forced convection, heat transfer increased by 300 percent for the metallic foams compared with empty channel at lower velocity, which reduced the power supply. The metallic foam increase thermal conductivity and decreased the pressures drop due to permeability and dissipation of more heat.

Li & Chao (2009) did variations on the plate-fin heat sinks to study their thermal performance. Variations in the fin height, width, and the Reynolds number were done. The conclusion was that the highest fin had the better thermal performance with a constant fin width. A combination of various fin widths and Reynolds numbers was taken up for achieving optimal thermal resistance. After certain values of Reynolds number at constant fin height and width improved the thermal performance to some extent. The pressure drops increased when the fin height, width, and Reynolds number increased. In electronic cooling, pin fins heat sinks are broadly used for getting better cooling.

Kobus & Oshio (2005) studied the thermal performance of the aluminum pin fin heat sinks analytically and experimentally. Correlations were obtained for a wide range of fin parameters in natural and combined
convection conditions. Experimental technique was developed to measure thermal characteristics of the aluminum heat sink, and the overall coefficient of heat transfer for the pin fin bundle. The theoretical model was compared with the experimental data for the heat sinks for several fin parameters. The work related to the influence of various aluminum pin fin heat sink parameters on the given optimal fin spacing. The thermal performance of the pin fin heat sink is a week function of fin diameter and it can be enhanced by increasing the fin length.

Kondo & Matsushima (1996) made an experimental study of the impingement cooling performance with the longitudinal fin heat sinks appropriate for LSI packages. The heat sink geometries of length, width and fin thickness were kept constant and the fin height and spacing between the fins were varied. For the longitudinal fin thickness of 1mm, the heat transfer rate increases per unit of pumping power and was maximum for a fin spacing of about 2 to 3 mm.

Van-Fossen (1981) is known for his experimental work on the heat transfer coefficients on short circular pin fin arrays over a Reynolds number range with variation from 300 to 60,000. Pin fins were found to be made of copper and wood, and placed in rectangular cross-section channels. The Nusselt and Reynolds number were compared with the available correlations of longer pin fins for their constant parameters and thermal property conditions. The short pin fin heat transfer coefficients were significantly higher than the plain channel with no pins and the heat transfer was smaller than data available in the literature on longer fins. Pin fin surface heat transfer coefficients were estimated as about 35 percent higher than those on the end walls surfaces.

Olson (1992) studied the heat transfer performance for three different flow geometries of compact heat exchangers. He assessed the
behavior of helium gas at 3.5 MPa with Reynolds number of 450 to 36,000. Three different flow geometries of rectangular channel, circular tube and staggered pin fin with tapered pin at different ratios of wall-to-fluid temperature were investigated. Development of correlations for the isothermal friction factor and Nusselt number was the function of the Reynolds number and fluid to wall temperature ratio. At constant pumping power conditions, the specimen with the pin fin design had better heat transfer rate but the pressure drop is higher than the other specimens.

Chyu et al. (1999) have experimentally evaluated the heat transfer coefficient of cylindrical aluminum pin fin heat sinks. The pin fins were arranged in both inline and staggered arrays in a cooling chamber with identical geometric parameters and studied for the Reynolds number range between 5000 to 25000. The coefficient of heat transfer on pin fin heat sink was approximately 10 to 20 higher than that of uncovered end wall. The staggered pin-fin shows enhanced heat and mass transfer more than the in-line arrays. The results revealed increase in heat transfer by a factor of two through introduction of one pin fin array in the channel.

Moores & Joshi (2003) conducted experiments to study the effect on fin tip clearance over the shrouded pin fins with three different pin fin diameter-to-height ratios. The working fluid water that flowed through with the Reynolds number range varied from 200 to 10000. The fin arrays were exposed to a constant heat flux of 0.02 to 0.26 W/mm². The result revealed that the small tip clearance increased the heat transfer since the tip provided more heat transfer area and decreased due to bypassing of the flow through the fin tip clearance. Mean heat transfer rate and overall pressure drop across the fin array appeared to increase due to additional surface area when exposed to the cooling fluid through the clearance.
Ames et al. (2004) made measurements of the pressure drop, temperature, turbulence intensity and mean velocities in a cooling channel with staggered pin-fin arrays. The local heat transfer rate was documented and their results showed the peak heat transfer rate is at the third row in the array for the Reynolds number beyond 10,000 and pressure coefficient had its maximum value at the first row and further reduces downstream towards the exit.

