INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

OPEN ACCESS

Received: 25.06.2021

Accepted: 13.10.2021

Published: 30.10.2021

Citation: Sushma S, Chandrashekar TK (2021) An Experimental Investigation on Performance of Heat Transfer Using Heat Sink of Different Shape for Electronic Applications. Indian Journal of Science and Technology 14(35): 2789-2801. https://doi.org/10.17485/IJST/v14i35.1179

* **Corresponding author**.

sushma.s@cittumkur.org

Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

An Experimental Investigation on Performance of Heat Transfer Using Heat Sink of Different Shape for Electronic Applications

S Sushma[1]*, T K Chandrashekar[2]

1 Assistant professor, Department of Mechanical Engineering, Channabasaveshwara Institute of Technology, NH 206, B.H Road, Gubbi, 572216, India
2 Professor, Department of Mechanical Engineering, RNS Institute of Technology, Chennasandra, Uttarahalli main road, Bangalore, 560060, India

Abstract

Objectives: To enhance heat transfer by using different shaped heat sinks. **Method**: The results from the experimental forced convection are compared for different heat sinks like honeycomb-shaped, radial-shaped, and flared-shaped. The experiment is conducted by varying the voltage input and the heat dissipation is compared. Also, certain other parameters like surface temperature, Nusselt number, Reynolds number, and effectiveness are found. The heat sink which has greater Nusselt number and heat transfer coefficient along with lower thermal resistance are considered as a comparatively better heat sink. **Findings:** Experimental analysis shows that the Honey comb shaped heat sink for 100V of voltage input has higher heat transfer coefficient which is more by 20.01% and 22.73%, also shows higher Nusselt number by 9.7% and 8.9% along with decrease in thermal resistance by 20.1% and 22.73% with respect to radial and flared heat sinks respectively. **Novelty:** It leads to findings of different shaped heat sink, which can be used in electronic components for better heat dissipation.

Keywords: Brass material; convection (forced); Experimental setup; heat sink; performance comparison

1 Introduction

To amplify the rate of heat transfer and thermal performance the powerful tool is used in the enhancement of heat transfer. The urge to increase the heat transfer rate is found more in electronic components/devices as the working of the components/device at designed efficiency is required. This in turn leads to the invention of a greater number of different types of heat sinks and out of which the performances of few works are as stated- that the average heat transfer coefficient, heat transfer rate increase with the reduction of weight in discrete fins and perforated fins compared to the solid fins block. The Nusselt number rises with an increase in heat input for all types[1–7]. Also found that Elliptical fin with elliptical perforation has maximum efficiency[8]. Investigation on heat transfer is done using circular (Spherical) and Oval (elliptical)dimples. Enhancement in heat transfer is observed for both the dimples with Reynolds number ranging from 600 to 2000 by experimentation. Numerical analysis shows that the oval type dimpled plate pressure drop is small compared to the circular type dimpled plate. Whereas the thermal performance is high for oval type plate[9]. Numerical analysis of heat transfer is done using fins of different shapes. Simulation is done using Ansys FLUENT Staggered conic fins have better performance in comparison with staggered rectangular fins with respect to heat transfer, quality factor and pumping power, longitudinal pin fin, radial fins with inverted trapezoidal shaped with holes kinds of heat sinks were also proved as better[10,11]. The effects of different shapes like plain, rectangular and wavy fins. The thermal-hydraulic performance is analyzed by varying the velocity of air and tube inclination angles. It is found that the high heat transfer is obtained from rectangular fin whereas the highest efficiency is obtained from plain fin with the lower pressure drop[12]. Different cavity shapes like triangle, rectangular, trapezoidal, and semicircular are considered on rectangular extension. Heat transfer coefficient, efficiency, and effectiveness are numerically and analytically calculated using simulation. It is found that the fin with a rectangular-shaped cavity has more effectiveness and rate of heat transfer[13]. Experimental investigation on aluminium fin by varying shapes like circular, square and triangular extensions are done and found that the circular fin has high heat transfer rate[14]. Experimental study of heat transfer characteristics using circular, aerofoil and square fins inside a rectangular duct is done. An aerofoil geometrical fin has high heat transfer rate and less pressure drop compared to others[15]. The hydrothermal performance of flattened microchannel heat sink. The performance of three different geometric designs is obtained by varying six different parameters. The optimal design is selected with the most uniform temperature distribution and the lowest thermal resistance. It is observed that increase in pumping power increases thermal resistance and flattened cross section produces less thermal resistance compared to rectangular cross section[16]. The influence of heat sink's geometric shape filled with lauric acid on heat dissipation and melting. With the increase in size of the additional fins, it is observed that along with the height of the region, melting occurs more evenly. The heating element temperature can be reduced by increasing the transverse fins length is evaluated[17]. An experimental investigation is done on heat sink with pin-fin array under forced convection. Experimental results have shown that Nusselt number and heat transfer coefficient increases with increase in Reynolds number. As Reynolds number increases thermal resistance decreases and also found that the twisted fins have lower thermal resistance. With the increase in twisting angle, the friction factor and pressure drop reduces. It is also observed that the non-twisted fins when compared to twisted fins, the latter have the lower efficiency[18]. Experimental, CFD analysis and Numerical analysis shows that the above said all variations can be used as an alternate heat sink. The capacity of heat transfer is also studied in all different cases. This experimental study compares the different new shaped heat sinks of same brass material which in turn helps to find the heat sink of better shape. Here forced convection air cooling approach is used to remove the heat.

