NUMERICAL ANALYSIS ON THE PERFORMANCE OF THE HEAT SINK WITH DIFFERENT FIN ANGLES

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ABSTRACT

Heat dissipation techniques are the prime concern to remove the waste heat produced by Electronic Devices, to keep them within permissible operating temperature limits. Heat dissipation techniques include heat sinks, fans for air cooling, and other forms of cooling such as liquid cooling. Heat produced by electronic devices and circuitry must be dissipated to improve reliability and prevent premature failure. Integrated circuits such as CPUs, chipset, graphic cards, and hard disk drives are susceptible to temporary malfunction or permanent failure if overheated. As a result, efficient cooling of electronic devices remains a challenge in thermal engineering. The objective of this project is to present an Optimal Heat Sink for efficient cooling of electronic devices. The choice of an optimal heat sink depends on a number of geometric parameters such as fin height, fin length, fin thickness, number of fins, base plate thickness, space between fins, fin shape or profile, material etc. Therefore for an optimal heat sink design, initial studies on the fluid flow and heat transfer characteristics of a standard pin fin, splayed pin fin and Hybrid pin fin heat sinks have been carried through CFD modeling and simulations. It is observed from the results that optimum cooling is achieved by splayed & hybrid pin fin heat sinks. These heat sink designs promises to keep electronic circuits 20 to 40% cooler than standard pin-fin heat sinks.

Keywords: Heat Sink, heat dissipation and CFD modeling and simulations.

5. INTRODUCTION

Heat sinks are the most common thermal management hardware used in electronics. They improve the thermal control of electronic components, assemblies, and modules by enhancing their surface area through the use of pin fins. Applications utilizing pin fin heat sinks for cooling of electronics have increased significantly during the last few decades due to an increase in heat flux densities and product miniaturization. Today's cutting edge electronic circuits dissipate substantially heavier loads of heat than ever before. At the same time, the premium associated with miniaturized applications has never been greater, and space allocated for cooling purposes is on the decline. These factors have forced design engineers to seek more efficient heat sink technologies. One of the more powerful cooling technologies that have emerged in recent years is the pin fin technology. The unique pin fin design generates significant cooling power and is highly suitable for "hot" devices and applications that have limited space for cooling. Pin fin heat sinks for surface mount devices are available in a variety of configurations, sizes and materials. Pin fin heat sinks, which contain an array of vertically oriented round pins made of copper or aluminum, deliver significantly greater performance than standard heat sinks with flat fins. The aerodynamic nature of the round pins and their Omni-directional configuration enable pin fin heat sinks to transfer heat very efficiently from the heat generating device to the ambient environment. As a result, this superior heat sink style is used in a wide range of applications and industries, wherever difficult cooling challenges takes place.

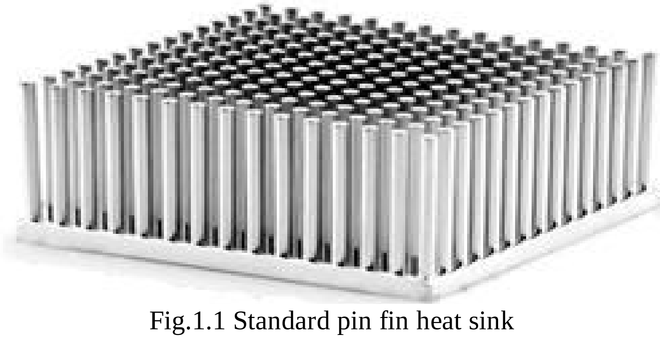


Fig.1.1 Standard pin fin heat sink

Even though standard pin fin heat sinks as shown in Fig 1.1 provide significant levels of cooling, there are applications in which even greater cooling power is required. With these applications in mind, two pioneering derivatives of the pin fin heat sink were developed. Splayed pin fins as shown in Fig 1.2 and hybrid pin fins as shown in Fig 1.3 both possess the round pins associated with the standard pin fin heat sink. But as result of their structural and metallurgical enhancements, these two new heat sink styles drive heat sink performance to advanced levels.

Splayed pin fin heat sinks are relatively new derivatives of the standard pin fin heat sink. Unlike standard pin fin heat sinks, which contain an array of vertically oriented pins, splayed pin fins features pins that gradually bend outward. Curving the pins in this way increases the spacing between the pins and allows surrounding air streams to enter and exit the pin array more efficiently without sacrificing surface area. The impact of increased pin spacing on heat sink performance is magnified at lower air speeds because weak air streams have less power to penetrate the array of pins.

