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Numerical Investigation of Natural Convection Enhancement from Trapezoidal Interrupted Pin-Fins

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Abstract: in this paper, Steady-state external natural convection heat transfer from horizontally-mounted trapezoidal pin-finned heat sinks used in electronic devices is investigated numerically. The trapezoidal pin heat sink was designed to minimize the pressure loss across the heat sink by reducing the vortex effects and to enhance the thermal performance by maintaining large exposed surface area available for heat transfer. The energy equation was written under assumptions then solved numerically using finite element method. The heat transfer is examined for parameters of fin material, surface emissivity, external temperature and input heat flux. It was found that the heat transfer enhancement is more pronounced at high thermal conductivity, surface emissivity and low external temperature. All the results of the problem were presented in graphical form and discussed.

Keywords: Electronic cooling, Heat sink, *Natural convection, Numerical study, Trapezoidal fin*

Nomenclature

u	velocity in x-direction ($m.s^{-1}$)
v	velocity in y-direction ($m.s^{-1}$)
w	velocity in z-direction ($m.s^{-1}$)
h	convection heat transfer coefficient ($W.\ m^{-2}.\ k^{-1}$)
k	thermal conductivity ($W.\ m^{-1}.\ k^{-1}$)
T	temperature (K)
x,y,z	coordinates
n	normal coordinate
q''	heat flux ($W.\ m^{-2}$)
Greek letters	
ϵ	emissivity
σ	Stefan-Boltzmann constant
Subscripts	
ext	external

I. INTRODUCTION

Advances in the field of electronics have resulted in significant increase in density integration, clock rates and emerging trend of miniaturization of modern electronics. This resulted in dissipation of high heat flux at chip level. In order to satisfy the junction temperature requirements in terms of performance and reliability, improvements in cooling technologies are required. To overcome this problem, the efficient heat sinks are of the essence. Free convection from these devices is one of the considered cooling techniques and played an important function in conserving their certain operation.

Extended surfaces that are known as fins are typically used to enhance the heat transfer in many industries. The thermal network of a finned heat sink consists of conductive, radiative, and convective resistances. From the junction of the device, heat is transported by conduction from the device through the interface and into the heat sink from which heat is usually removed by means of convection and radiation cooling.

The cooling aspects have been studied by many investigators, Kang et al. [1] presents a physics based analytical model to predict the thermal behavior of pin fin heat sinks in transverse forced flow. Both experimental data and simplified CFD simulations are used to develop the two building blocks of the model, the thermal wake function and the adiabatic heat transfer coefficient. The model provides detailed but easily interpreted results regarding heat transport and temperatures within the heat sink structure. Sachin et al. [2] provides a survey about Investigation of thermal performance in natural convection from rectangular interrupted fins where both the continuous and interrupted must be keeping into account simultaneously. It is conclude from these an important contribution on analyzing the natural convective heat transfer from vertical fins with similarity solutions for boundary layer equations for the cases of uniform surface heat flux. Hireholi et al. [3] analyzes heat transfer of a commercially available heat sink. The work includes experimental investigations and theoretical modeling.

Theoretically predicted temperatures of the heat sink are compared with the measured temperatures. Comparative thermal tests have been carried out by Chapman et al. [4] using aluminum heat sinks made with extruded fin, cross-cut rectangular pins, and elliptical shaped pins in low air flow environments.

