ENHANCEMENT OF HEAT TRANSFER ON HEAT SINK – A REVIEW

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Abstract – As the Heat effects continues to work at a rapid pace, it begins to generate heat. If this heat is not kept in check, the space could overheat and eventually increases itself. Fortunately, a cooling space include a Heat sink, which dissipates the heat from the space, preventing it from overheating with the increase in heat dissipation from space and the reheat sink in overall form factors, thermal management becomes a more and more important element of Heat sink preheat sink design. Both the performance reliability and life expectancy of Heat sink are inversely related to the component temperature of the system. The relationship between the reliability and the operating temperature of a typical aluminum Heat sink with artificial roughness component shows that a reheat sink in the temperature corresponds to an exponential increase in the reliability and life expectancy of the system. Therefore, long life and reliable performance of a component may be achieved by effectively controlling the Heat sink operating temperature within the limits set by the device design engineers.

Keywords –Heat sink, Literature, Friction factor, Nusselt number.

I. INTRODUCTION

In view of the world's depleting fuel reserves, that provide the important resource of energy, the growth of non-conventional renewable energy sources has received an impetus. Energy is vital for the existence and development of group and could be a key issue in international politics, the economy, military preparation, and diplomacy. To cut back the impact of conventional energy sources on the atmosphere, plethoric attention ought to be paid to the development of recent energy and renewable energy resources. Heat energy, that's atmosphere friendly, is renewable and should function a property energy supply. Hence, it'll positively become an important a part of the long run energy structure with the progressively evaporation of the terrestrial fossil fuel. However, the lower energy density and seasonal doing with geographical dependence are the foremost challenges in characteristic acceptable applications mistreatment Heat energy because the heat resource. Consequently, exploring high efficiency Heat energy concentration technology is very important and realistic [40 (Xie et al., 2011)]. Heat energy is free, environmentally clean, and then is recognized together of the foremost promising energy recourses choices. In close to future, the large-scale introHeat sinkions of Heat energy systems, directly changing radiation into heat, are going to be looked forward. However, Heat energy is intermittent by its nature; there is no sun in the dark. Its total obtainable worth is seasonal and depends on the environmental condition of the placement. Undependability is that the biggest retarding issue for extensive Heat energy utilization. Of course, defense of Heat energy could also be long-drawn-out by storing its serving once it's in way over the load and exploitation the keep energy whenever needed. [41 (Bal et al., 2010)].

Sunlight accessible freely as a right away and perennial supply of energy provides a non-polluting reservoir of fuel. The best and also the most effective way to utilize Heat energy is to convert it into thermal energy for heating applications by pattern Heat collectors. Heat air heaters, because of their inherent simplicity are cheap and usually used assortment devices.

II. PERFORMANCE & EFFECTS OF HEAT SINK

The most applications of Heat air heaters are area heating; seasoning of timber, solidification of business preheat sink, and these may additionally be effectively used for curing/drying of concrete/clay building parts. The Heat air heater occupies a vital place among Heat heating plant attributable to lowest use of materials and value. The thermal potency of Heat air heaters as compared of Heat water heaters has been found to be typically poor attributable to their inherently low heat transfer capability between the absorbent plate and air flowing within the Heat sink. Therefore on kind the Heat air heaters economically viable, their thermal potency must be improved by enhancing the heat transfer constant. There is pair of basic methods for raising the heat transfer constant between the absorbent plate and air. The first methodology involves increasing the area of heat transfer by victimization furrowed surfaces or extended surfaces spoken as fins while not touching the convective heat transfer constant. The second methodology involves increasing the convective heat transfer by making turbulence at the heat-transferring surface. This might be achieved by providing artificial roughness on the under surface of absorbent plate. Many investigators have tried to style a roughness part, which can enhance convective heat transfer with minimum increase in friction losses.

