Enhancement of Forced Convection Heat Transfer with Permeable Fins: A Review

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Abstract-- **High rates of heat flow is in demand for a number of engineering application like cooling of electronic chips, heat exchanger, cooling of IC engine etc. In all these cases, major heat transfer from the surface to the surrounding fluid takes place by the process of convection. Hence in order to increase heat transfer rate one must increase the surface area, therefore such an application demands efficient design of fins for high heat transfer rate. With advancement in technology the research works on convective heat transfer appeared in the open literature on the augmentation of heat transfer using permeable fins. The purpose of this review article is to summarize the important published articles on the enhancement of the forced convection heat transfer with permeable fins.**

***Index Terms*-- Permeable Fin, Parameters, Effectiveness, Efficiency, Convective heat transfer, Micro channel Heat Sink, Electrohydrodynamic heat transfer.**

1. INTRODUCTION

THE phenomenon of heat transfer from the surface to the surroundings through the fins takes place by the convection mode of heat transfer. In order to increase the heat transfer rate one must think to increase the surface area, but increasing the surface area also results in increasing the overall dimension of the equipment and making it bulky, and hence further increasing the material cost and space requirement. Therefore to increase the heat transfer rate, we have to increase the effective area by designing the proper fin (permeable fin).

The convective heat transfer is classified as Natural and Forced. In Natural convection, the surrounding molecules are made to flow naturally without any external force, whereas in forced convection the fluid molecules are forced to move over the surface with the help of some external source. When a mass of fluid is subjected to an external force, it starts flowing with a certain velocity. The velocity of the fluid indicates the level of turbulence in the flowing fluid; this generated turbulence enhances the mixing of fluid particles which is essential for heat transfer. Hence, in forced convection the rate of heat transfer is mainly governed by the velocity of the flowing fluid, but when the velocity is low as in case of laminar flow, the other parameters like density, viscosity etc. come into picture. However as the velocity increases, the turbulence in the flowing fluid starts increasing and dominates the convection pheno -menon making all the other parameters less significant. Hence, the heat transfer coefficient is a function of velocity only.

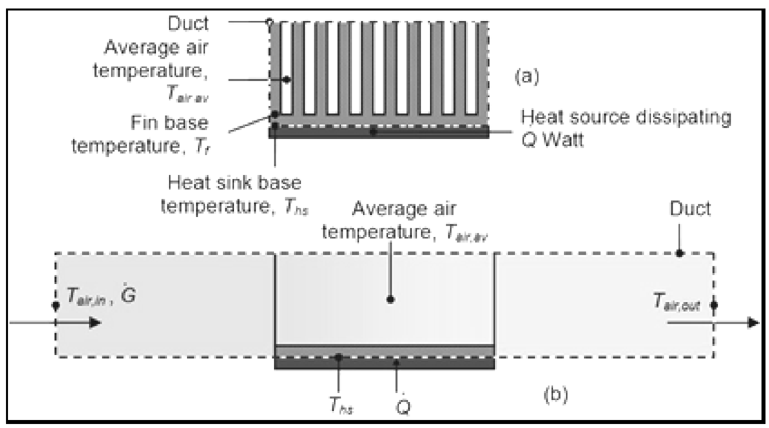

Fig1. Heat flow in a pin fin [1]

The conduction through the fin takes place along the length of the fin as well as in radially inward or outward direction. Hence, the temperature gradient within the fin exists along the length as well as over cross-section of the fin. But we assume that the length of the fin is longer than its width and hence the temperature gradient along the width is uniform and hence the conduction takes place only along the length of the fin which simplifies the calculation.

I. Performance Parameters of a Fin:

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The performance of fins can be evaluated using parameters like efficiency, effectiveness, density of fins, spacing etc. but our ultimate goal is to increase effectiveness and efficiency. In general, effectiveness gives the percentile change in the heat flow rate caused by the fins. On the other hand, the efficiency of the fins gives the percentage increase in the effective area of the system. It is a fact that as length of the fins increases its effectiveness increases while efficiency decreases.

I. Effectiveness of Fins:

When we provide the fins on base surface, they increase the surface area available for heat transfer. Thus, we get some additional heat flow but it also covers some part of the base area and therefore some part of the heat transfer from the base surface is decreased. Hence effectiveness is defined as the "ratio of the rate of heat transfer from the fin surface to the rate of heat flow from the covered surface when it is exposed to the surrounding fluid".

$$\varepsilon = q_f / q_b \qquad (1)$$

Where ε = effectiveness of fin.

q_f = heat flow rate from fin surface.
q_b = heat flow rate from the base .