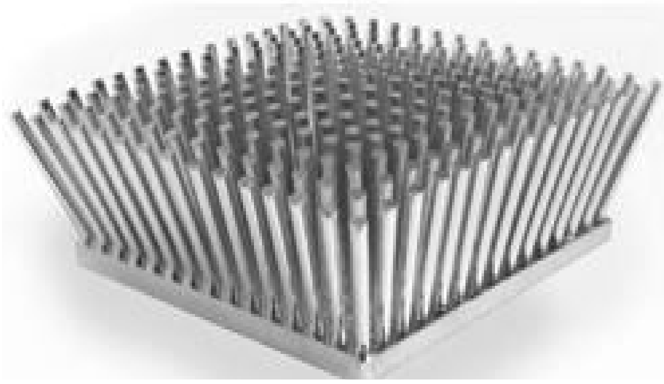


Fig.1.2 Splayed pin fin heat sink

In low air speed environments and in natural convection, the increased spacing between the pins reduces the heat sink's thermal resistance by up to thirty percent versus a standard pin fin heat sink. As a result, splayed pin fins are recommended for low and moderate airspeed environments and for natural convection cooling. Hybrid pin fins shown in Fig 1.3 feature the same pin configuration as standard pin fin heat sinks, but change the material used in the base. Unlike standard pin fin heat sinks that are either composed of aluminum or copper, hybrid pin fin heat sinks consist of aluminum pin fins that are reflowed onto a copper plate.

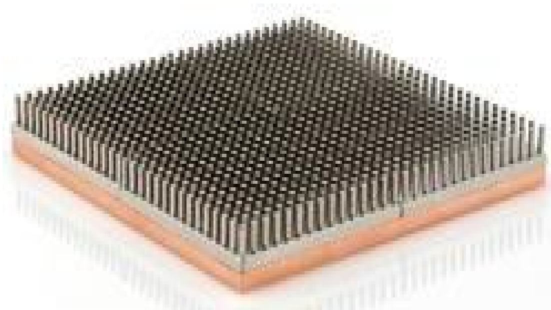


Fig.1.3 Hybrid pin fin heat sink

Hybrid heat sinks are designed for devices that feature small and focused heat sources. Such devices require heat sinks that are significantly larger than the devices they reside on. These heat sinks are also intended for multi device cooling, in which a single heat sink is used to cool more than one module.

Both of these technologies are becoming more popular as designers try to maximize the space available for cooling purposes. They do so by using application space that is not directly over the heat generating device. In each case, the heat sink must be able to spread the heat quickly along its base to operate efficiently. Otherwise the areas of the heat sink far away from the device will not able to provide any cooling When compared to all copper heat sinks, hybrid heat sinks provide similar spreading power, as the spreading of the heat occurs just along the base. The major advantage of hybrid heat sinks over all copper models is their lighter weight.

Copper is approx. 3.2 times the weight of aluminum. So, depending on the size of the heat sink, hybrids may be up to 50% lighter than all-copper heat sinks of the same size. In the most challenging cooling applications, designers can deploy splayed pin fin heat sinks and hybrid pin fin heat sinks to achieve the required cooling without making excessive tradeoffs in heat sink size or weight. As with vertical pin fin designs, these new variations are highly customizable. Designers can adapt heat sink footprints, pin counts, and other parameters for optimum cooling in their applications.

6. LITERATURE REVIEW

Wirtz et al. reported experimental results on the thermal performance of model pin-fin fan-sink assemblies. They used cylindrical, square, and diamond-shaped cross-sectional 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 pressure rise or fan power and fin height [1].

Jonsson and Bjorn performed experiments to compare the thermal performance of 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 midrange velocities [2].

The steady-state thermal and air-flow resistance performances of horizontally based pin-fin assemblies were investigated experimentally by Tahat et al3 .They studied the effects of varying geometrical configurations of the pin-fins and found the optimal Pin fin separation in both stream wise and span wise directions to achieve maximum heat transfer rate[3].

Jung and Maveety performed numerical experiments to investigate the turbulent fluid flow and heat transfer from three pin-fin heat sink geometries over the Re D range from 7800 to 19,700 with air impingement cooling. They used a standard κ– turbulence model to predict the Reynolds stresses. They found that the maximum heat transfer dissipated from a heat sink was obtained under turbulent flow conditions [4].