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The performance of the elliptical pin heat sink was compared with those of extruded straight and crosscut fin heat sinks, all designed for an ASIC chip. An experimental study was conducted by Abdul Razzaq [5] to investigate the heat transfer by natural convection in a rectangular fin plate by circular perforations heat sinks. It was observed that the heat transfer rate and the coefficient of heat transfer increases with increased number of perforation. Swapnali et al. [6] propose a modified experimental method to estimate the heat transfer and used it to calculate the thermal performance through different theoretical pressure drop equations with the use of waveform pin-finned heat sinks. Steady-state external natural convection heat transfer from vertically-mounted rectangular interrupted fins is investigated numerically and experimentally by Mostafavi et al. [7]. Results show that adding interruptions to vertical rectangular fins enhances the thermal performance of fins. A theoretical study is performed by Torii et al. [8] to investigate unsteady thermal and fluid flow transport phenomena over flat fins with heat sink, which are placed in a forced convection environment. Consideration was given to the effects of Reynolds number and fin pitch on heat transfer performance and velocity and thermal fields. Natural convection heat transfer from vertical rectangular fin arrays with and without notch at the center has been investigated experimentally and theoretically by Kharche et al. [9]. It is found that the heat transfer rate in notched fins is more than the unnotched fins. Pal [10] presents thermal analysis and simulation of rectangular fin, pin fin and trapezoidal scaled fins of heat sink for a high wattage LED system cooled by natural convection. A 5 X 5 LED array of total 25 watt is designed as power source; total heat load is 18.75 watt. The three types of heat sink are compared in similar conditions. It is found that of all designs simulated, heat sink with trapezoidal scaled fins performed best with a case temperature of 44.862°C. Sukumar et al. [11] reports CFD analysis of heat sinks which contain continuous rectangular fins, interrupted rectangular fins with through holes for electronic cooling. Results show that in the sense of junction temperature interrupted fins are efficient than continuous. It also found that through holes for the interrupted fins has better performance than interrupted rectangular fins.

In this paper, numerical analysis of natural convection heat transfer from interrupted trapezoidal fins used as heat sink was performed. The goal of this study was to investigate the effect of parameters such that material, surface emissivity, the external temperature and heat flux on temperature distribution in the heat sink.

II. METHODOLOGY AND MODELING

The considered trapezoidal fin heat sink geometry is shown in Fig.1. A horizontal flat platform of dimensions 155 X 250 X 5 mm and vertical fins of height 95 mm each is chosen. When the heat sink is heated, the buoyancy force causes the surrounding fluid to start moving therefore as a result thermal boundary layers start to develop at the bottom edges of the fins. The boundary layers mostly merge if the fins/channels are sufficiently long (continuous), creating a fully developed channel flow. Interrupted fins, therefore, disrupt the thermal boundary layer growth also maintaining a thermally developing flow regime, which can lead to a higher natural heat transfer coefficient.

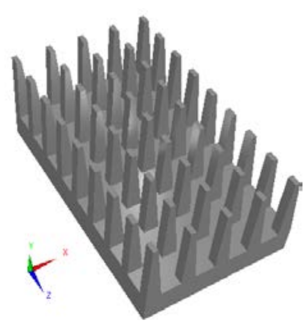

fig.(1): trapezoidal pin fin heat sink

III. ENERGY EQUATION (CONSERVATION OF ENERGY) AND NUMERICAL PROCEDURE

The model consisted of conduction heat transfer within each fin from the base to the tip and natural convection heat transfer on the wetted surfaces of the heat sink. The conservation of energy is based on assuming solid body (u = v =w = 0 everywhere in the body), steady, incompressible, constant properties with no internal heat generation and negligible viscous dissipation. Besides these assumptions, the following assumptions and simplifications apply:

i.The convection heat transfer coefficient 'h' is uniform and constant over the entire fin surface.

ii. Heat transfer through the fin is at steady state, and there is no physical thermal energy source in the fin.

iii. The temperature of the fluid between fins is uniform over the entire fin surface.

iv. The thermal conductivity of fin material 'k' is uniform and constant.

v. The base of the fin is at the temperature of the heater surface, which is uniform over the perimeter of the plate.

vi. The contact resistance between the heat sink and processor would be negligible when using a high quality thermal paste.