Yang et al. (2007) studied experimentally the heat transfer performance of aluminum pin-fin heat sinks. Twelve pin fin heat sinks with various cross-sections having elliptic, circular, and square fins in an in-line and staggered array arrangement were tested. There was an increase in the heat transfer coefficient for all the configurations with increase in fin density. The elliptic fin shows enhanced performance more than circular pin-fin in the staggered array arrangement, showing the least pressure drop and thermal resistance at a fixed pumping power for the same surface area.

Experimental studies were performed by Sara (2003) on the convective heat transfer performance analysis and friction characteristic on a rectangular duct with pin fin aluminum heat sinks with square cross section. The fins arrays were in inline and staggered arrangements. Various distances between the fins and clearance ratios were used with constant pumping power constraint. A comparison of the staggered configuration results with those of the inline arrangement showed the square cross section as a better heat transfer performance at lower Reynolds number. The average Nusselt number rose with a decrease in distance between the fins and clearance ratio.

Lin et al. (2005) studied the effect of the oblique planner fins with high pressure axial flow fans on thermal resistance in the enhancement of the heat transfer. Oblique fin planner heat sink and axial flow cooling fan were
designed, fabricated and tested. An oblique fin reduced the undesired obstruction in the incoming airflows and pressure drop across the sink which increased the overall heat transfer characteristics of the system. Oblique fin heat sink assembly showed enhanced heat-dissipating capability compare to the conventional vertical fin heat sinks.

Sparrow et al. (1980) conducted experiments on the performance analysis of heat transfer rate and pressure drop of in-line pin fins and made comparison with the staggered-fin arrays. In a staggered pin fin array, the coefficient of heat transfer and the pressure difference were higher than in the inline array. The constant mass flow rate and heat load the staggered array needed a smaller amount of heat transfer surface than inline array. On the other hand, for the conditions of equivalent heat transfer area and pumping power, staggered fin array transferred the heat lesser than inline fin array.

Kuang et al. (2012) made experimental study of the cooling performance of the open celled high porosity copper foam heat sinks under axil fan impingement flow. In comparison with plate fin heat sink with copper, foam heat sink requires 10% and aluminum required 30% of its weight and 50% of volume for the both to achieve heat dissipation of same level. The overall heat transfer performances of heat sink was enhanced by reducing the impinging distance and keeping the foam height within the range at fixed ratio of 0.22 with the optimal low thermal resistance.

2.2.2 Numerical Studies on Heat Sinks under Forced Convection

Choi & Jeong (2016) did investigation on a low noise small quiet fan usually fixed to the side of the central processing unit (CPU) for cooling electronic components. The heat sink in conjunction with a cooling fan is the conventional device for heat removal method for cooling the CPU type of the high-performance electronics devices. The air flow and thermal performance
analysis of the projected heat sink were simulated and validated with physical performance testing. The proposed heat sink was to have a smaller volume and lightweight which could provide a performance similar to that of the existing cooling device. The heat sink with circular design was proposed to dissipate 130W and the temperature level of less than 85°C with noise level of below 23 dBA.

Dilpak Saurabh & Taji (2016) conducted experiments on the natural and forced convection heat transfer over the vertical plate fin arrays with triangular perforated notch. The numerical model was established for various combinations of the fin height, spacing, and the heat inputs and was compared with experimental results. The researchers compared the heat transfer patterns among flat perforated fins. The heat transfer coefficient and total heat flux increased with increase in the perforations depth and the fin spacing moved towards the lower values with a drop in the Richardson number ($R_i$). For both the convection cases the experimental results closely matched with the numerical values.