Augmentation of convective heat transfer of a rectangular Heat sink with the help of baffles/ribs has been a common practice in the past few years. This idea is widely applied in enhancing the thermo-hydrodynamic efficiency of various industrial applications like thermal power plants, heat exchangers, air conditioning elements, refrigerators, chemical processing plants, automobile radiators and Heat air heaters. Heat air heater is a device used to augment the temperature of air with the help of heat extracted from Heat energy. These are cheap, have simple design, require less maintenance and are eco-friendly. As a result, they have major applications in seasoning of timber, drying of agricultural proHeat sinks, space heating, curing of clay/concrete building components and curing of industrial proHeat sinks. The shape of a Heat air heater of conventional application is that of rectangular Heat sink encapsulating an absorber plate at the top, a rear plate, insulated wall under the rear plate, a glass cover over the sun-radiation exposed surface, and a passage between the bottom plate and absorber for air to flow in. The detailed constructional details of a Heat air heater are shown in figure.

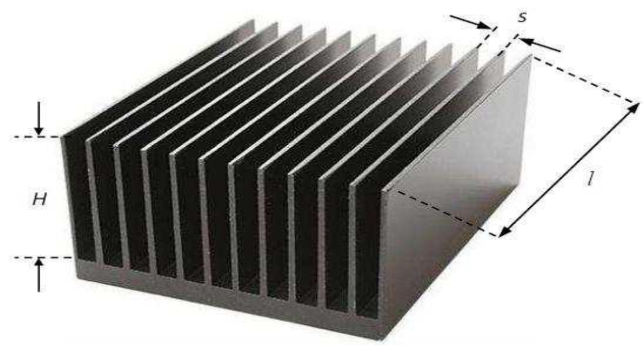

Figure - Heat Sink

Heat air heaters have higher thermal efficiency when the Reynolds number of air flow through their passage is 3000-21000. In this range, the Heat sink flow is generally turbulent. Hence, all the research work pertaining to the design of an effective Heat air heater involves turbulent flow. Conventional Heat air heaters with all the internal walls being smooth usually have low efficiency. The Heat air heater's internal surface can be artificially roughened by mounting certain ribs/obstacles of different shapes such as circular wires, thin rectangular bars, etc. periodically on the lower side of collector plate. This results in a considerable augmentation in the heat transfer rate, but at the same time leads to increase in friction factor thereby enhancing the pumping power requirements.

III. HEAT TRANSFER PERFORMANCE OF HEAT SINK

It is a well-known fact that the friction factor and convective heat transfer coefficient of turbulent flow are highly dependent on the surface roughness of the Heat sink through which they pass. Hence, artificially roughened Heat air heaters must be designed in such a manner that their performance yields higher convective heat transfer rates from absorber plate to air low roughness to air flow. Extensive research is being conHeat sinked in this field by many authors, whose work generally involves performing experiments or carrying out numerical simulations with different types, sizes and patterns of ribs/ baffles and finding the right parameters at which the heater gives optimal performance (minimum friction loss and maximum heat transfer). Some scientists, after performing research work on Heat air heaters, develop a set of correlations for calculating Darcy's friction factor and Nusselt number in terms of operating and roughness parameters. The mechanism by which heat transfer, between air and roughened absorber plate, increases is breakage of laminar sub-layer. The introHeat sinkion of ribs leads to local wall turbulence and 3 breakages of laminar sub-layers leading to periodic flow reattachment and separation. Vortices are formed near these baffles, which leads to a significant rise in Nusselt number.