the equation reduce to:

$$\frac{\partial^2 \mathrm{T}}{\partial \mathrm{x}^2}+\frac{\partial^2 \mathrm{T}}{\partial \mathrm{y}^2}+\frac{\partial^2 \mathrm{T}}{\partial \mathrm{z}^2}=0 \qquad (1)$$

subjected to the following boundary conditions:

$$-k\frac{\partial T}{\partial y}=q'' \text{ at: (x-z) plane (y=0)} \qquad (2)$$

$$-\mathrm{k}\frac{\partial \mathrm{T}}{\partial \mathrm{n}}=\mathrm{h}(\mathrm{T}-\mathrm{T_{ext}})+\sigma\epsilon\left(T^4-{T_{ext}}^4\right) \text{ at: fin surface} \qquad (3)$$

External (ambient) temperature is assumed at 298 K. Air convection coefficient assumed at 10 (W/ m^2.K). Heat transfer through radiation from fins surface is controlled by emissivity value of material used.

The above partial differential equations are solved using numerical analysis based on finite-element technique (Patankar [12]). The terms are discretized using a QUICK second order central differencing scheme proposed by Leonard [13]. Finite element software package has been used. In the finite element method, the mesh generation is the technique to subdivide a domain into a set of sub-domains, called finite elements, control volume, etc. Grid utility read meshes generated by INRIA and manipulates them. The grid geometry shown in Fig.2 consists of 185904 node, 156816 eight-node hexahedron volume element, 54982 four-node quadrilateral surface elements and 109964 linear line segment edge element. GUI utility imports finite element mesh, setting up PDE-systems to solve, and exporting model data for the Solver utility. the equations are linearized using the Picard linearization and Newton linearization methods. To improve the convergence of the nonlinear system, a relaxation factor below unity was used. Solution method for linear systems is done using the iterative Krylov methods, Biconjugate Gradient Stabilized (BiCGStab) is chosen. Rapid convergence generally requires the use of preconditioning, therefore, Jacobi preconditioner is used.

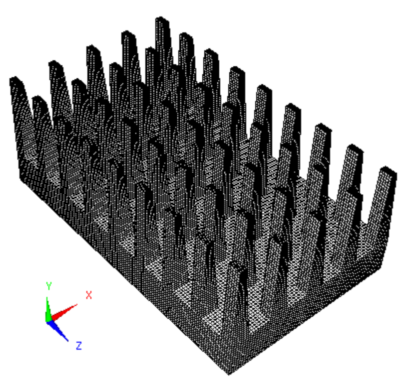

fig.(2): grid geometry of the heat sink

IV. RESULTS AND DISCUSSION

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In this section, a representative set of graphical results are presented to illustrate the influence of material, surface emissivity, external temperature and heat flux on the heat transfer characteristics when the temperature reaching steady state for each case of the heat input. The final value of the temperature is plotted.Fig.3 shows temperature contours for different heat sink materials(aluminum, copper, iron and stainless steel) at q''=3000 W/m^2 .

Generally there are two types of materials used for fins aluminum and copper. The thermal conductivity of aluminum is 225 W/m.K and that of copper is 385 W/m.K. The melting and boiling point of copper are 1084˚C and 2595˚C and that of aluminum are 658˚C and 2057˚C. Pure aluminum has silvery color and it has greater resistance to corrosion. It is used in deoxidizing molten irons and steel. It is used to prepare the metals from their oxides by heating a mixture of powdered aluminum and the oxides of the metal to be reduced. Its electrical resistivity is 2.669 micro ohms/cm. Copper is reddish brown in color. Refining of the metal is usually considered to begin when the copper is in the blister stage, the surfaces of the cast material being irregular and blistered due to the generation of gases during cooling. This copper is 99% pure and is further refined in the furnace by oxidation process which removes sulphur and other impurities. The excess of oxygen is removed from the metal by operation known as poling. Its electrical resistivity is 1.682 micro ohms/cm. from this figure, we can observe that since the heat sinks are made of metals which have high thermal conductivity(copper, aluminum), the variation of temperature within the heat sink is very small in comparison to the possible change in the temperature of the fluid. The primary thermal resistances within the heat sink are across the thickness of the base of the heat sink and along the length of the fins which is characterized by the fin efficiency. We see that T_{max}=456 K and T_{min}= 307 K for aluminum and T_{max}=869 K and T_{min}= 298 K for stainless steel indicating that aluminum is more efficient in heat dissipation to the surrounding than stainless steel.