Recent literature points out growing interest in the heat sinks with the horizontal base in natural convection, where fin spacing affects the air flow pattern and heat transfer rates to the surroundings. The existing literature on the fin heat sinks in natural convection concerns mostly plate fins, although pin fins provide better performance as shown by sparrow and vemuri [2].

The research established a number of important results for pin fin heat sinks in natural convection and radiation. In particular, they showed that a horizontal base sink with upward facing fins out performs an identical sink with a vertical base and horizontal fins and they found that for effective heat transfer from fin takes place when the ratio of the fin diameter to the center-to-center spacing is considered, and it was established that the optimum value of the ratio is about 1/3, whereas the heat transfer from more densely populated sinks is less effective. They framed a numerical model which reconstructs meticulously the physical one, validated versus the experimental results.

I. Efficiency of the Fins:

Heat transfer augmentation has been the subject of many researches. In the 1980s , the benefits of this field began to emerge in the industry and also in open literature[3]. There are several thousand papers that have been published on the subject of heat transfer enhancement. Bergiles et al. [4] compiled the available literature on convective heat transfer. They sampled several papers, journals and patents to generate a database of over 5000 papers and they have also given the various parameters to define the proper function of fins and hence efficiency is defined as the actual rate of heat flow obtained from the fin to the maximum possible rate of heat flow that can be obtained from the same fin.

$$\eta = q_{actual} / q_{\max} \qquad (2)$$

the maximum heat flow is a hypothetical concept, i.e. when the entire fin is supposed to have same temperature as that of base surface, then the temperature difference over the entire length of fin will be same and equal to its maximum possible value. Obviously, the rate of heat flow will be maximum at that situation.

III. Enhancement of Convective Heat Transfer:

In the earlier studies by Sahiti et al. [5,6], it was demonstrated that pin fin arrays offer the most effective way of enhancing the heat transfer rate within the particular heat exchanger volume. However, the pressure drops in such heat exchangers are usually much higher than those in others, as a result this defect greatly lowers the overall heat transfer performance of pin fin heat exchanger & further their applications are restricted. In order to reduce the pressure drops and improve the overall heat transfer performance for pin fin heat exchanger, porous or permeable pin fin arrays may be used instead of traditional solid metal pin fin arrays.

As porous media can significantly intensify the mixing of fluid flow and increase the contact surface area within fluid inside, it has been regarded as an effective way to enhance heat transfer by using permeable fins. The researches on forced convection with permeable fin have been investigated extensively in the last few years. Hadium [7] studied the laminar forced convection in a fully or partially filled porous channel containing discrete heat sources on the bottom of wall. He found that when the width of the heat source and the space between the porous layers were of the same magnitude as the channel height, the heat transfer enhancement in the partially filled channel was almost the same as that in the fully filled porous channel while the pressure drop was much lower. They also found that when the heat source width was decreased; there was a moderate increase in heat transfer enhancement and a significant decrease in pressure drop.

Jian and Min [8] studied on the same concept around permeable fin; they developed a numerical model and experimental setup with different shapes of permeable fins like elliptical shape, circular & rectangular. On account of this, they studied the forced convection heat transfer in three-dimensional porous fin channel and the performances for both air and water were carefully compared. They found that with the proper selection of metal foams, such as PPI=30, significant enhancement of heat transfer takes place and the overall heat transfer efficiencies in porous pin fin channel are much higher than those in solid pin fin channels, which are 119.5% and 37.9% higher for air and water cases at Re=2291, respectively. With the same physical parameter the pressure drop and the heat fluxes are the highest in short elliptic porous pin fin channel while the overall heat transfer performances are the highest in long elliptical porous pin fin.

The circuit temperature is one of the most important parameters affecting the performance of an IC. Air cooling has been the most commonly used cooling method for chips used in computer application but it is not effective for large amount of heat removal rates. Microchannel heat sink is an innovative cooling technology for the removal of a large amount of heat from a small area. The heat sink is usually made from a solid with a high thermal conductivity such as silicon or copper.