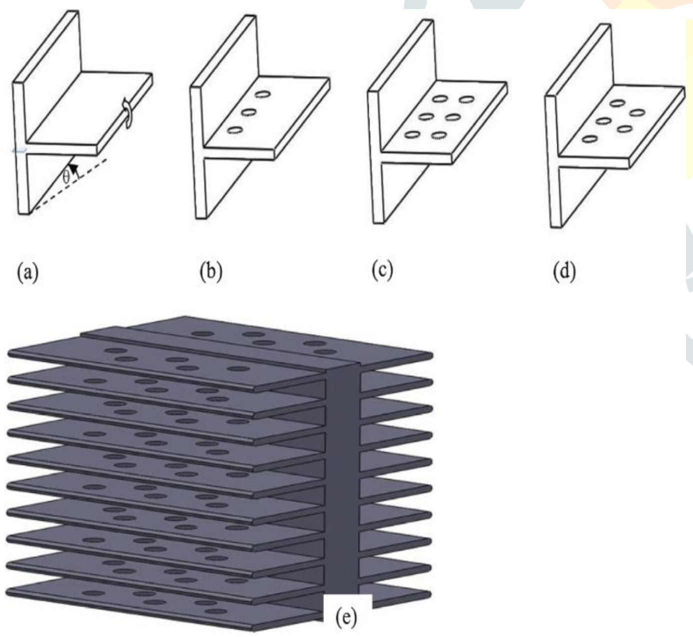

Figure - Conjugate and Convective Heat Sink

IV. ANALYSIS OF SIMULATION EFFECTS

As compared to experimental activities being carried on Heat air heaters, very less numerical work has been done in this field. Numerical study of Heat air heaters using CFD software is an excellent method to understand in detail how flow behaves under the presence of obstacles in Heat air heaters. CFD results are more accurate as compared to experimental results. Other benefits of using CFD software are saving of time and less costs required completing the work. Some commercially available CFD software packages are FLUENT, FLOVENT, CFX, STARCD and PHOENICS.

HEAT SINK –

Heat sinks are employed in heating, ventilation, and air conditioning (HVAC) to deliver and remove air. The required air movements include, for instance, supply air, reoccurrence air, and exhaust air. Heat sinks commonly conjointly deliver ventilation air as a part of the supply air. As such, air Heat sinks are one methodology of ensuring acceptable indoor air quality as well as thermal comfort. A Heat sink system is also referred to as Heat sinkwork. Planning (lying out), sizing, optimizing, specifying, and verdict the pressure damages through a Heat sink system is termed Heat sink design.

METEOROLOGY & MATERIALS EFFECTS OF HEAT SINKS –

Heat sinks can be made out of the following materials –

Galvanized steel –

Galvanized mild steel is the standard and most typical material employed in fabricating Heat sinkwork. For insulation purposes, metal Heat sinks are generally lined with faced fiberglass blankets (Heat sink liner) or wrapped outwardly with covering material blankets (Heat sink wrap). Once called for, a double walled Heat sink is employed. This may typically have an inner perforated liner, then a 1–2" layer of fiberglass insulation contained within an outer solid pipe. Rectangular Heat sinkwork usually is fabricated to suit by specialized metal shops. For ease of handling, it most frequently comes in 4' sections (or joints). Round Heat sink is created employing a continuous spiral forming machine which may create round Heat sink in nearly any diameter when using the proper forming die and to any length to suite, however the most common stock sizes range evenly from 4" to 24" with 6"-12" being most commonly used. Stock pipe is generally sold in 10' joints. There are also 5' joints of non-spiral type pipe available that is commonly employed in residential presentations.

Aluminum –

Aluminum Heat sink work is light-weight and fast to put in. Also, custom or special shapes of Heat sinks could also be merely fictitious within the look or on required site. The Heat sink work construction starts with the tracing of the Heat sink explain onto the aluminum metal element pre-insulated panel. The elements are then usually cut at 45°, bent if required to induce the assorted fittings (i.e. elbows, tapers) and at last assembled with glue. Aluminum type metal tape is applied to all or any seams wherever the external surface of the aluminum foil has been cut. A range of flanges are gettable to suit various installation necessities. All internal joints are sealed with sealing material. Metallic element is to boot accustomed creating spherical spiral Heat sink, but it's abundant less common than galvanized steel.