Peles et al. (2005) did a study and validation of the heat transfer performance and pressure drop phenomena of the circular micro pin-fin array heat sink. The parameters affecting the total thermal resistance were discussed and were experimentally examined and compared with numerical results. The fin efficiency decreased due to large heat transfer co-efficient for micro scale pin. The efficiency was increased by using short pins, but the heat transfer coefficients for intermediate pins length were found insufficient for the demand for the low Reynolds number. Still many researches have been carried out for the analysis of the thermal performance, pressure drop characteristics of micro channel heat sinks in both single and two-phase fluid flow.
Deshmukh & Warkhedkr (2013) have used the physical measurement technique for indirect measurement of the overall coefficient of heat transfer under mixed (natural and forced) flow conditions of the fully-shrouded elliptical and circular pin fin heat sinks. A theoretical model was established for predicting the influence of thermal resistance on heat sinks for various thermal, geometrical and flow parameters. The optimum design parameters such as pin aspect ratio, spacing along longitudinal and transverse direction. Configuration air flow and its orientation were examined. The results showed increase in the fin spacing in longitudinal and transvers directions in turn the fin bundle void fraction. With increase in the void fraction, the coefficient of heat transfer apparently increased faster, causing increase in thermal performance. When the void frication rose much beyond a= 0.702, the convective heat transfer coefficient apparently increased as fast as the fin surface area decreased, causing increase in the thermal performance. The heat transfer coefficient in elliptical staggered array increased due to large fin surface area and intermixing fluid in contact with the cooling fluid.

Jouhara & Axcell (2009) studied the thermal performance of the rectangular fin heat sink under laminar forced convection. The performance of the heat sink was analysed analytically and numerically using commercial CFD software. The calculated result showed the fin effectiveness and the overall heat transfer coefficient with significant variations along the flow path in axial direction from entry to exit. Enhanced performance on the heat sink could be obtained from laminar flow, using calculations in mean values for the Nusselt number and the fin efficiency derived from analytical expressions.

Zhou & Catton (2011) did investigation of the forced convective heat transfer for different types of heat sinks through the channels. The thermal and hydraulic performance on pin-fins for five different cross-sections shapes (Square, circular, elliptic, drop form and National Advisory Committee for Aeronautics (NACA). profile) with different pin width to fin
spacing ratios using finite volume method was studied. All tested shapes of pin fin had an enhanced heat transfer as well a higher pressure drop. The NACA and the elliptic pin fins were seen having a better overall performance.

Aihara et al. (1990) conducted experiments on the heat transfer performance of the pin-fin arrays placed on the vertical base plate. Studies were made for the radiative heat transfer and temperature along the pin-fins arrays. The average coefficient of heat transfer of the multiple pin fin arrays was obtained by subtracting the base plate convective and radiative heat transfer rate of the heat sink from the total heat transfer rate and correlated with the dimensionless parameters based on effective horizontal pin spacing and array length. The generalized characteristics are similar to those of rectangular fin arrays.

Naphon & Sookkasem (2007) fabricated a tapered aluminum pin fin heat sink and investigated numerically and experimentally the heat transfer phenomena under defined heat flux in an inline and staggered arrangement. The turbulent heat transfer characteristic was simulated using k-ε turbulence model for different Reynolds number and heat fluxes. The array arrangement had a remarkable effect on the air flowing over the heat dissipater which increases the heat transfer rate. The first-row shadow had an effect on the second-row flow characteristics. The higher Reynolds number was able to overcome the effect of shadow, providing reasonable experimental measured values when compared with the measured results with the predicated values. Adewumi et al. (2017) made numerical analysis of the convective heat transfer characteristics and fluid flow through single micro channel micro pin-fin heat sinks for diverse cross-sections, for maximizing the heat transfer with the best geometric parameter when micro channel heat sink was heated at the base under incompressible steady laminar fluid flow. For a constant total volume with various cross-sectional shapes of micro pin-fin, there were variations in number of rows from three to seven rows for the axil distance
between 1 to 10 mm. The combined heat sink with circular shaped pin-fin with the six rows showed a better thermal performance than the single micro channel heat sink without pin-fin.