2 Methodology

Experimental Setup consists of mild steel Tube table which has top frame cover and panel which consists of Digital Ammeter, Voltmeter, Blower, Flow control valve, Heater control, Manometer, Selector Knob, and gate valve. The test duct is chosen with the dimension of 70mm*100mm*190mm. Air is the fluid used for convection and the type of flow chosen is turbulence. Further the entrance ledge is not considered into account.

Fig 1. Experimental setup

The heat sinks are made from brass with a heater. Along with the brass plate, there is a bottom insulation plate. The extended surfaces with a perforated design which is similar to the honeycomb structure has six thermocouples placed on it.

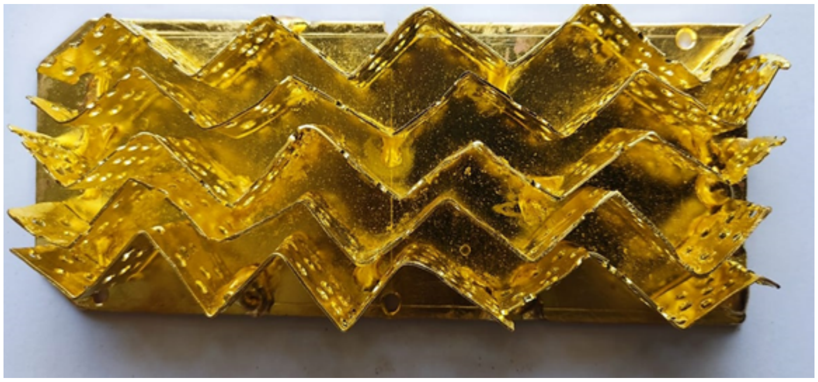

Fig 2. Honey Comb Shaped Heat sink

The location of the first two thermocouples is on the base source plate, the next two thermocouples are on the extended fins, the fifth thermocouple is at the air inlet point and the sixth thermocouple at the air exit point.

Fig 3. Radially Curved Heat sink

Fig 4. Flared Heat sink.

Fig 5. Heat sink with thermocouples

3 Experimental Procedure

Three different shaped heat sinks made up of brass material is tested in the test rig as shown in Figure A for knowing its heat dissipation capacity. Each sample plate has dimensions of 38mm width, 68mm length and 1mm thickness. For Forced condition, the blower is kept in ON condition, set manometer by adjusting the valve slowly as the mains gets switched ON, the heater control knob is rotated to set the required voltage, after reaching steady-state readings of voltage, current and all temperatures are noted. The experiment is repeated for different heat inputs.

4 Result and Discussion

The heat transfer coefficient is calculated using the Newton's law of cooling i.e.

$$h = Q * A * dT$$

Where h is heat transfer coefficient in $W/m^{2o}C$

A is the area of heat transfer surface in m^2

Q is the rate of heat transfer in W

dT is the Temperature difference between the surface and the surroundings.