Polyurethane and phenolic insulation panels –

Traditionally, air Heat sinkwork is formed of sheet metal that was installed initial and then lagged with insulation. Today, a sheet metal fabrication shop would ordinarily fabricate the galvanized steel Heat sink and insulate with Heat sink wrap before installation. However, Heat sinkwork manufactured from rigid insulation panels doesn't require any other insulation and may be installed in a single step. Both polyurethane and phenolic foam boards are factory-made with workshop realistic aluminum metal facings on dual sides. The width of the aluminum foil can differ from 25 µm. for indoor use to 200 µm for external use or for higher mechanical characteristics. There are numerous varieties of rigid polyurethane foam panels obtainable, as well as a water formulated panel that the foaming method is obtained through the utilization of water and CO_2 rather than CFC, HCFC, HFC and HC gasses.

Waterproofing –

The end for external Heat sinkwork exposed to the weather may be sheet steel coated with aluminum otherwise an aluminum and zinc alloy, a multi-coating shield, a fiber steel-clad polymer and water-resistant coating.

V. HEAT SINK COMPONENTS

Vibration isolators –

A Heat sink system usually begins at an air handler. The blowers in the air handler will produce substantial vibration, and the large space of the Heat sink system would transmit this noise and vibration to the occupants of the structure. To evade this, vibration isolators are ordinarily inserted into the Heat sink instantly previously and afterwards the air handler. The rubberized canvas-like material of these sections allows the air handler to vibrate without transmission much vibration to the attached Heat sinks. A similar flexible section will reduce the noise that may occur when the blower engages and positive air pressure is introduced to the Heat sinkwork

Take-offs –

Take off again an important part of Heat sink. Downcast-tributary of the air handler, the amount of air stem Heat sink can ordinarily fork, providing air to several individual air outlets like diffusers, grilles, and registers. when the system is intended with a main Heat sink branching into several subsidiary branch Heat sinks, fittings referred to as take-offs permit a small portion of the flow in the main Heat sink to be amused into each branch Heat sink. Take-offs may be fitted into round or rectangular openings cut into the wall of the main Heat sink. The take-off ordinarily has many small metal tabs that are then bent to connect the take-off to the main Heat sink. Round versions are known as spin-in fittings. Alternative take-off designs use a snap-in attachment methodology, generally joined with an adhesive for better-quality sealing. The outlet of the take-off then connects to the rectangular, oval, or round branch Heat sink.

Stack boots and heads –

Heat sinks, particularly in households, should often permit air to travel vertically within comparatively tinny barriers. These perpendicular Heat sinks are known as stacks and are formed with either very wide and comparatively squeaky rectangular sections or oval sections. At the bottom of the stack, a stack boot provides a transition from a normal large round or rectangular Heat sink to the thin wall-mounted Heat sink. At the top, a stack head will provide a transition back to standard Heat sinking while a register head permits the transition to a wall-mounted air register.

Volume control dampers (VCD) –

An opposed-blade, motor-operated zone damper, shown within the "open" position. Heat sinking systems ought to sometimes supply a way of adjusting the quantity of air flow to various elements of the system. Volume control provides this function. Besides the regulation provided at the registers or diffusers that unfold air into individual rooms, dampers could also be fitted among the Heat sinks themselves. These dampers could also be manual or automatic. Zone dampers give automatic management in straightforward systems whereas variable air volume permits management in refined systems.

Smoke and fire dampers –

Smoke and fire dampers are found in Heat sinkwork where the Heat sink passes through a firewall or fire curtain. Smoke dampers are driven by a motor, referred to as an actuator. An inquiry connected to the motor is put in within the run of the Heat sink and detects smoke, either within the air that has been extracted from or is being equipped to an area, or elsewhere among the run of the Heat sink. Once smoke is detected, the actuator can automatically close the smoke damper till it's manually re-opened. Fire dampers may be found in the same places as smoke dampers, depending on the application of the area when the firewall.

Turning vanes –

Turning vanes are installed inside Heat sinkwork at changes of direction (e.g. at 90° turns) so as to minimize turbulence and resistance to the air flow. The vanes guide the air thus it will follow the modification of direction more simply.