Wei & Joshi (2003) evaluated the overall thermal characteristics of the micro-channel stacked heat sinks with simple network thermal resistance model. The thermal resistance for the stacked micro-channel heat sinks could be minimized by increasing the pumping power but there was a reduction in the effectiveness. Optimized stacked micro-channel has strong dependence on the channel length and the thermal resistance is less for smaller channel.

Khan & Yovanovich (2007) made a theoretical study of the effect of cylindrical pin-fin heat sink approaching the airflow that passed at the lateral sides and top of the heat sink. The overall thermal and hydraulic performances of laminar forced convection on the heat sink were investigated. Empirical and analytical correlations were used. The conclusion was that the lateral and top clearance ratios reduced, the heat transfer and pressure drop. The in-line arrangement provided a low pressure drop but thermal resistance was more across the sink with a decrease in the overall performance of the heat sinks.

Sathe et al. (1997) did numerical analysis of the flow and heat transfer characteristics of the three-dimensional flows in the heat sink of ceramic substrate on which fins made of aluminum-copper alloy. They analyzed with two different air flow rate through the nozzle with steady laminar flow over the fins. Provision of uniform heat flux to the ceramic base was assumed. The temperature at the ceramic base next to nozzle was found to be low and rose gradually towards the center region and increased outward. The predicted pressure drops and base to tip temperatures of the fins were compared experimentally and found to be well within the experimental
observations. This type of analyses gives better accurate results evaluating different designs in an economical manner thus reducing the cycle time.

Yeom et al. (2016) studied the heat transfer performance and pressure drop of copper micro pin fins in a rectangular channel experimentally for various air flow rate ranging from laminar to turbulent. The smaller micro fin height of 150 µm and 250 µm with a larger diameter provided a higher heat transfer rate. The maximum rate of heat transfer was achieved when the micro pin fin length was 250µm and diameter was 400 µm.

Abdullah & Autee (2015) experimentally investigated the square perforated pin-fin in staggered arrays in a rectangular channel compared with perforated cylindrical pin-fins. Fin height, pitch distance and the Reynolds number were seen as the main factor affecting the heat transfer performance. The maximum heat transfer for cylindrical fins was observed when the fin height was 100 mm, inter fin spacing ratio 3.417 and Reynolds number 17350. The fin height had a control over the friction factor and minimum friction factor was observed when the fin height was 50 mm with a pitch distance of 3.417and 42000 Reynolds number.

Muhammad (2013) investigated the heat transfer performance of hexagonal pin fins with circular, square and rectangular configurations arranged in staggered and in line arrays. The hexagonal fin yielded lower Nusselt number compared to circular fins and a higher Nusselt number than square fins. In hexagonal fin geometry, the total heat transfer rate was higher like in circular fins in a staggered arrangement compared for all the Reynolds number. The total heat transfer rate is higher in staggered arrangement than in-line. The circular pin fins with staggered array yielded highest Nusselt number and lowest in inline rectangular pin fins.
2.3 HEAT TRANSFER PERFORMANCE ENHANCEMENT WITH SURFACE TREATMENT

Surface treatment is the recent trend for enhancing the heat transfer at the interface of the contacting surfaces. It comprises surface preparation by the addition of materials, chemically deposited over the surfaces or mechanically creating roughness on the surfaces. There has been considerable research supported through various studies on heat transfer, wetting behavior on hydrophobic/super hydrophobic surfaces. New material coatings have resulted in a significant enrichment in thin film and coating technologies. Nano particles to the heat sinks have shown encouraging outcomes, with a better feasibility in heat dissipation. Grit-blasting is normally used in preparing surface roughness. The grit basting on the heat sink was utilized to modify the surface structure which increases the roughness. Surface topography shows a significant influence on the properties as a result of the grit blasting at the surface interface.

