Characterization of Radial Curved Fin Heat Sink under Natural and Forced Convection

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Abstract: Heat exchangers are important structures widely used in power plants, food industries, refrigeration, and air conditioners and now widely used in computing systems. Finned type of heat sink is widely used in computing systems. The main aim of the design of the heat sink is to maintain the optimum temperature level. To achieve this goal so many geometrical configurations are implemented. This paper presents a characterization of radially curved fin heat sink under natural and forced convection. Forced convection is studied for the optimization of temperature for better efficiency. The different alternatives in geometry are considered in characterization are heat intensity, the height of the fin and speed of the fan. By recognizing these alternatives the heat sink is characterized by the heat flux usually generated in high-end PCs. The temperature drop characteristics across height and radial direction are presented for the constant heat input and air flow in the heat sink. The effect of dimensionless elevation height \(0 \leq Z \leq 1\) and Elenbaas Number \(0.4 \leq El \leq 2.8\) of the heat sink were investigated for study of the Nusselt number. Based on experimental characterization, process plan has been developed for the selection of the similar heat sinks for desired output (heat dissipation and temperature distribution).

1. Introduction

Due to the fast development of the computing devices, heat dissipation also increases which results in the failure of the system due to adverse effects of heat on the performance of semiconductor-based components. Thus, heat sinks are a major component of the computing devices for increasing the heat transfer area which automatically cools the system by natural or forced convection. The natural convective heat sinks are widely used in the computing devices, industrial heat sinks, high-end PCs, LED (Light Emitting Diode) and in so many fields. Researchers have studied in last decades for increasing the performance by optimizing the size of the heat sink, weight, fan speed and possibilities of alternative materials. A new procedure has been demonstrated for least material optimization under natural convective heat transfer for vertical rectangular longitudinal plate fin [1]. There are many studies carried out by both experimentally and numerically on the design of heat sink for LED. A developed procedure was introduced and then followed for finding the new geometrical configuration for a heat sink operating under natural convection. This enhanced technique was given by the partial derivatives of core temperature as for of heat sink which is subjected to involved volume [2]. Parametric studies have been performed to investigate the compactness, lightweight and efficient
design of high-end computing devices [3-4]. Heat sinks are studied along the vertical cylinder with longitudinal fins which are broadly utilized in heat dissipation of LED bulbs [5]. An inclined cross-cut cylindrical heat sink was examined to enhance the energy transformation and managing the LED light bulbs. The thermo-flow features were investigated to improve the cooling performance of a cylindrical heat sink, which is the cooling gadget utilized for LED light bulbs [6]. Recent studies [7-8] have investigated over natural convection heat transfer around a radial heat sink consists of rectangular fins with a concentric ring and circular base and with its orientation. These studies have presented on the effect of fin length and spacing between the fins on thermal performance. A generalized correlation has presented to predict the Nusselt number in the non-dimensional form. A study [9-10] has presented the optimization and selection of heat sink over a wide range of application domain. The characterization has made by constraining one parameter to analyse the performance of another parameter. A study [11] have presented for improvement in the heat transfer by optimizing the thermal resistance and mass of the heat sink. Furthermore investigations have carried over forced convection for improving the results. The experimental and numerical investigation has been carried out for finding the optimal distribution of heat source array to minimize the maximum excess temperature and to study the effect of substrate board conduction on heat transfer over natural and forced convection [12]. A Recent study [13] presented the evaluation of convective heat transfer coefficient at the surface of gray cast iron plate fins. Laminar forced convection heat transfer investigated on the laterally perforated-finned heat sink. A study [14] presents cooling performance, thermal resistances and improvement in temperature uniformity. A Recent study [15] presents unsteady forced convection over a cylinder with radial fins in cross flow and effect of Reynolds number in the effectiveness of the heat sink. A recent study [16] on forced convection has presented the orientation effect of driven air flow on heat sink for investigation the cooling performance. The heat transfer characteristics have studied experimentally on both vertical-placed fan and horizontal-placed fan. Furthermore, studies [17-19] have presented experimental results for the plate fins with variable thickness and height for electronic cooling applications.

In this experimental study, the heat transfer characteristics are investigated for natural and forced convective heat sink consist of radial curved fins connected to the cylindrical core. The different alternatives considered in the analysis are power input, dimensionless height, length and spacing of the curved fins. By recognizing these variants the temperature drop is calculated for the constant heat input and variable fan speed. The effect of dimensionless elevation height \((0 \leq Z^* \leq 1)\) and Elenbaas Number \((0.4 \leq El \leq 2.8)\) were investigated for obtaining the Nusselt number of the heat sink.