The Nusselt number is calculated using

$$\mathrm{Nu} = \mathrm{C}^{*}\, \mathrm{Re}^{m*}\, \mathrm{Pr}^{n*}\, (\mathrm{Pr_f}/\mathrm{Pr_w})^{0.25}$$

Where Nu is Nusselt number

Re is Reynolds number

Pr is Prandtl number

Pr_f is Prandtl number at film temperature

Pr_w is Prandtl number at wall temperature.

The values of C and m are chosen based on Reynolds number and value of n is based on Prandtl number.

Forced Convection:

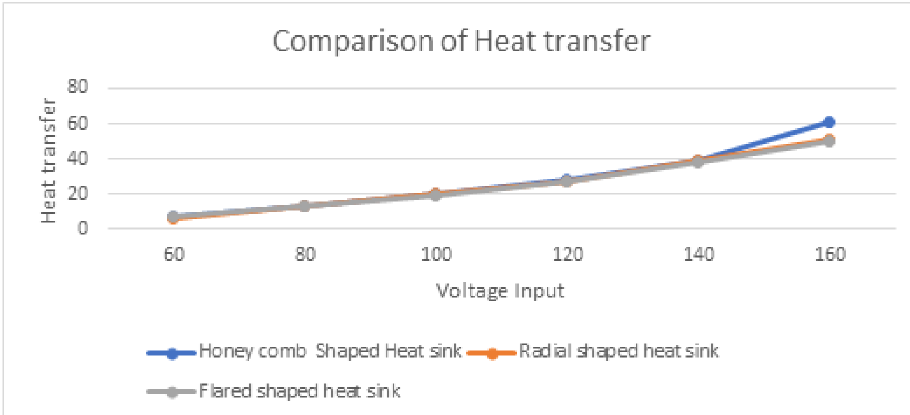

Fig 6. Comparison of forced convection heat transfer

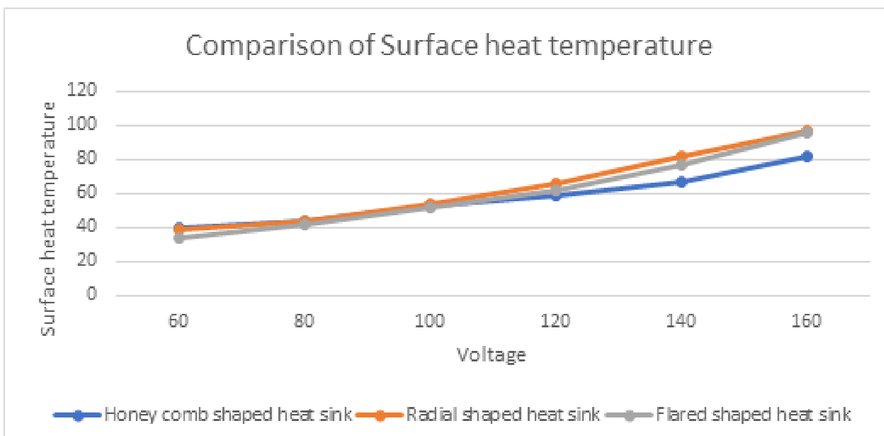

Fig 7. Comparison of forced convection surface heat temperature

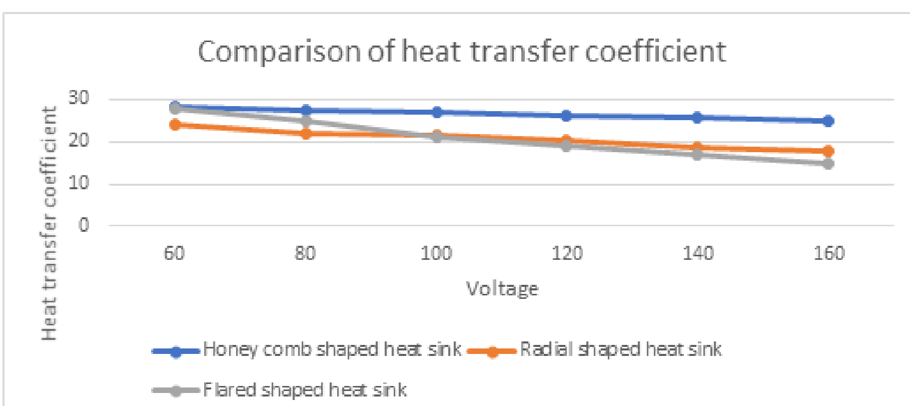

Fig 8. Comparison of forced convection heat transfer coefficient

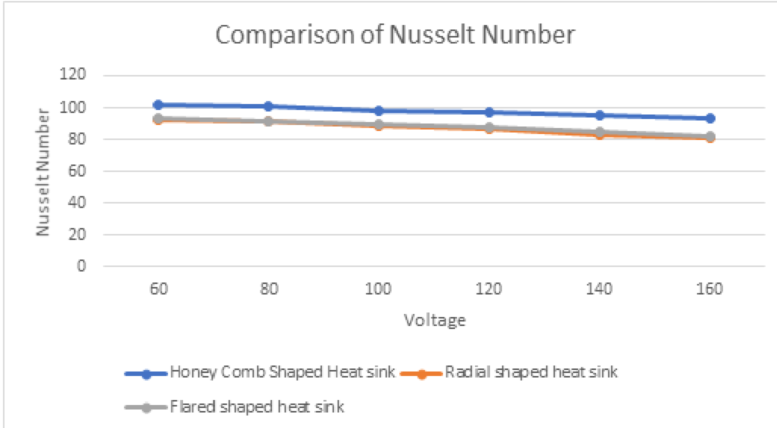

Fig 9. Comparison of forced convection Nusselt number

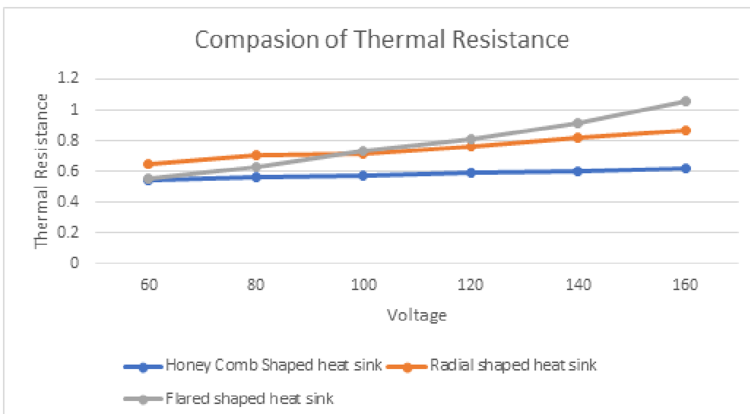

Fig 10. Comparison of forced convection Thermal resistance

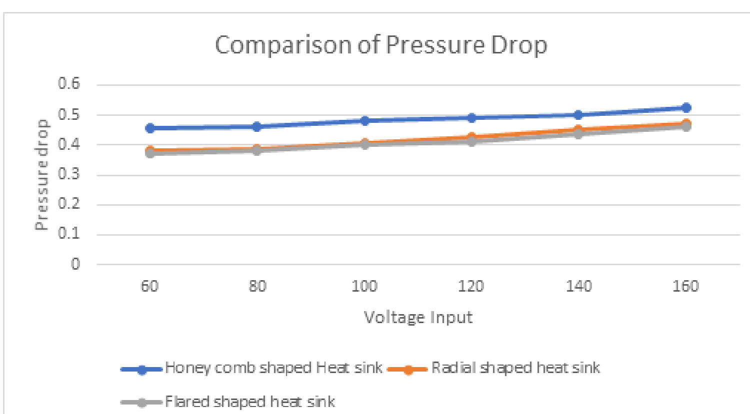

Fig 11. Comparison of forced Convection Pressure drop