Plenums –

Plenums are the central distribution and collection units for an HVAC system. The return plenum carries the air from many large return grilles (vents) or bell mouths to a central air handler. The supply plenum directs air from the central unit to the rooms that the system is intended to heat or cool. They have to be rigorously planned in ventilation style.

Terminal unit–

Whereas single-zone constant air volume systems usually don't have these, s multi-zone systems often have terminal units in the branch Heat sinks. Typically there's one terminal unit per thermal zone. Some sorts of terminal units are VAV boxes, and inHeat sinkion terminal units. Terminal units can also include a heating or cooling coil.

Air terminals –

Air terminals are the supply air outlets and return or exhaust air inlets. For supply, diffusers are most common, but grilles, and for very small HVAC systems registers are also used wide. Exhaust grilles are used primarily for look reasons, but some collectively incorporate an air cleaner and are mentioned as filter returns.

ROUGHNESS –

So as to achieve higher heat transfer coefficient, it's desirable that the flow at the heat-transferring surface is created turbulent. However, energy for creating such turbulence has to come from the fan or blower and the excessive power needed creating the air flow through the Heat sink. it's thus desirable that the turbulence should be created solely within the region terribly near the heat transferring surface, i.e., within the laminar sub layer solely wherever the heat exchange takes place and the flow should not be unduly disturbed so on avoid excessive friction losses. This can be done by keeping the height of the roughness element small in assessment with the Heat sink measurement. Although there are many parameters that characterize the arrangement and form of the roughness, the roughness component height (e) and pitch (p) are the most vital parameters. These parameters are typically specified in terms of dimensionless parameters, namely, relative roughness height (e/D) and therefore the relative roughness pitch (p/e). The roughness components are two-dimensional ribs or three-dimensional separate components, thwart wise or angled ribs or v-shaped continuous or broken ribs.

VI. LITERATURE SURVEY

Hamdi E. Ahmed, M.I. Ahmed, et al [2015] – In this proposed article presents the varied impact of nano fluid and vortex on heat transfer and friction factor in equilateral triangular Heat sink. 2 kinds of nanofluids Al_2O_3 and SiO_2 nanoparticles immersed in H_2O with two particle concentrations were ready and tested. At totally different Reynolds number was taken from 500 to 8000. The results of smooth triangular Heat sink utilizing water as a significant fluid is valid with experimental information and a decent result was obtained. this results shows a decent result in heat transfer by handling vortex generator with fluid as water whereas a major improvement was registered by handling the compound of vortex generator and nano fluids are decrease within the friction factor. [3]

Alireza Zamani Aghaie, Asghar B. Rahimi et al [2015] – This article presents the Thermal management concept includes maximization of heat transfer coefficient and minimum factor of friction factor. Increment of thermal management factor for optimization. At a constant flow of Reynolds number at high value of 10,000, rib relative pitch (P/H), rib relative height (e/H), rib relative tip breadth (a/H) are utilized because the shape optimization factors. Results show that rib pitch, rib height, rib tip breadth and rib front shape have the best advantage on the thermo-hydraulic performance. Triangular rib geometry with rib height of 0.2H and P ¼ 2H during which the rib front is perpendicular to the flow direction is recognized as optimum configuration. [4]

Adem Acır [2015] – This research article presents a the heat transfer, friction factor and thermal performance factor of a Heat air heaters with circular type tabulators having different angle of attack angles and distances were performed. Effect of the pitch ratio and angle ratio were analyzed to boost performance in heat transfer during a range of between 3000 and 7500 Reynolds number under radiation heat flux. The experimental results obtained using various tabulators were analyzed and compared with conventional plain tube. [5]