Behnia et al compared numerically the heat transfer performance of various commonly used fin geometries (circular, square, rectangular, and elliptical).They fixed the fin cross-sectional area per unit base area, the wetted surface area per unit base area, and the flow passage area for all geometries. They found that circular pin fins outperform square pin fins and elliptical fins outperform plate fins. They also found that elliptical fins work best at lower values of pressure drop and pumping work whereas round pin fins offer highest performance at higher values [5].

3 COMPARISON OF APPROACHES

The below Table 3.1 shows the advantages & disadvantages between different approaches

Approach	Advantages	Disadvantages
Experimental	1. Capable of being most Realistic	1. Equipment required 2. Scaling problems 3.Tunnelcorrections 4.Measurement difficulties 5. Operating costs
Theoretical	1.Clean, general information, which is Usually in formula form.	1. Restricted to simple geometry and physics. 2. Restricted to linear Problems
Computational	1. No restriction to linearity 2. Complicated physics can be treated 3. Time evolution of flow can be obtained	1. Truncation errors. 2. Boundary condition problems 3. Computer costs

Table 3.2 Comparison between Computational & Experimental Methods

Area	Computational methods	Experimental methods
Capability	Software used for all flow types. Turbulence rarely resolved except through use of simpler models. Enable physical situations to be modeled where experiments would be unsafe. Allows geometry variation to be achieved quickly.	Exact simulation if full-scale situation can be used. Experimental situation also being a model of desired flow situation.
Accuracy	Depends on algorithms used. Depends on mesh density.	Should be correct within the limits of experimental errors, if geometry and scale effects are realistic and

		equipment is appropriately designed and calibrated.
Detail	All variables are calculated at every mesh point or cell. Variables can be integrated to find overall properties.	Easy to find overall properties such as pressure drop, forces and moments Difficulty and expensive to instrument so that anything more than a crude sample of the data is produced.
Time	Solutions can take long time to iterate. This depends on the problems being solved and the speed of computer being used.	Time needed for setup and calibration. Results are usually quick to gather once this is done.
Cost	Requires relatively cheap hardware but expensive software. Time and care is needed to get good results. Specialists are required to achieve good results.	Instrumentation is expensive in many cases. Raw experiment is cheap to carry out but data achieved is limited.

THE DESIGN OPTIMIZATION PROBLEM

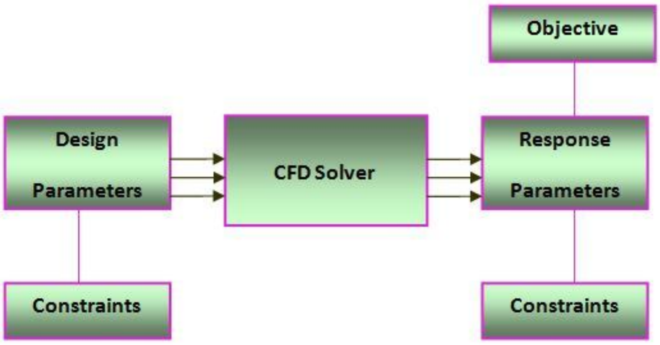


Fig 3.1 The design optimization flowchart.

At present, in order to shorten product development time, there is a strong tendency to perform design using computational fluid dynamics (CFD) tools instead of experiments. CFD is a method that is becoming more and more popular in the modeling of flow systems in many fields, including reaction Engineering. The block diagram in Fig 3.1 explains the optimization problem it is recognized that experiments remain essential during the final design stages. CFD based modeling however have many advantages during preliminary design, because it is less time-consuming than experiments and because it allows greater flexibility. Early experience with CFD based modeling has shown that these computational tools should be used carefully. Any kind of CFD computation requires the specification of inlet and boundary conditions. Obviously these conditions determine the flow and temperature field resulting from the CFD computation. The specification of inlet and boundary conditions requires appropriate measurements or available data onsite.

3.1 GOVERNING EQUATIONS OF CFD

CFD is playing a strong role as a design tool as well as a research tool. In CFD the physical aspects of any fluid flow is governed by three principles.
The fundamental equations of fluid mechanics are based on the following
Universal laws of conservation:

1. Conservation of mass
2. Conservation of momentum
3. Conservation of energy

These fundamental physical principles can be expressed in terms of basic mathematical equations. These equations are generally in integral or partial differential form. These equations and their derivatives are replaced in CFD by discretised algebraic forms, which are in turn solved to get flow field values at discrete points in space and/or time. The end product is a collection of numbers, in contrast to closed-form analytical solution. In CFD approach, the equations that govern a process of interest are solved numerically. Numerical methods have evolved especially FDM, FVM algorithms for solving ordinary and partial differential equations.