Shanmugan & Mutharasu (2014) coated 400 nm thickness of Aluminum Nitride (AIN) on Copper (Cu) substrate using Direct Current (DC) sputtering for thermal interface material application. A reduction in junction temperature and thermal resistance was observed compared with un-coated Cu substrate. For high power LED’s the use of AIN thin film as interface material provided improved enhanced results. Schowalter et al. (2003) indicated the use of Aluminum Nitride (AIN) as a substrates material for electronics applications for emerging wide-band gap and opto-electronic devices.

Senthilkumar et al. (2013a) did experimental investigation on the un-coated and coated carbon nano tubes on the rectangular brass extended surfaces. The rectangular brass extended fins were coated with carbon nanotubes. The heat transfer rate and surface temperature were investigated.
for several heat inputs were investigated. The heat transfer characteristics and the temperature were investigated using the Taguchi method for experimental design. The heat transfer performances of un-coated and coated brass rectangular extended surfaces were compared. The average increase in the heat transfer rate was seen to be around 12%. Senthilkumar et al. (2013b) chose rectangular aluminum fins for the analysis and coated with carbon nanotubes using the Physical Vapor Deposition (PVD) method for enhancing the fin heat transfer rate. The heat transfer coefficient and fin efficiency for un-coated and coated surfaces were calculated and compared. A 5% improvement in the average percentage in fin efficiency for carbon nano-coated aluminum surfaces was seen.

Dietz & Joshi (2008) have done experimental comparative study to facilitate better removal of heat in electronics cooling by growing Copper Nanotubes (CNT) on the bottom surface of silicon micro channels. The hydrophobic nature of CNTs on silicon micro channel increased the thermal resistance which was credited due to the contact resistance between them. Based on an investigation, the thermal performance gained by increasing the surface area within the micro channel was reported for a constant pressure drop. This was overshadowed by a reduction in mass flow rate for a fixed pressure drop. Taha et al. (2016) have studied experimentally the impact of the convective heat transfer behavior on Carbon Nanotubes (CNTs) with different layer thickness deposits on a silicon substrate inside a rectangular micro channel. The heat transfer performance of the CNT deposited layer samples was compared with that of the bare silicon samples. The dependence of heat transfer enhancement upon the CNT layer thickness, resulting in higher effective thermal conductivity inside the thermal boundary layer was reported. The augmentation was attributed to effective surface thermal conductivity inside the thermal boundary and the surface area. Khanikar et al. (2009) examined the benefits of CNT coating on the base wall surface of a rectangular micro-
channel. The copper CNT-coated and uncoated surfaces share some resemblances in boiling behavior. Coated surfaces were tested with same mass velocities to see any time dependence parameter of critical heat flux. At high mass velocities, substantial changes in the impact of CNT coatings were seen compared to low velocities. The CNT coated surface flow with high velocities caused significant changes in the morphology. Drawing a clear conclusion from the work on enhancement potential of nanostructures was a difficult job.

Teng & Teng (2013) have referred to vertically aligned multi wall carbon nano tubes (MWCNTs) on a micro channel that improved the thermal conductivity within the boundary layer. There was a 12.9% reduction in power consumption in the most of the LED lamps for the fixture with housing coated with MWCNT of 1.328 wt. % at the projecting angle of 0°. The nano-coating improved the longevity of the related components. Vertically aligned multi wall carbon nano tubes on a micro channel improved the thermal conductivity within the boundary layer. This could extensively contribute to saving in energy and carbon emission reduction. Shahzad et al. (2016) have done investigation on vertically aligned multiwall carbon nanotubes grown on the patterned silicon (Si) surfaces using the chemical vapor deposition technique. The heat transfer coefficients for silicon substrate fins coated with and without MWCNT were measured. About 40% enhancement in convective heat transfer was for the silicon substrate fin coated with MWCNT was found experimentally.