Anil Kumar, et al. [2015] – In this thermal-fluid flow parameters in Heat air Heat sink having different V-rib with staggered rib roughness. Four kind's turbulent models (RNG k–e model, realizable k–e model, standard k–e model and SST k–x model) were simulated for smooth Heat air Heat sink. The RNG k–e models were finally selected as the most suitable one. The impact of relative breadth ratios of various multi V-rib with staggered rib form on the common Nusselt number, average friction factor and overall thermal performance are expected. [6]

Dongxu Jin, Manman Zhang et al [2015] – In this study, a numerical analysis of heat transfer and fluid flow is analyzed in a Heat air heater Heat sink having variable V-shaped ribs on the absorber plate is done in this study. 3-D simulations are performed using the ANSYS FLUENT code and the Renormalization-group k-ε turbulence model. The computational equation analysis are performed for various rib geometries with a variable span wise V-rib number, relative rib pitch, relative rib height, and angle of attack, and for various Reynolds numbers. [7]

R S Gill [2015] – In this paper, results of experiment was analyzed on heat transfer and friction on rectangular Heat sinks roughened with broken arc-rib roughness combined with staggered rib piece has been presented. The rib roughness has relative gap width of 0.65, relative staggered rib position of 0.6, relative staggered rib size of 2.0, and relative roughness pitch of 10, arc angle of 30° and relative roughness height of 0.043. The relative gap size was varied from 0.5 to 2.5. The effects of gap size on Nusselt number, friction factor and thermo-hydraulic performance parameter have been analyzed and results compared with smooth Heat sink and continuous arc rib roughened Heat sink under similar conditions. [10]

Surendra Agrawal, J.L. Bhagoria, Rupesh Kumar Malviya [2014] – It is accepted indisputable fact that the heat transfer coefficient between the absorbent material surface of Heat air collector & flowing fluid i.e. air may be improved by providing artificial roughness geometry on heat transfer surface (absorber surface). During this approach the Thermal efficiency is enhanced. However at instant time because of roughness geometry pumping power of Heat air collector in enhanced because of fictional losses in Heat sink. Therefore it necessary to look at the form, size & flow pattern different roughness components to get most efficiency with minimum resistance losses. so the choice of roughness geometry should be supported the parameter that takes into consideration each Thermal & Hydraulic (friction) performance i.e. Thermo-hydraulic Performance of Heat air collector. Number of roughness components has been investigated on heat transfer & friction characteristics of Heat air collectors. during this paper, reviews of different artificial roughness components used as passive heat transfer techniques, so as to enhance Thermo-hydraulic performance of Heat air collectors is reviewed & given. Correlations developed by numerous researchers with the assistance of experimental results for heat transfer & friction factor for Heat air collector by taking various roughness geometries are given & these correlations are helpful to predict the Thermo-hydraulic performance of Heat air collector having rough Heat sinks.

Uttara Shakya, R. P. Saini, M. K. Singhal [2013] – Artificial roughness as kind of ribs on the absorbent material plate is a good technique to boost the rate of heat transfer to flowing fluid within the rough Heat sink of Heat air heater. Numerous artificial roughness geometries are reported within the literature by investigators, for deciding the result of varied roughness geometries on heat transfer improvement and friction characteristics in rough Heat sink of Heat air heater. Reviews of varied studies are given during this paper. Development of correlation for heat transfer coefficient and friction factor by investigators and comparison of thermo hydraulic performance of Heat sink has been given. [18]

Shailesh Gupta, Alok Chaube and Prakash Verma [2013] – The impact of the rib angle orientation and influence of a gap provided in integral ribs on heat transfer and pressure drop by a sq. Heat sink with 2 opposite in-line ribbed walls is investigated. The experimental investigation has been performed for continuous ribs (with no gap) and ribs with a gap having relative roughness pitch (p/e) of ten, relative roughness height (e/Dh) of 0.060 and rib attack angle of 90° and 60° for Reynolds number from 5000 to 40,000. Distinct ribs with relative gap position (d/W) of 1/5 and relative gap width (g/e) of 1.0 are investigated to compare their heat transfer performance with corresponding continuous ribs (without gape). The improvement in heat transfer and friction factor of this roughened Heat sink is additionally compared with smooth Heat sink with similar flow condition. The results show that inclined ribs performs better than transverse ribs for each the cases i.e. for continuous ribs and ribs with a gap. The 60° ribs with a gap yields concerning 3.8-fold enhancements in Nusselt number and concerning 7.4-fold increase within the friction factor compared with smooth Heat sink and concerning 1.1 times and 1.2 times that of 60° continuous ribs (without gaps) for the whole vary of parameters investigated. But for 90° ribs the improvement in heat transfer and factor is incredibly low as compared to it of corresponding 60° ribs. [21]