The equation that results from applying the conservation of mass to a fluid is called the continuity equation. Conservation of momentum is based on application of Newton's Second Law to a fluid element, which yields a vector equation, which is also called Navier-Stokes Equation.

The conservation of Energy is based on the application of First Law of Thermodynamics to a fluid element. In addition to the equations developed from these universal laws, it is necessary to establish relationships between fluid properties in order to close the system of equations. An example of such a relationship is the equation of state, which relates the thermodynamic variables pressure p, density ρ, and Temperature T. Historically there have been two different approaches taken to derive the equations of fluid mechanics viz., phenomenological approach and kinetic theory approach. In the phenomenological approach certain relationship between stress and rate of strain, heat flux and temperature gradient are postulated, and the fluid dynamic equations are then developed from the conservation laws. The required constants of proportionality between stress and rate of strain and heat flux and Temperature gradient (which are called Transport Coefficients) must be determined experimentally.

In the kinetic theory approach also known as the mathematical theory of non-uniform gases, the fluid dynamic equations are obtained with the transport coefficients defined in terms of certain integral relations, which involves dynamics of colliding particles.

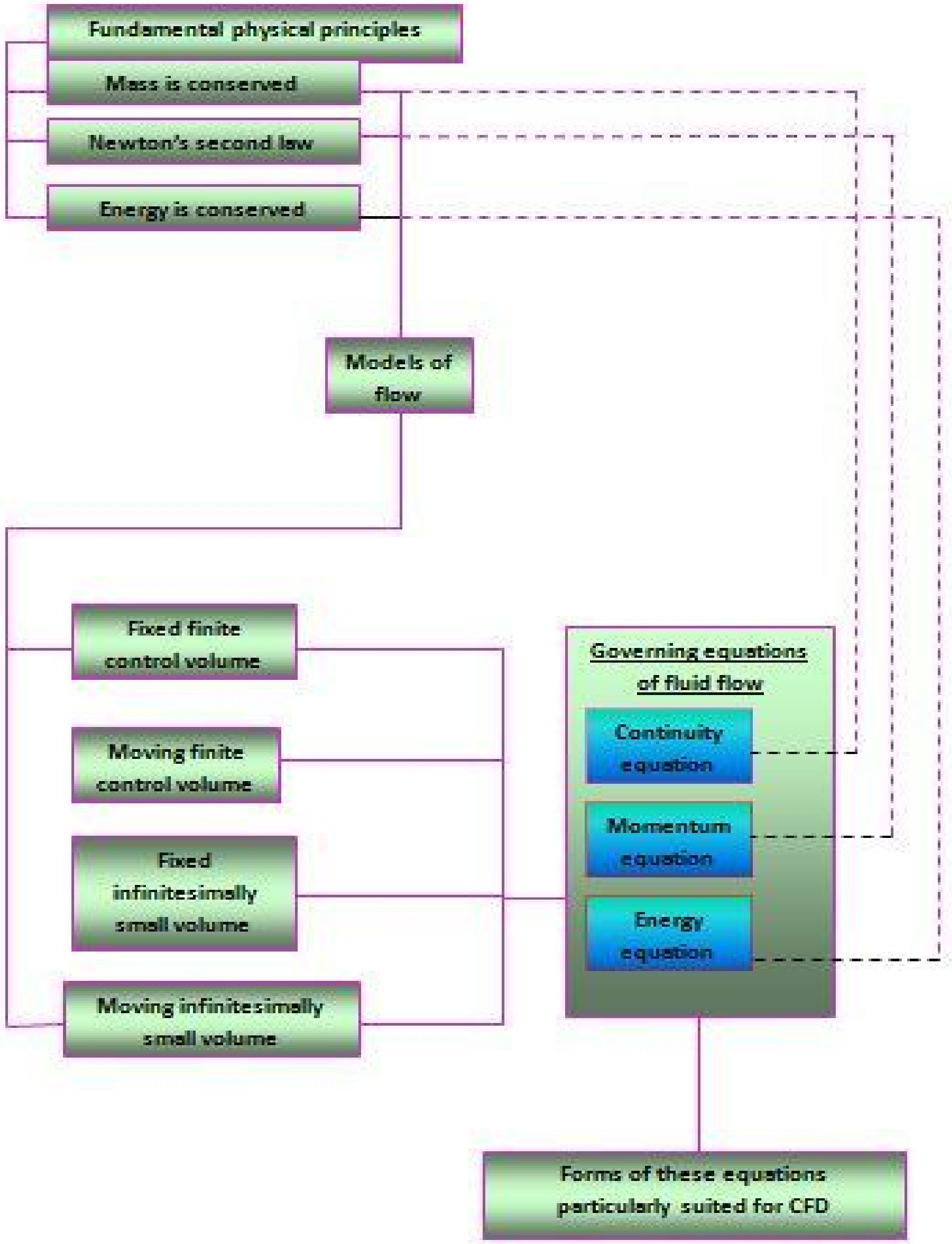
A viscous flow is one where transport phenomenon of friction, thermal conduction and/ or mass diffusion is included. These transport phenomena are dissipative. So they always increase the entropy of the flow. For this type of viscous flow modeling the “Navier-stokes” equations are applied. If these phenomena are neglected, the flow is called “inviscid flow” and for this “Euler” equations are applied. These are mathematical statements of three fundamental physical principles upon which fluid dynamics is based shown as flow chart in fig 3.2.