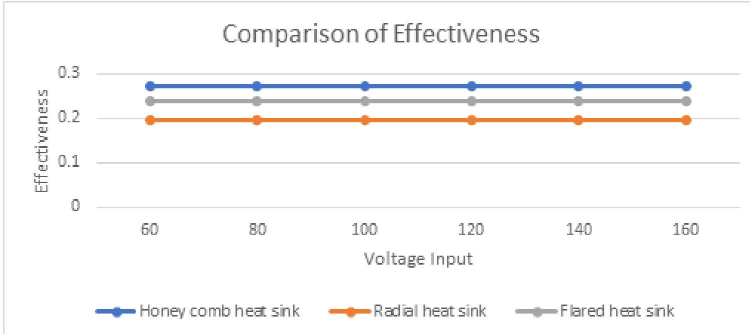

Fig 12. Comparison of forced convection Effectiveness

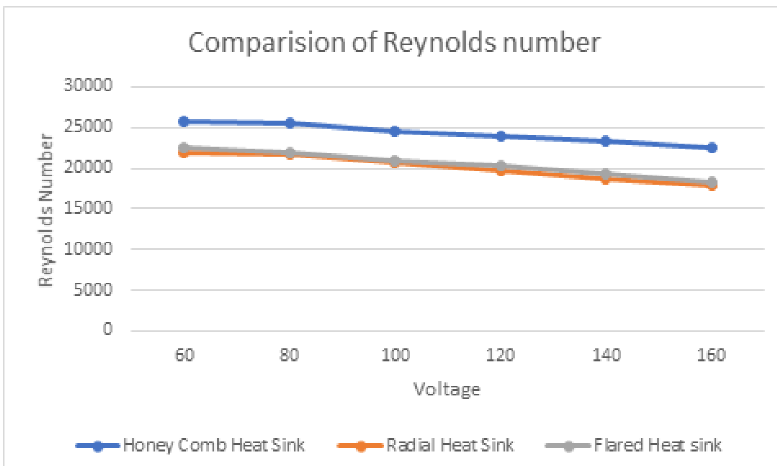

Fig 13. Comparison of forced convection Reynolds number

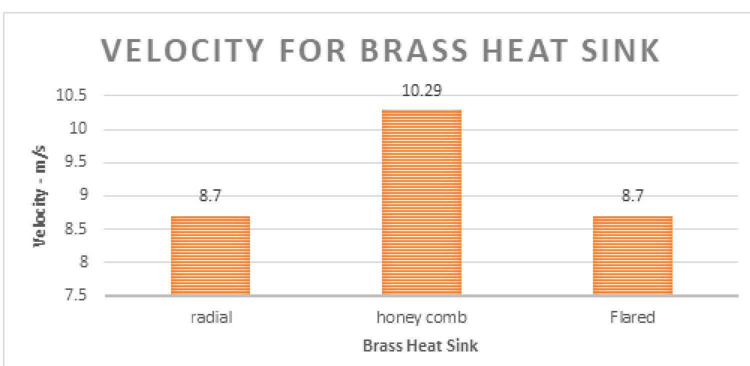

Fig 14. Comparison of velocity for Brass Heat sink

Figure 6 Shows the comparison of forced convection heat transfer vs voltage input. As we know that heat generation is proportional to the power dissipation, also power is defined as voltage times current. Thus, it is noticed that the heat transfer increases with the increase in voltage. The honeycomb-shaped heat sink has high heat transfer.

Figure 7 Shows the comparison of forced convection average surface temperature vs voltage input. It is noticed that the average surface temperature increases with an rise in voltage because the increase in voltage helps to increase the flow of current which leads to the rise in surface temperature. The radial and flared-shaped heat sinks have a high average surface temperature.

Figure 8 Shows the variation of heat transfer coefficient vs voltage input in forced convection. It is noticed that the heat transfer coefficient decreases with the rise in voltage due to the increase in thermal conductivity. The honeycomb-shaped heat sink has a high heat transfer coefficient compared to radial and flared-shaped heat sink.

Figure 9 Shows the variation of Nusselt Number vs voltage input in forced convection. It is observed that the Nusselt number reduces with an rise in voltage because the Nusselt number is inversely proportional to the thermal conductivity of air. The honeycomb-shaped heat sink has a high Nusselt number compared to radial and flared-shaped heat sink.

Figure 10 gives the comparison of thermal resistance vs voltage input in forced convection. It is found that the thermal resistance magnifies with the increase in voltage due to more vibrations of atoms, which enhances the difficulty of the flow of electrons. The honeycomb-shaped heat sink has a lesser thermal resistance and increases with a slower pace compared to radial and flared-shaped heat sink.