Tuckerman and Pease[9] introduced the concept of microchannel fabrication into the surface of the solid part by the application of micro fabrication technology. They fabricated a rectangular micro channel heat sink in a 1 × 1 cm^2 area where the channels had a width of 50μm and depth of 302μm, and were separated by 50μm thick walls. Using water as cooling fluid, the microchannel heat sink was capable of dissipating a large amount of heat and also a very less amount of pressure drop.

Tao [10] presented three possible mechanisms for the single-phase heat transfer enhancement. These mechanisms are as follows; (1) decreasing the thermal boundary layer, (2) increasing the flow interruption; and (3) increasing the velocity gradient near the heated surface. It is the manipulation of these three mechanisms that result in heat transfer augmentation. He presented an experimental and numerical study for a stacked microchannel heat sink. Effects of coolant flow direction, flow rate allocation layers, and non-uniform heating were studied, they showed that tacked microchannel compared with the single-layered microchannel provide larger flow passage, so that for fixed heat load, the required pressure drop is significantly reduced.

O.Aboulai and N.Baghernezhad[11] presented a numerical investigation for two types of grooves i.e. rectangular and arc shape fabricated in the microchannel ,which leads to enhancement in single-phase cooling. The pressure drop and the heat transfer characteristics of the single phase microchannel heat sink were investigated numerically for laminar flow. For this purpose, the conjugate heat transfer problem involving simultaneously determination of temperature fields in both the solid and liquid regions was solved numerically.

The numerical model was validated with comparison to experimental data in which good agreement was seen. They found that the grooves with an arc shape have a better effect on heat removal performance of the microchannel compared to the rectangular grooves, although the pressure drop for the former is higher. A grooved microchannel even performs better as compared to a simple microchannel, which has a minimum fin thickness. It was shown that a grooved microchannel removes 23% heat more from the substrate even with a lower mass flow rate. For microchannel with arc grooves, the situation is better and the removal heat flux is 30% more. But the depth and size of the grooves are limited due to viscous dissipation effect. By using the microchannel concept the number of fins can be reduced drastically and hence saves a lot of material and leads to higher enhancement of heat transfer.

U.V Awasarmol and A.T Pise[12] investigated on enhancement of natural convection heat transfer from engine cylinder with the permeable fins. They performed experiment in which fins were attached to the engine cylindrical block and heater was placed to simulate the combustion process. They showed that by using permeable fins with different orientation of holes, it enhances the heat transfer performance. They depicted the temperature profile and found out that the average heat transfer coefficient and the ratio of the heat transfer coefficient of the cylinder with permeable fins to the cylinder with the solid fins has increased significantly and also there has been reduction in cost due to reduction in the area. Thus, the cost of the material saved is considered approximately as 10 to 30%.

D.Sahray[13] also worked on the same line, he investigated on the optimization of horizontal-base pin fin heat sinks in natural convection. He explained the effects of fin height and fin population density are studied experimentally and numerically. The heat sinks are made of aluminum, and there is no contact resistance between the base and the fins. All the sink fins have a constant square cross section whereas the fin height and pitch may vary. From the experiment, he found that outer fin contributes about 98% of heat transfer whereas the inner fins are proved to be highly inefficient. He also commented on the spacing between the fins should be, the ratio of fin diameter to the center to center spacing is about 1/3.

Hussam Jouhara and Brian P. Axcell[14] worked on the modeling and simulation techniques for laminar forced convection heat transfer in heat sinks with rectangular fins. The analysis and calculations performed were carried out using both the classical heat transfer theory as well as the computational approach to model the temperature rise in adjacent fins. The thermal performance of a single heat sink was analyzed for approach velocities ranging from 1 to 8 m/s by using four different calculation methods.

The experiment was carried out using two heat sinks back-to- back with length (l) = 115 mm and containing 15 fins. The dimensions of the fins was; height (H) = 49 mm, thickness (t) = 1.25 mm and fin gap (b) = 2.18 mm. The Reynolds number during the experiment ranged from 512 to 4175. The initial in-line base calculations were performed with the cooling at the base temperature and the heat transfer rate denoted by Q_{ideal}. Secondly, on the basis of the Nusselt number for the flow a uniform fin efficiency was employed giving rise to Q_{approx}. They varied the heat transfer coefficient and the fin efficiency and by integrating the rate of heat loss from each element concluded the thermal output of the heat sink i.e. Q_{num}. The value of Q_{CFD} was calculated by a CFD analysis for two of the flow rates. The results pertaining to the experimental calculations revealed that the rate of heat transfer due to numerical investigation Q_{num} was less than Q_{approx} and similarly the value of Q_{CFD} was found to be more than Q_{approx}.