2. Radial heat sink model

Figure 1 shows the CAD model of the radial heat sink consists of equally spaced radially curved fins attached to the central cylindrical core. This model is used for the analysis of its effectiveness under natural and forced convection (with variable swept volume of air by varying the fan speed placed centrally on top of the radial heat sink). In application, the heat sink under study is mounted over the processors of the computing devices for easy dissipation of the heat. This heat sink made of 6061 T6 aluminum alloy is commercially used in general purpose computing devices such as Intel dual core processors (LGA775). In order to investigate the temperature distribution along the radial and vertical plane of sink thermocouples were attached to the fin at different locations. The fins were circumferentially organized at consistent intervals as presented in figure 1. The general radius and height of the implemented heat sink are signified as \(R\) and \(H\) respectively (refer figure 1). Dimensions \(R\) and \(H\) are 45\(mm\) and 18\(mm\) respectively. Further, \(H\) is the sum of \(H_f\) and \(H_b\), where \(H_f\) and \(H_b\) are the height of fin and base respectively. The base of the heat sink is shown in figure 1 (b). Dimensions \(H_f\) and \(H_b\) are 15\(mm\) and 3\(mm\) respectively with thickness of fin \(t_f = 1\(mm\)\) and radius of the cylinder \(r = 19\(mm\)\).
3. Normalized Governing equations

The process effectiveness constraints are signified in a non-dimensional way to have a generalization of the analysis. The Nusselt number and Elenbaas number are main non-dimensional constraints in the study of heat transfer. Nusselt number presents the intensity of convective heat transfer and Elenbaas number measures the variability of a level of fluid due to the difference of temperature and density at the top and bottom. Mathematically Nusselt number and Elenbaas number are defined as:

$$\text{Nu} = \frac{hH_f}{k_{air}} \quad (1)$$

Where $k_{air}$ is thermal conductivity of air and $h$ is the average heat transfer coefficient at the fin which is the ratio of the heat flux to the temperature difference as follows:

$$h = \frac{q}{T_f - T_\infty} \quad (2)$$

Where $q$ is the applied heat flux, $T_f$ is an average of fin surface temperature, and $T_\infty$ is the ambient temperature. In this study, the effects of non-dimensional elevation height $(0 \leq Z^* \leq 1)$, and the dimensionless Elenbaas number $(0.4 \leq El \leq 2.8)$ were investigated to obtain the Nusselt number of the heat sink. Above mentioned two dimensionless factors are defined as follows, respectively:

$$Z^* = \frac{Z}{H_f} \quad (3)$$

$$El = \frac{g \beta(T_f - T_\infty)S_{avg}^4}{H_f \alpha v} \quad (4)$$

Where $Z$ is the elevation at which thermocouples are attached, $g$ is the gravitational constant, $\beta$ is thermal expansion coefficient, $\alpha$ is thermal diffusivity, and $v$ is kinematic viscosity. The $S_{avg}$ is an average fin spacing, which can be designed as follows:

$$S_{avg} = \frac{1}{2} \left[ \left( \frac{2\pi R}{N} - t_f \right) + \left( \frac{2\pi(R-1)}{N} - t_f \right) \right] \quad (5)$$
Where the number of fins is \( N \), \( t_f \) is the thickness of the fin and \( l \) is the length of the fin. Mathematically, the length of the fin is \( (R - r) \).

4. Experimental setup

Experimental studies were performed on the heat sink selected for the study (refer figure 1) to investigate the temperature distribution along the vertical fin plane with natural and forced convection. Figure 2 shows the schematic diagram of the experimental setup. This setup consists of a hot plate which runs on AC power supply. Thus hot plate is the heat source in the setup having a temperature range from 50 °C to 350 °C at the surface of the plate. The temperature of the hot plate can be regulated by switch and controller of the hot plate assembly. The heat sink is to be mounted on the surface of the plate for experiments. The heat generated from the hot plate shall be transmitted to the heat sink without loss. Teflon sheet is placed over the hot plate in a way to avoid undesirable heat loss and only to have a transfer of heat to heat sink. Teflon sheet is designed for the same size of the hot plate (10” X 12”) and 3 mm in thickness with the provision of a hole at the center equal to the base diameter of the heat sink (refer figure 2 (b)). The heat sink is located above this Teflon sheet in the central hole. Furthermore, thermal grease is applied at the interface of the heat sink and hot plate. Thermal grease is used to minimize the thermal resistance and also to act as an adhesive agent so the heat sink should fix properly with the hot plate. Heat loss over the Teflon can be calculated by the following equation:

\[
Q_{\text{loss}} = \frac{k_T A_T (T_b - T_f)}{H_T}
\]  

Where \( k_T \) is thermal conductivity of the Teflon, \( T_f \) is the temperature of the Teflon upper surface, \( T_b \) is the heat sink base temperature and \( H_T \) is the height of Teflon. The total heat applied to the heat sink can be found by:

\[
Q_{\text{heat sink}} = Q_{\text{total}} - Q_{\text{loss}}
\]