Yao et al. (2012) have fabricated uniform Silicon Nanowires (SiNW) structures on the bottom, top and lateral wall surfaces of the microchannel copper heat sinks using the two-step electro less etching process. The micro/ nano hierarchical structure was found to yield higher boiling heat transfer characteristic. Its enhanced maximum heat flux was
150% over the microchannel heat sinks and 400% on the plain silicon heat sinks surface.

Ali et al. (2011) did experimental studies the single-phase heat transfer and pressure drop characteristics of the microchannel copper heat sinks with copper nanowires (CuNWs) coated on the bottom wall surfaces for different Reynolds number. Reduction in the temperature curves of coated heat sinks with copper nanowires by several degrees compared to bare microchannel heat sinks at all the thermocouple location under the same power input and flow rate was observed. A rise in Reynolds number tended to decrease in the percentage enhancement in thermal performance. It was more effective at lower Reynolds number.

Lotfizadeh et al. (2015) investigated the thermal performance of four innovative types of the heat sinks using metallic foam and aluminum nanoparticles. The effect of air flow velocity on thermal resistance was investigated and conclusion was that the heat sink coated with aluminum nanoparticle and metallic form heat sinks displayed an enhanced performance more than the uncoated heat sink. They found that the innovative heat sinks with aluminum nanoparticles having a better thermal resistance than the other heat sinks considered for comparison. The metallic foam heat sinks have a large dirt absorbing property and are expensive. Shih et al. (2005) demonstrated the aluminum-foam heat sinks performance for different height to diameter ratios under jet-impingement flow condition. When the ratio of fin height to diameter was reduced, the Nusselt number of the heat sink was found to increase initially and then decrease. This was due to the reduction in the area of heat transfer between the aluminum-foam heat sink and the surrounding air. The reductions in porosity and pore density increased the Nusselt number and enhanced the convective heat transfer. Kuang et al. (2016) made experimental study of the performance of the open celled high porosity copper foam heat sinks under axil fan flow impingement. The
aluminum plate fin heat sink required only 30% of its weight and 50% of volume while comparing with copper foam heat sink to achieve the same level of heat dissipation. The overall heat transfer performance of heat sink was enhanced by reducing the impinging distance by keeping the foam height constant.

Sabarish et al. (2015) performed experiments on the square and cylindrical pin fins of aluminum and copper materials. Nano graphene was coated on the fins and analysis was made for their fin efficiency, effectiveness and heat transfer rate through natural and forced convection. Copper square fin had higher fin efficiency in natural convection and forced convection compared to aluminum cylinder. The fin effectiveness of copper cylinders was greater than that of the aluminum cylinder. Thanigaivelan and Deepa (2017) have conducted experiments on fabricated test samples of aluminum and copper. The specimen coated with aluminum and copper and un-coated micro-fins were considered for experiments. Their main aim was to improve the convective heat transfer coefficient after doing coating on the micro-fin structure with various fins spacing. The convective heat transfer rate was found to increase by 49% in aluminum coated aluminum test piece; this showing a greater response before and after coating.

Peterson & Fletcher (1990) did experimental investigation of the effective thermal conductivity and contact conductance of chemically polished aluminum test sample and seven anodized coatings samples. There were variations in the specimen thickness from 60.9 µm to 163.8 µm, and were tested, while in contact with single aluminum un-anodized surface. The result showed a decrease in the overall joint conductance with increase in the anodized layer thickness and increase with increasing interfacial load. The thermal conductance increased with increase in thickness. The dimensionless expressions were correlated with the overall joint conductance of the
aluminum coating properties, roughness, thickness and the interfacial pressure.

Kunugi et al. (2006) formed a Nano Micro Scale Porous Layer (NMPLS) on the lateral wall surface by combining the chemical etching process with nanoparticles and then the non-electrolyzed plating technique. The NMPLS was formed in a simple way with minimal cost. Correlations were achieved for the ultra-high convective heat transfer performance compared to the conventional heat transfer. This showed a 40% enhancement in the heat transfer performance for an air water concurrent co-axil flow tube compared to bare plate case.