3.2 FLUID FLOW FUNDAMENTALS

The Physical aspects of any fluid flow are governed by three fundamental principles: Mass is conserved; momentum and Energy is conserved. These fundamental principles can be expressed in terms of mathematical equations, which in their most general form are usually non-linear partial differential equations. Computational Fluid Dynamics (CFD) is the science of determining a numerical solution to the governing equations of fluid flow whilst advancing the solution through space or time to obtain a numerical description of the complete flow field of interest.

The governing equations for Newtonian fluid dynamics, the unsteady Navier-Stokes equations, have been known for over a century. However, the analytical investigation of reduced forms of these equations is still an active area of research as is the problem of turbulent closure for the Reynolds averaged form of the equations. For non-Newtonian fluid dynamics, chemically reacting flows and multiphase flows theoretical developments are at a less advanced stage.
Experimental fluid dynamics has played an important role in validating and delineating the limits of the various approximations to the governing equations.

The wind tunnel, for example, as a piece of experimental equipment, provides an effective means of simulating real flows. Traditionally this has provided a cost effective alternative to full scale measurement. However, in the design of equipment that depends critically on the flow behavior, for example the aerodynamic design of an aircraft, full scale measurement as part of the design process is economically impractical. This situation has led to an increasing interest in the development of a numerical wind tunnel.



4. MODELLING & CFD ANALYSIS

The modelings of pin fin heat sinks are made by GAMBIT 2.4.6 software. This analysis is based on the following assumptions:

1) The fins are with adiabatic tip.
2) The fluid, air is assumed to be incompressible throughout the process.
3) The airflow is normal to the fins.
4) Air properties are taken at film temperature.
5) The flow is steady, laminar and two dimensional.
6) There are no heat sources within the fin itself.
7) The radiation heat transfer is negligible.
8) The temperature at the base of the fin is uniform.
9) The heat flow in the fin and its temperatures remain constant with time.

10) The fin material is homogeneous and isotropic.

Geometry

Heat sinks, used in electronic devices, usually consist of arrays of pin-fins arranged in an in-line manner as shown in Fig 4. The pins are attached to a common base and the geometry of the array is determined by the pin dimensions, number of pins and pin arrangement. The geometry of an in-line pin-fin heat sink is shown in Fig 5.The dimensions of the base plate are L × W × tb, where L is the length in the stream wise direction, W is the width, and tb is the thickness. Each pin fin has diameter D and height H. The longitudinal and transverse pitches are SL and ST respectively. The approach velocity of the air is Uapp. The direction of the flow is parallel to the x-axis. The base plate is kept at constant heat flux and the top surface (y = H) of the pins is adiabatic. The average local wall temperature of the pin surface is Tw(x). The heat source is idealized as a constant heat flux boundary condition at the bottom surface of the base plate.

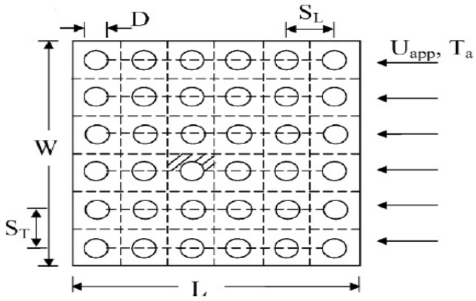


Fig 4.1: Schematic of in-line pin-fin heat sinks

The mean temperature of the heat source is Ts. It is assumed that the heat sink is fully shrouded and the heat source is situated at the centre of the base plate. It is assumed that the fluid temperature is averaged over the height of the heat sink, with Tf = Tf(x), so the fluid temperature Tf (x) is the bulk mean fluid temperature. Fully developed heat and fluid flow are assumed in the analysis, and the thermo physical properties are taken to be temperature independent. The overall mesh of the geometry is shown in Fig.4.3.