In this experimental investigation, the maximum heat loss was calculated around 20% of the total heat. Based on \( Q_{\text{heat sink}} \), Nu number is established by using equation (1). The heat flux which appears in the equation (2) is estimated by the function of heat dissipation through the heat sink and the surface area of the heat sink. \( Z \) is the height of point where temperature by the thermocouple is recorded. \( Z_i \) indicates that thermocouple is attached to the bottom of the fin plane. Similarly \( Z_z \) and \( Z_t \) at the middle and top position of the fin plane respectively. Figure 3 shows the schematic representation of the points of placement of the thermocouple to the heat sink. Six K-type thermocouples are attached to one of the fins of the heat sink to capture the temperature radially and in the vertical direction (refer figure 2 (a)). These thermocouples are coupled to a data acquisition system (refer figure 2) to measure the temperature in two different planes in real time. The experiments are carried out for the natural convection around 50 W/m², 90 W/m², and 130 W/m² respectively. Similar experiments are carried out for the forced convection for different levels of air flow velocity attained by a centrifugal fan attached at the top of the heat sink. The speed of the fan is regulated by using a 5KΩ potentiometer for the rotational speed of 800 rpm, 1200 rpm, 1500 rpm, and 2000 rpm.
5. Results

The temperature distribution is observed at various heat inputs such as around 50 W/m$^2$, 90 W/m$^2$, and 130 W/m$^2$ at natural convection and same as in forced convection where fan speed as 800 rpm, 1200 rpm, 1500 rpm, 2000 rpm. Figure 4 shows a comparative plot of experimental data of temperature drop $\Delta T \left( \Delta T = T_f - T_a \right)$ across fin against applied heat flux. Due to positioning effect of the
thermocouple, the graph for $Z_i$ is lifted upwards. As in forced convection at high fan speed, it gives smaller $\Delta T$ because high fan speed is related to high Reynolds number which results in great temperature drop.

Figure 4. Comparative plot of temperature distribution vs heat flux $\left( \Delta T = T_f - T_w \right)$.

Figure 5. Effect of Elenbaas number and dimensionless fin elevation on the Nusselt number $\left( 0 \leq Z' \leq 1 \right)$.

Figure 5 shows the experimentally estimated graph of Nusselt number against Elenbaas number. The effect of Nu number of the heat sink was studied over dimensionless elevation height $\left( Z' \right)$ and Elenbaas Number $\left( El \right)$. As presented in figure 5, the Nusselt number is high at the smallest Elenbaas number. This Elenbaas number varies from 0.4 to 2.8. Nusselt number is a function of heat transfer coefficient $\left( h \right)$ and $\Delta T$, whereas Elenbaas number is also a function of $\Delta T$. As $\Delta T$ varies it fundamentally points to increase in Nu number and decrease in Elenbaas number. Experimental
observations point out the nonlinear increase in Nusselt and Elenbaas number. These results are validated with previous generalized studies [7] by comparing the behaviour of the results across \( \text{Nu} \) and \( \text{El} \). From the results, it has been seen that heat sink gives better heat dissipation by increasing the height of the sink as compared to the radial direction and increasing fan speed. Hence the optimum dimensions of radial and height of the sink with optimum fan speed can be obtained for a chosen Elenbaas number.

Based on the experimental result a new process plan has been developed for selecting the optimum dimensions and optimum fan speed. Figure 6 shows the flowchart for the design of new heat sink. The amount of required heat dissipation, maximum heat sink temperature or the optimum \( \Delta T \) and maximum size of the heat sink are the basic constraints for the design of a heat sink. From known heat dissipation and optimum \( \Delta T \), dimensionless elevation height \( (Z^*) \) can be obtained from a comparative plot of \( \Delta T \) against heat flux (refer figure 4). From the equation of \( Z^* \left( Z^* = Z / H_f \right) \), \( H_f \) can be calculated by recognizing the elevation height \( (Z) \). Then \( \text{Nu} \) can be found as ‘\( h \)’ is the heat transfer coefficient and function of the \( \text{Nu} \) number. The Elenbaas number can be found by obtained \( \text{Nu} \) number and at particular \( Z^* \) (from figure 5). Elenbaas number is the function of the geometrical term \( S_{avg} \), where, by constraining one of the parameters such as the thickness of the fin \( (t_f) \) or number of fins \( (N) \), another parameter can be obtained. This procedure will be helpful in the similar design of the heat sink with natural or forced convection problem.