The value calculation was carried out using the nusselt number and the fin efficiency with the discrepancies varying from 3% to 1% from lower to higher flow rate. The above results resemble the fact that, in spite of comparing the most complex case of a full numerical simulation, accurate predictions of heat sink performance are attainable using analytical methods incorporating average values of fin efficiency and heat transfer coefficients.

Research done by Giovanni Tanda[15] extends its focus on forced convection heat transfer and highlights the pressure drop in a rectangular channel with diamond-shaped fins. The diamond shaped elements due to their low thermal conductivity were considered to be adiabatic and their purpose was to generate turbulent flow in order to increase the end wall heat transfer. He performed experiments for both (in-line and staggered) fin arrays for different transverse and longitudinal spacing. The experimental was carried out using six (2 in-line and 4 staggered) arrangements of diamond shaped pin fins (made of Plexiglas) with height-to-side ratio (H/W) of 4. The transverse (ST) and longitudinal (SL) spacing varied between 40 and 20 mm. He also used thermo-sensitive, cholestric LC sheet of thickness 0.15 mm to measure the temperature difference on the heated surface.

On the impingement of the airflow and the supply of DC current to the heater slowly different image patterns of airflow was captured for the two configurations with different values of S_T and S_L. For the in-line configuration, the distribution patterns for heat transfer coefficients along the intersection of diamond centers is characterized by high values both upstream and downstream owing to impinging effect and vortex generation but in case of distribution pattern along longitudinal symmetry line, the heat transfer coefficient first decreases then reaches a quasistatic value owing to less spreading of the wakes.

Experimentation carried out by N.Kasayapanand[16] investigated electrohydrodynamic enhancement of heat transfer by natural convection in vertical fin array (square enclosure) using computational fluid dynamics technique. Electrohyrodynamic heat transfer is the technique of convective heat transfer which involves utilization of electric field or electrostatic force from the polarization of a dielectric fluid. The numerical analysis investigates the extent to which the electrostatic forces exerted enhance the natural convection heat transfer.

The parameters for the defining of the flow characteristics and heat transfer rate were the supplied voltage, number of electrodes, Rayleigh number and number of fins. The upper and lower walls were maintained at temperature of 300K while the left and right walls were thermally insulated. The dimensions of the enclosure were 15×15 cm2. The supplied voltage is taken to be 12 V for all the calculations. He conducted independent grid analysis by varying the other parameters keeping the voltage constant. With the increment in Rayleigh number oscillation were observed in flow pattern due to interaction between thermal buoyancy and electrical body force. For the inclined angles, convective regime is developed and maximum temperature gradient is obtained at θ =30°. With an increase in angle, isotherms indicate quasi-conductive regime along the boundaries due to reduction in circulation strength. The effective flow arrangement yields the vortices in the fin and highest average velocity in the enclosures. An important find of the experiment is that for higher value of Rayleigh number, the flow field is augmented irrespective of the position and length of fins. There is an enhancement observed in the fluid flow velocity with an increase in number of electrodes due to momentum transfer from free chargers.

2. Conclusion

The paper should conclude the work and state proposed work if any. On reviewing the results and findings of the various research experiments undertaken on natural as well as forced convection heat transfer enhancement included in this paper, it can be said that permeable fins improve the heat transfer capability significantly. The heat transfer through permeable fins also depends on a lot of geometrical design parameters such as fin diameter, fin spacing, arrangement of pin-fins, orientation of heat sink, etc. Some designs may be suitable to be used for forced convection, while some for natural convection. The theoretical modeling and experimental works have made it easy to understand the effectiveness of fins in various applications.

The overall enhancement in heat transfer rate with controlled pressure reduction is achieved through permeable pin fin array in comparison to the traditional solid pin fin arrays, as the permeable fins intensify mixing of fluid flow and increase the contact area within the fluid. The mode of cooling also heavily affects the performance of the heat sink.

3. Nomenclature

η Efficiency
q_{actual} Actual heat transfer rate
q_{max} Maximum heat transfer rate
Re Reynolds number
θ Inclined Angle
Q_{ideal} Ideal heat flow rate
Q_{approx} Approximate heat flow rate
Q_{num} Numerically calculated heat flow rate
Q_{CFD} Heat flow rate by CFD analysis

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