Effect of surface emissivity for aluminum heat sink with q''=2500 W/m^2 is shown in Fig.4. Each heat sink had a finish with an estimated emissivity of 0.3 and 0.9 minimum. This was done by black sulfuric acid anodizing the extruded heat sinks, and using black paint for the cast elliptical pin heat sink. Thus, radiative heat transfer was included in the testing and combined with the convection component to represent parallel heat transfer from the surface of the fins. High surface emissivity means more heat transferred to the ambient by radiation. This can deduced from the figure with T_{max}=414 K and T_{min}= 303 K at ϵ=0.3 and T_{max}=396 K and T_{min}= 300 K at ϵ=0.9. The nature of air flow on extended cooling surfaces is to form a layer of stagnant, insulating air over any surface exposed to the air stream. This insulating layer results in a heat sink temperature rise and is caused by the viscous nature of air, or any other fluid, used to transfer heat in a convective mode. The build-up of this "film" or "boundary layer" decreases the amount of heat energy that can be dissipated from each square centimeter of cooling area by acting as an insulation layer between the heated surface and the cooling air, Fig.5 explains the effects of increasing the external temperature from T_{ext}=303 K to T_{ext}=313 K on the temperature distribution within a stainless steel heat sink at q''=2500 W/m^2. As the external temperature increases, the difference in temperature between fin surface and surrounding decreases which cause a reduction in the amount of heat transferred according to the Newton's law of cooling. Fig.6 shows the variation of the steady state temperature difference (T_{base}-T_{tip}) as a function of input heat flux for different heat sink materials. From this figure one can observe the increase in the temperature's value from base to tip along the fin as the input heat flux value at the base increases as a result of the increase in the temperature gradient at the base. also, this figure tell us that the material with high thermal conductivity (small thermal resistance) will diffuse heat faster and dissipate it to the ambient more efficient results in small temperature difference along the fin as seen from the comparison between copper and stainless steel.