![Flow chart for the design of a new heat sink.](image)

6. Conclusion

This paper presents an experimental investigation of the heat transfer characteristics about a heat sink consists of radial curved fins attached to the central cylindrical core subjected to natural and forced convection. In the experiments, heat input is considered as the heat liberated from the high-end computing system. The effect of dimensionless elevation height \( (0 \leq Z^* \leq 1) \) and Elenbaas Number \( (0.4 \leq El \leq 2.8) \) were investigated for obtaining the Nusselt number of the heat sink. At top of the fin plane, the temperature difference is least as compared to the bottom side, so the heat transfer
coefficient is more at the outer surface and gives the high Nusselt number. The temperature drop characteristics across height are presented for the constant heat input and variable fan speed in the heat sink. These results are validated through previous studies. After the validation a new process plan has been developed for the selection of the similar heat sinks for desired output over these experimental results. Present experimental set up may be extended for the study of various other types of industrial heat sinks for natural and forced convection investigation.

7. References

[1] Avram Bar-Cohen, Madhusudan Iyengar and Allan D. Kraus 2003 Design of Optimum Plate-Fin Natural Convective Heat Sinks, *J. Electron Packaging* **125** (2) 208–216.

[2] Vitor A.F. Costa and Antonio M.G. Lopes 2014 Improved Radial Heat Sink for Led Lamp Cooling, *Appl. Therm. Eng.* **70** (2) 131-138.

[3] Seung-Hwan Yu, Kwan-Soo Lee and Se-Jin Yook 2010 Natural convection around a radial heat sink, *Int. J. Heat and Mass Transfer* **53** 2935–2938.

[4] Choi and Minjoong Jeong 2016 Compact, lightweight, and highly efficient circular heat sink design for high-end PCs, *Appl. Therm. Eng.* **92** 162–171.

[5] Qie Shen, Daming Sun, Ya Xu, Tao Jin, Xu Zhao, Ning Zhang, Ke Wu and Zhiyi Huang 2016 Natural convection heat transfer along vertical cylinder heat sinks with longitudinal fins, *International Journal of Thermal Sciences* **100** 457-464.

[6] Seung-Jae Park, Daeseok Jang and Kwan-Soo Lee 2016 Thermal performance and orientation effect of an inclined cross-cut cylindrical heat sink for LED light bulbs, *Int. J. Heat and Mass Transfer* **103** 1371-1377.

[7] Bin Li and Chan Byon 2015 Investigation of natural convection heat transfer around a radial heat sink with a concentric ring, *Int. J. Heat and Mass Transfer* **89** 159–164.

[8] Bin Li and Chan Byon 2015 Orientation effects on thermal performance of radial heat sinks with a concentric ring subject to natural convection, *Int. J. Heat and Mass Transfer* **90** 102–108.

[9] Seri Lee 1995 Optimum design and selection of heat sinks, *Semiconductor Thermal Measurement and Management Symposium* 48-54.

[10] Mukesh Kumar, Anil Kumar and Sandeep Kumar 2013 Optimum design and selection of heat sink, *International Journal of Application or Innovation in Engineering & Management* **2** (3) 541-549.

[11] Daeseok Jang, Se-Jin Yook and Kwan-Soo Lee 2014 Optimum design of a radial heat sink with a fin-height profile for high-power LED lighting applications, *Applied Energy* **116** 260-268.

[12] Shankar Durgyam, S.P. Venkateshan and T. Sundararajan 2017 Experimental and numerical investigations on optimal distribution of heat source array under natural and forced convection in a horizontal channel, *International Journal of Thermal Sciences* **115** 125-138.

[13] M.J. Silva, P.S.B. Zdanski and M. Vaz Jr. 2017 Forced convection on grey cast iron plate-fins: Prediction of the heat transfer coefficient, *Int. Communications in Heat and Mass Transfer* **81** 1-7.

[14] Mohammad Reza Shaeri and Richard Bonner 2017 Laminar Forced Convection Heat Transfer from Laterally Perforated-Finned Heat Sinks, *Applied Thermal Engineering* **116** 406-418.

[15] Sajjad Bouzari and Jafar Ghazanfarian 2017 Unsteady Forced Convection over Cylinder with Radial Fins in Cross Flow, *Applied Thermal Engineering* **112** 214-225.

[16] Tzer-Ming Jeng, Sheng-Chung Tseng, Yan-Cih Huang 2017 The orientation effect of driven air flow on cooling performance of the cylindrical heat sink with a built-in horizontally-placed fan, *International Communications in Heat and Mass Transfer* **81** 190-200.

[17] Dong-Kwon Kim, Jaehoon Jung and Sung Jin Kim 2010 Thermal optimization of plate-fin heat sinks with variable fin thickness, *International Heat Transfer Conference* **53** 5988–5995.

[18] M. Morega and A. Bejan 1994 Plate fins with variable thickness and height for air-cooled electronic modules, *Int. J. Heat Mass Transfer* **37** 433-445.
[19] Rajesh B Kolambekar and Kiran Bhole 2015 Development of prototype for waste heat energy recovery from thermoelectric system at Godrej vikholi plant, *International Conference on Nascent Technologies in the Engineering* 1-6.