VII. RESULT ANALYSIS AND DISCUSSION

A three-dimensional model is developed to investigate flow and conjugate heat transfer in the Heat sink for comfort cooling applications. A series of numerical calculations have been conHeat sinked by FLUENT and the results are presented in order to show the effects of temperature distribution, Friction factor, and Surface Nusselt number with respect to relative gap width in the Heat Heat sink with Semi Semi-circular V-Rib roughness.

The validation of the Experimental result is done by carrying out the simulation work on the ANSYS Fluent 15.0 Work bench.

Experimental and Simulation Result –

The friction factor of the Heat Heat sink with Semi- circular V-Rib roughness, f, can be defined by-

$$F = \frac{2(\Delta P)_d D}{4\rho L V^2}$$

Where ΔP is Pressure drop between the highest pressure on the Heat Heat sink and the ambient air pressure, and Q is heat dissipation power applied on the Heat sink base. Properties of the working fluid are the same as those of ambient air, and the material of Heat Heat sink is aluminium with thermal conHeat sink of 202 W/(m-K). Both simulation results and Rajesh Maithani, J.S. Saini experiment results [1] for friction factor and nusselt no. of the Heat Heat sink with Semi Semicircular V-Rib roughness are plotted in Fig and respectively. As can be seen in these figures.

VIII. CFD GOVERNING EQUATIONS SOLVE BY FLUENT:

This section is a summary of the governing equations used in CFD to mathematically solve for fluid flow and heat transfer, based on the principles of conservation of mass, momentum, and energy. These equations solve by the fluent software. The conservation laws of physics form the basis for fluid flow governing equation

Law of Conservation of Mass

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Momentum Equation:

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = \frac{\partial}{\partial x_i}\left(\mu \frac{\partial u_i}{\partial x_i}\right) - \frac{\partial p}{\partial x_j} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Energy

$$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}\left(\frac{k}{c_p}\frac{\partial u_i}{\partial x_i}\right) \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

The fluid behavior can be characterized in terms of the fluid properties velocity vector u (with components u, v, and w in the x, y, and z directions), pressure p, density ρ, viscosity μ, heat conHeat sinkivity k, and temperature T. The changes in these fluid properties can occur over space and time But for simplification we use changes occurs only in space. Using Fluent, these changes are calculated for the fluid, following the conservation laws of physics listed above. The changes are due to fluid flowing across the boundaries of the fluid element and can also be due to sources within the element producing changes in fluid properties.

Solution Techniques:

After create geometry and meshing, incorporate boundary conditions as per model and then export this file as an .msh file. Now the problem is ready to solve by using fluent software. The solution algorithm SIMPLE (semi-implicit method for pressure-linked equations) is used to solve for the velocity field in all three directions and the pressure.

IX. CONCLUSION:

The performance of integrated fan heat sinks improves significantly when multiple fan layers are used. A multilayer scaling model showed that the overall device performance depends on the pumping and power characteristics of the integrated fans as well as the flow resistance of the inlet to the heat sink's core. Radial inlet layers were investigated as a way to decrease the overall inlet resistance, and were shown to result in drastic performance improvements under certain conditions (namely, when the inlet resistance dominates the flow in the fan layers). The flow resistance in the central core was shown to have an effect, albeit one that may be neglected when the fans have a sufficient open area in the core region.

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