Wang et al. (2012) did experimental study of the heat transfer characteristics and pressure drop of a shot air-cooled copper pin fin heat sinks Photolithography and electroplating technology was employed to establish and grow the desired pin fin patterns and shape on the copper base plate. The pressure drop and heat transfer enhancement were studied using Taguchi method for various pin fin cross sectional shapes, parameters and distance between the fins. Overall heat transfer enhancement increases for the pin fin with circular cross section with increase in height and diameter. Thermal conductance increased by 78.3% and pressure drop only by 8.6% with the optimal design of pin fin coupons when compared with plain coupons. This showed that the fabrication of devised pin-fin as an effective and efficient approach to improve the thermal characteristics performance of air cooled plate-fin heat sinks.

Ochterbeck (1992) is known for experiments on the thermal contact conductance over interface pressures of 200 kPa to 2000 kPa for a normal state BiCaSrCuO superconductor/ copper interfaces at cryogenic temperatures. The overall enhancement was found to be greater for indium coatings. Increase in the temperature on the micro hardness of oxygen-free
high conductivity copper bar with an approximate 35 percent increase with decrease in temperature to 85K from 300 K was reported.

Durgam et al. (2017) conducted experiments on aluminum heat source array mounted on a substrate board in a horizontal tunnel with horizontal and vertical orientation under the natural and forced convection cooling. Three substrate board materials of different thermal conductivity compared with the maximum excess temperature and some guidelines were proposed for placing the highest heat generating electronic modules in the circuit board (PCB). The optimal configuration of non-dimensional geometric distance parameter ($\lambda$) was found when $\lambda=1.3$. Numerical COMOSOL results provided good agreement with experimental values. Alternate surface treatments adopted for heat transfer performance by various researchers were reviewed and the characterizations of surfaces and the heat transfer enhancement due to surface roughness with various techniques adopted by several researchers have been reported.

Singh & Patil (2015) did variations in the surface irregularities in the form of embossed impression at an angle from 30° to 90° and impression pitch considered as 12 mm, 16 mm, and 20 mm under various heat inputs under natural convection conditions. The Nusselt number was shown as a strong function and the maximum enhancement was found as between 1.63 and 2.86 corresponding to the impression angle and pitch of 45° and 12 mm respectively. The irregularities and impressions on the surfaces improved the heat transfer performance more than the smooth fin. There was a drop in effectiveness with a rise in heat input for all the embossed fin configurations.

Alam et al. (2013) studied the surface characteristics on heat transfer behavior to enhance the performance of the micro gap heat sinks. Experimental investigation on the influence of surface roughness on heat transfer and pressure drop was carried out. Heat transfer coefficient increased
with the increase in surface roughness. The roughness surfaces maintained uniform lower temperature over the heated surface.

Guo et al. (2015) studied the effect of heat transfer performance on the surface modified micro channels under laminar flow. Heat transfer and flow resistance are very sensitive to the micro channel surface morphology and surface roughness play a positive role on both the cases under laminar flow. Kandlikar et al. (2003) studied the heat transfer performance and pressure drop in a small roughened circular tube of different diameters. The heat transfer and pressure drop increased in small diameter tubes compared to large diameter tube for the same roughness. The smaller diameter tubes showed a larger impact on the heat transfer characteristics.

Prakash (2012) found the shot peening has the most effective mechanical surface treatment largely applied to improve the fatigue life of engineering Surface modification technique, namely controlled impact ball peening, was used for synthesizing the nanostructured surface layer and to impart residual stresses (compressive) on metallic material surface to augment the overall surface properties. Ball impact peening was for the generation of nano-crystalline structure and the surface properties increased by 67–122% depending on the ball travelling velocity compared with un-peened sample.

The influence of grit blasting process parameters like grit size, type of blasting system, grit blasting pressure, blasting angle and standoff distance on surface roughness of the substrate surface discussed in the literatures have been studied by Amada and Hirose (1998), Chander et al. (2009), Griffiths et al. (1996), Harris & Beevers (1999), Mohammadi et al. (2007), Sertkaya et al. (2011), Guan et al. (2005) and Jang et al. (2014).