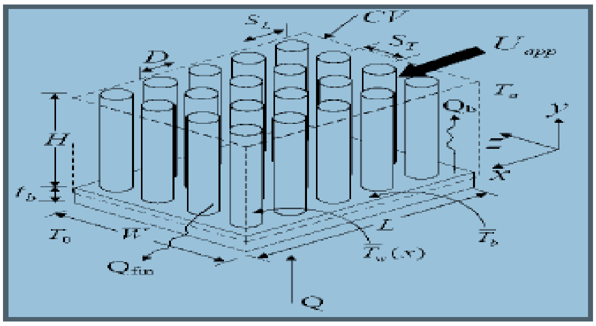


Fig 4.2. Geometry of in-line pin-fin heat sink

Table 4.1 Dimensions used to determine performance of heat sinks

Quantity	Dimension
Footprint (mm^2)	52×52
Base plate thickness (mm)	3
Overall height of fin(mm)	30
Approach velocity (m/s)	3
Thermal conductivity of solid aluminium(W/m•K) for aluminium	237
Thermal conductivity of solid copper(W/m•K)	401
Thermal conductivity of air (W/m•K)	0.0284
Density of air (kg/m3)	1.086
Specific heat of air (J/kg•K)	1007
Kinematic viscosity (m2/s)	18.15×10^{-6}
Absolute viscosity (Ns/m^2)	19.70×10^{-6}
Prandtl number (Air)	0.6976
Heat load (W)	130
Ambient temperature (K)	297
Base plate temperature (K)	353

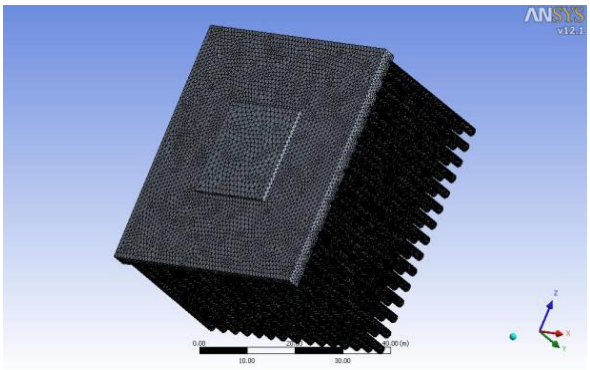


Fig 4.3. Meshing of In-Line Pin-Fin Heat Sink

4.1 Calculations

To form an appropriate model for calculations, the following assumptions are made.
1. The contact resistance between the heat sink and processor would be negligible when using a high quality thermal paste
2. The average temperature of the air flowing through the heat sink would be 325 K, and used the values of material properties at 325 K.
3. The Intel, core i7-970 processor is selected as heat source of 130W, to evaluate the pin fin heat sink performance.

Heat transfer coefficient over flat plate

Reynolds's number (Re_L) = $(\rho \ v \ L)/\mu$
Nu = 0.332 ReL0.5 Pr 0.333 ⟹ Nu= h1L/k ⟹ h_1 = Nu k/L

Heat transfer coefficient across bank of tubes Reference Velocity

The mean velocity in the minimum free cross section between two rows, Vmax, is used as a reference velocity in the calculations of fluid flow and heat transfer for inline arrangement, and is given by

Vmax= [ST/(ST-D)] Uapp

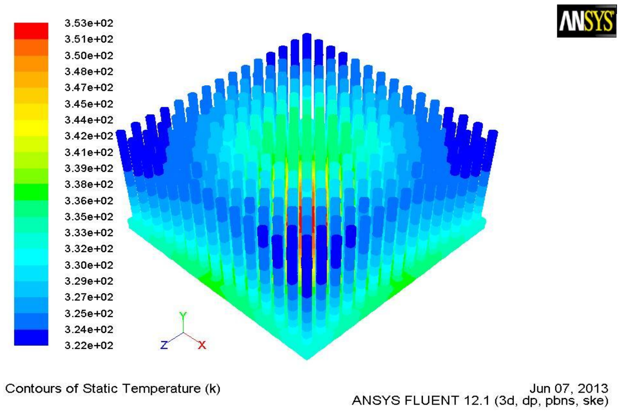
Where Uapp is the approach velocity, SL, and ST are the dimensionless longitudinal and transverse pitches,