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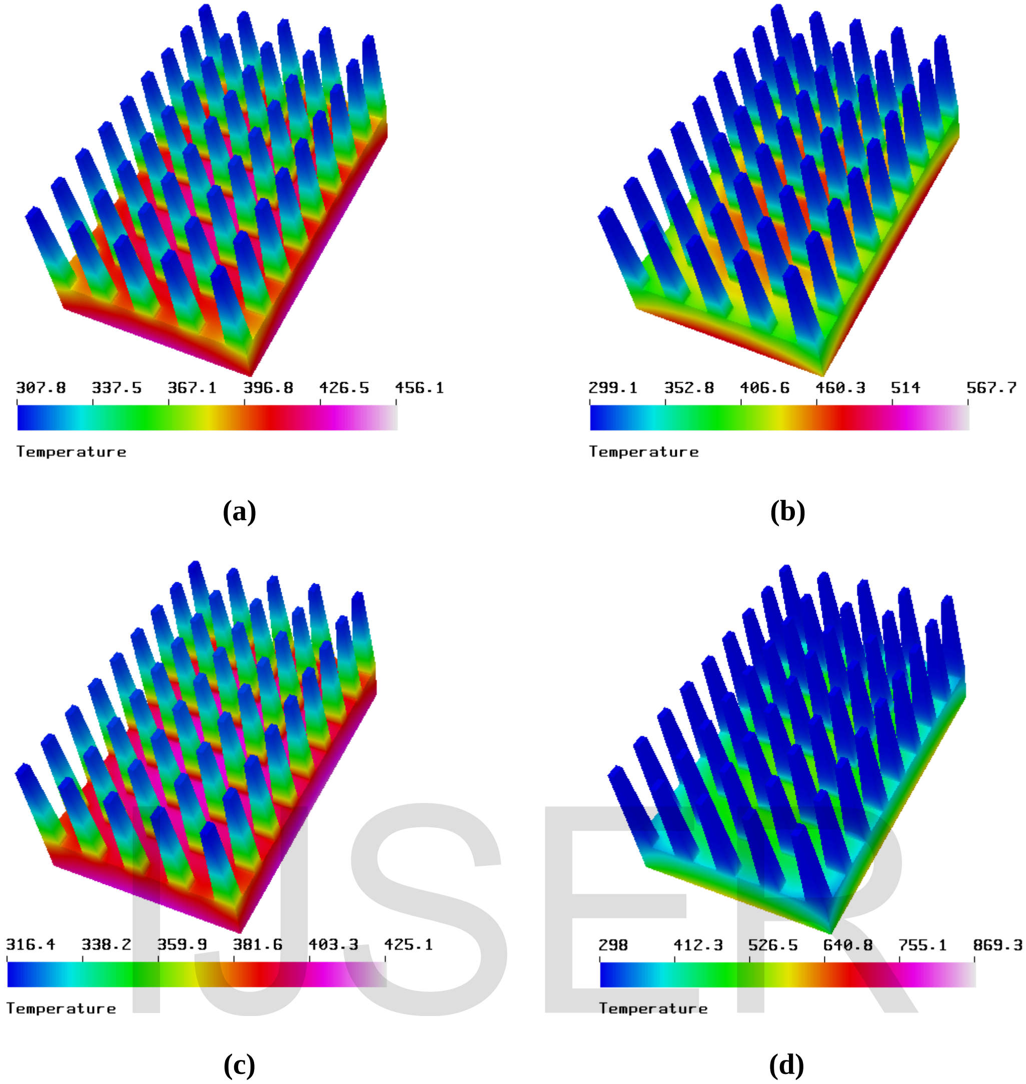


fig.(3): temperature contours for: (a) aluminum,(b) iron,(c) copper,(d) stainless steel at q''=3000 W/m^2