Grooten & Geld (2012) studied the influence of how changes in surface properties on heat transfer in a Ti coated heat exchanger. The effects
of surface properties on dropwise condensation topology were assessed. The heat transfer rate was promoted in dropwise condensation than in film wise condensation. Promoting drop wise condensation is cheaper than constructing extended surface to improve heat transfer. Leipertz & Froba (2008) found the contact angle dependent on the roughness of the surface as minimum for homogeneous and very smooth surfaces. The condensation could be realized by the properties of the heat transfer surface. DWC offered intensified heat transfer efficiency compared to FWC. Koch et al. (1998) have performed the heat transfer measurements using FWC and DWC of water vapor at ambient pressure on coated copper surface. Heat transfer characteristics were studied under different coating methods. Coatings produced water contact angles of θ of 65, 74 and 90° and could be stable and well reproducible for heat transfer.

The surface roughness on wettability effects have been studied using surface roughness factors by Nakae (1998), Oner (2000) and Meiron (2004). Kim et al. (2018) studied super hydrophobic surfaces on aluminum sheets under different temperatures by storing in different media. The water contact angle increased from 172° from micro-terrace to micro terrace nano-leaf hierarchical structure. The super hydrophobicity was maintained for long duration under all conditions. Xin et al. (2010) studied the surface morphology and grain size of sputtered Au films by x-ray diffraction and atomic force microscope. The surface roughness increased with increase in grain size. Li et al. (2018) in his article has pointed out to increase in the roughness characteristics with increase in particle size.

2.4 MAJOR OBSERVATIONS FROM THE LITERATURE SURVEY

In electronics cooling, to meet the strict design constraints aluminum is most widely used material for the heat sinks due to its light
weight, low cost and high thermal conductivity. The pin-fin configuration is used in most of the heat sinks as the heat transfer area compared to the plate fin configuration is very high.

The pin-fin configuration is used in most of the heat sinks as the heat transfer area compared to the plate fin configuration is very high. It is construed from the existing literature survey that most of the earlier studies on heat sinks with pin-fins have considered the individual geometry compared with other types of fin geometry, materials and fin arrangement. It is observed that the main factors affecting the cooling performance are fin geometric parameter, shape, pitch distance between the fins, clearance ratio, orientation and arrays of the fins and this combination meets the strict design constraints. The overall information on the heat transfer in micro channel heat sinks under different convection conditions is experimentally and numerically studied and that focused on shape and size optimization of fins under natural and forced convection conditions.

Recent literature shows that the surface treatments on the surface resulting in an appreciable enhancement in heat transfer. Advanced coating technologies are used in heat sinks for a significant increase in the heat transfer rate within design constraints. The recent pioneering advancement in nano technology paves the way to further enhance the heat transfer in pin-fin heat sinks, through various types of nano-coatings. It is construed from the existing literature survey that only limited work is present with nano-coated heat sinks for heat transfer enhancement under heating and cooling application. Though there are research studies on the use of a grit blasting surface to enhance the heat transfer in selective applications in the recent years, the concept was not attempted for heat sinks to enhance the heat transfer.
2.5 SPECIFIC OBJECTIVES

Considering the major gaps observed from the literatures and the recent advances in nano technology and other surface treatment techniques the following specific objectives were formulated for the present research.

- To prepare various nano-coated surfaces in an aluminum-based pin-fin heat sink through electron beam physical vapour deposition method.

- To increase the surface roughness of a pin-fin heat sink through grit blasting using steel grit balls.

- To characterize the treated surfaces through various analyses such as SEM & EDAX analyses, 3D surface roughness profilometry, XRD analysis and water contact analysis.

- To construct an experimental setup to study the heat transfer performance of a heat sink under natural and forced convection conditions.

- To investigate the heat transfer enhancement performance of the nano-coated and grit blasted surface heat sink compared to the bare heat sink during heating and cooling under natural and forced convection conditions at various surrounding temperatures thereby achieving higher heat transfer or reducing the material requirement.