Re_{Dmax}= (ρ Vmax D) / μ ⟹ Nu= C $(Re_{Dmax})^n$

For the values of C and n from HMT data book
Nu= h_2D/k ⟹ h2 = Nu k/D

4.2 CFD SIMULATION APPROACH

The ANSYS FLUENT 12.1 CFD code was used for the simulations. The simulation procedure was started with pre-processing. The computational mesh was generated using tetrahedral elements. In order to accurately resolve the solution fields in the high gradient regions, the grid was stretched. The discretization scheme was first order upwind scheme. A SIMPLE algorithm was used. For the simulations presented here, depending on the geometry used, fine mesh of up to 3, 33,998 elements were used. The flow field and heat transfer were determined by iteratively solving the governing momentum and energy equations. The under-relaxation factors were first set at low values to stabilize the calculation process, and were increased to speed up the convergence.
The normalized residuals were set at 10^{-4} for velocity components and at 10^{-7} for energy equation, which proved to be adequate.



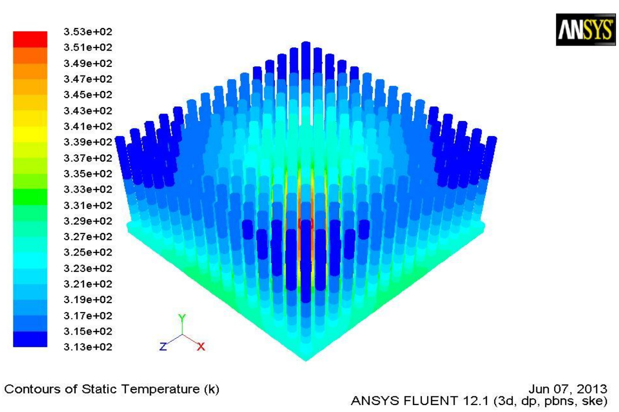
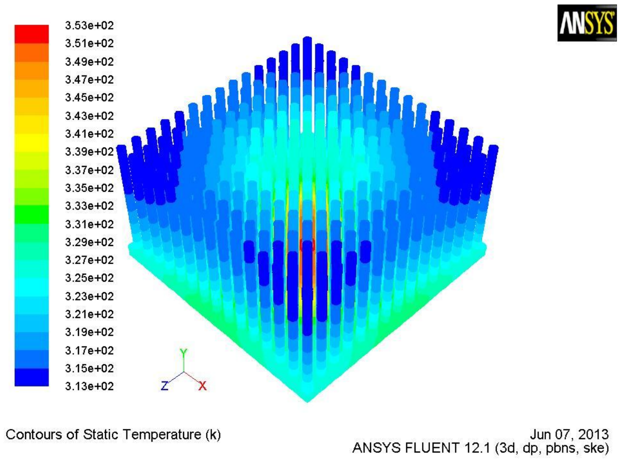


Fig 4.4 & Fig 4.5 Temperature contours of std aluminum pin fin and std. copper pin fin heat sink with 3 m/s velocity.



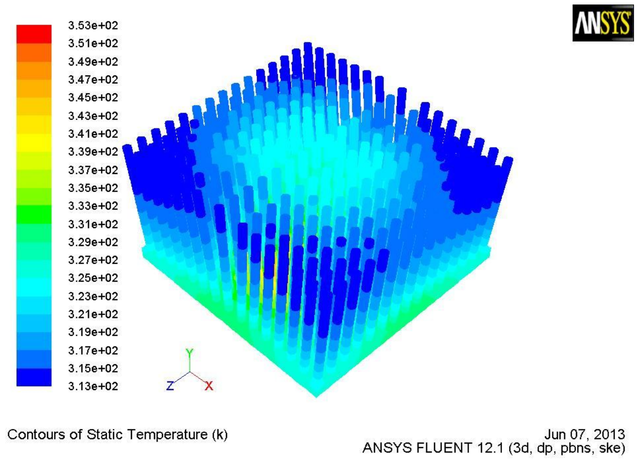
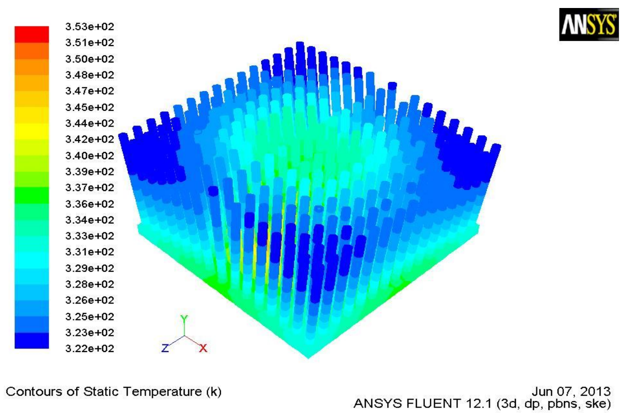