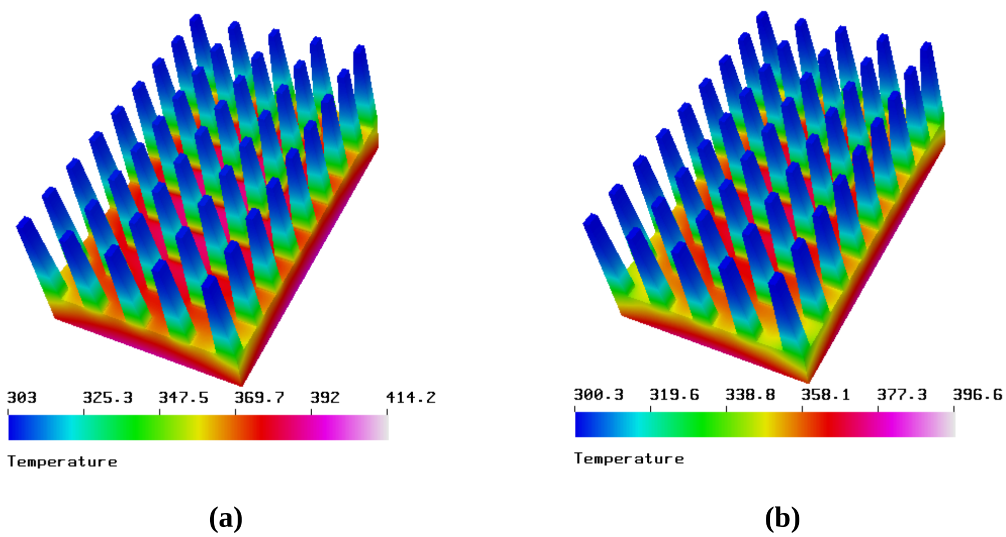
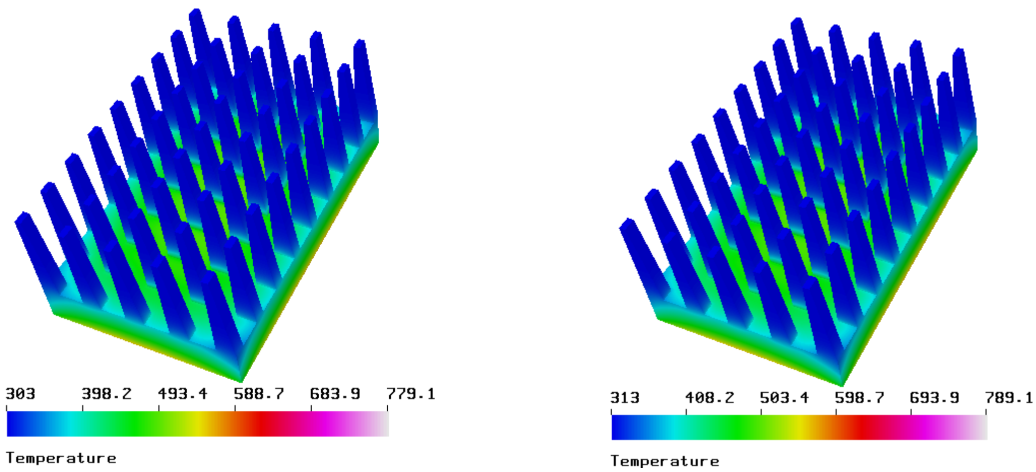


fig.(4): temperature contours for aluminum at: (a) ϵ = 0.3,(b) ϵ = 0.9, q''=2500 W/m^2



(a) **(b)**

fig.(5): temperature contours for stainless steel at: (a) T_{ext}=303 K,(b) T_{ext}=313 K, q''=2500 W/m^2

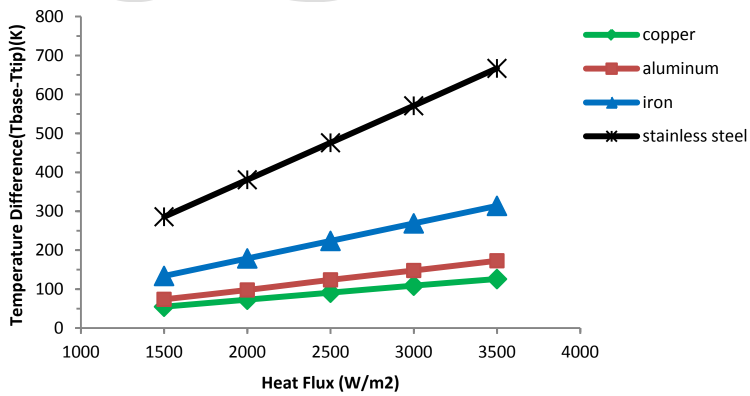


fig.(6): steady state temperature difference versus input heat flux for different heat sink materials

V. CONCLUSIONS

A numerical study has been performed on steady natural convection over interrupted trapezoidal fins used in heat sink. Consideration was given to the effects of fin material, surface emissivity, external temperature and input heat flux on heat transfer performance. It was found that:

1. Metals which have high thermal conductivity are more efficient in heat dissipation to the surrounding.
2. High surface emissivity means more heat transferred to the ambient by radiation.
3. As the external temperature increases, the difference in temperature between fin surface and surrounding decreases which cause a reduction in the amount of heat transferred.
4. As the input heat flux value at the base increases the temperature's value from base to tip along the fin increases

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