Fig 4.6: Temperature contours of standard hybrid pin fin heat sink (copper base plate with al heat sink) with 3 m/s velocity. And Fig 4.7: Temperature contours of splayed al pin fin heat sink with 3 m/s velocity

Fig.4.4, Fig.4.5 and Fig.4.6 Illustrate the Temperature variation of Standard pin fin heat sinks.



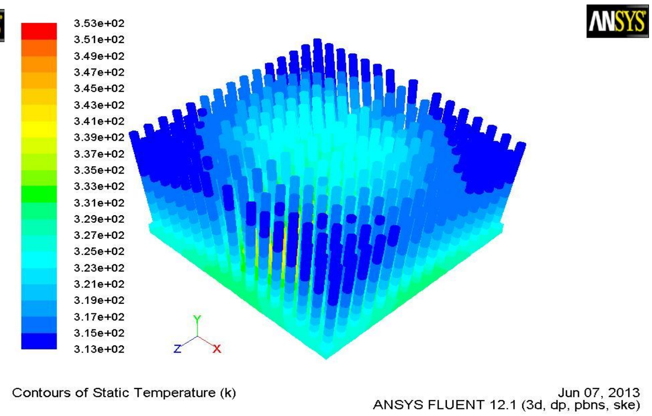


Fig 4.8: Temperature contours of splayed copper pin fin heat sink with 3 m/s velocity.

Fig 4.9: Temperature contours of splayed hybrid pin fin heat sink (copper base plate with al heat sink) with 3 m/s velocity.

Fig.4.7, Fig.4.8 and Fig.4.9 Illustrate the Temperature variation of Splayed pin fin heat sinks.

5. RESULTS & DISCUSSION

The result obtained from CFD Simulation approach shown in fig 4.4 to 4.9 illustrates that copper pin fin heat sinks have lower thermal resistance and superior heat spreading capabilities when compared with aluminum pin fin heat sinks. As a result, copper pin fin heat sinks are generally suitable for two types of design scenarios. The first would be any design with extreme cooling requirements such that aluminum pin fin heat sinks cannot achieve sufficiently low thermal résistance. The other scenario is any application in which the heat sink is significantly larger than the device being cooled. In that case, the ability of copper to spread heat rapidly through the base of the heat sink becomes a necessity to ensure the effectiveness of the fins located far away from the heat generating device. However, the drawback of copper pin fin heat sinks is more cost and more weight than aluminum. In that case hybrid pin fin heat sinks are the best alternative for cooling. Because hybrid pin fin heat sinks exhibits similar characteristics of copper. The comparative temperature values for aluminum, copper and hybrid pin fin heat sinks with standard and splayed structures are shown in Table 5.1.

	Temperature distribution across fin in K		
	Al	Cu	Hybrid
Standard	342	337	330
Splayed	339	327	324

It is clear analysis that splayed pin fin heat sink enhances the heat transfer, when compared to the standard pin fin heat sink.

CONCLUSIONS & FUTURE SCOPE OF WORK

In the present CFD analysis of Splayed pin fin heat sinks for electronics cooling is investigated. Based on the results obtained it can be concluded that in the sense of junction temperature splayed pin fins are efficient. It is also found that Hybrid pin fin heat sinks have better performance than aluminum and copper pin fin heat sinks. The splayed pin fin structure enables air to enter and exit the pin array in a more efficient fashion and, therefore offers a substantial cooling premium. Splayed pin fin heat sink generates a cooling premium of 20% to 30% over standard pin fin heat sinks when operating in low-airspeed environments and in the natural convection mode. The smooth round pins reduce resistance to incoming air streams and enhance air turbulence between the pins. Due to the combination of high cooling power and low pressure drop splayed pin fins are ideal for heavily populated boards in which the management of air flows along the PCB is critical.

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