Figure 11 Shows the comparison of pressure drop vs voltage input in forced convection. It is found that the pressure drop elevates with the rise in voltage, because of the increase in gas viscosity. Pressure drop is found more for the honeycomb-shaped heat sink compared to radial and flared-shaped heat sink.

Figure 12 Shows the comparison of Effectiveness vs voltage input in forced convection. It is found that the effectiveness almost remains the same with an increase in voltage. Effectiveness is found more with a honeycomb-shaped heat sink followed by flared shaped heat sink compared with a radial-shaped heat sink.

Figure 13 Shows the comparison of Reynolds number vs voltage input in forced convection. It is found that the Reynolds number lowers with an rise in voltage. Reynolds number is found more with a honeycomb-shaped heat sink compared to flared shaped heat sink and radial-shaped heat sink. Figure 14 Shows the velocity of different heat sinks made by brass material, the honeycomb-shaped heat sink has high velocity compared with radial and flared-shaped heat sink.

Table 1. L_9 orthogonal array for optimization.

Voltage(A)	Shape of Heat sink (B)	Heat transfer coefficient	Nusselt number	Thermal resistance	SNRA1	SNRA2	SNRA3
80	Honey Comb	27.33	100.56	0.5664	28.7328	40.0485	4.93754
80	Radial	22.02	91.32	0.7031	26.8563	39.2113	3.05966
80	Flared	24.77	91.77	0.6250	27.8785	39.2540	4.08240
100	Honey Comb	27.19	98.27	0.5693	28.6882	39.8484	4.89318
100	Radial	21.73	88.74	0.7125	26.7412	38.9624	2.94430
100	Flared	21.01	89.53	0.7368	26.4485	39.0394	2.65301
120	Honey Comb	21.12	97.01	0.5903	26.4939	39.7363	4.57854
120	Radial	20.35	86.34	0.7609	26.1713	38.7242	2.37345
120	Flared	19.20	87.67	0.8062	25.6660	38.8570	1.87114

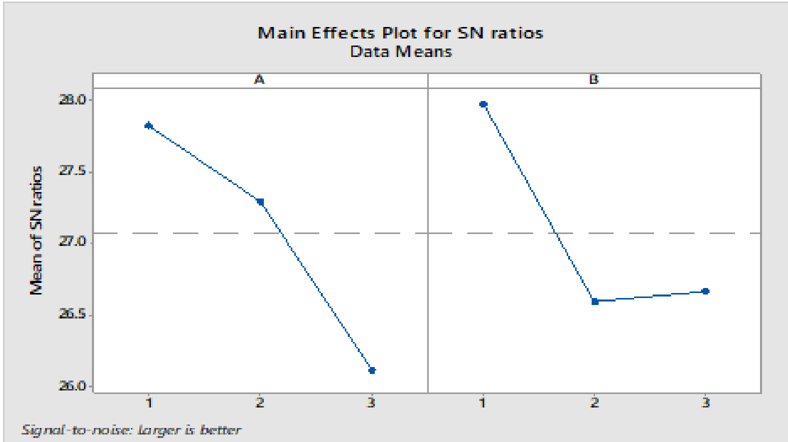

Fig 15. SN ratio of heat transfer coefficient

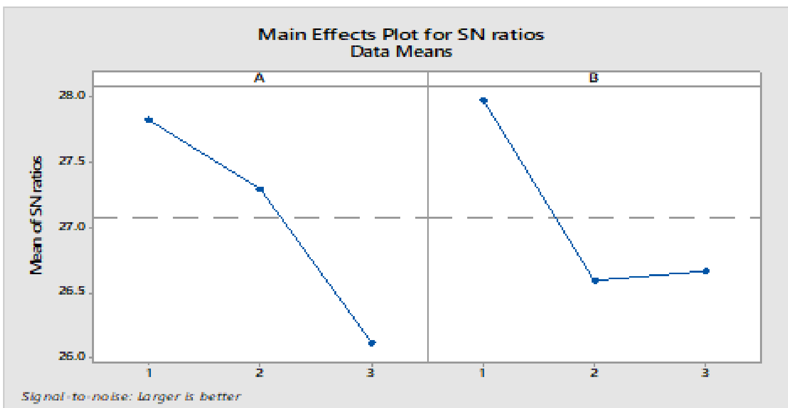

Fig 16. SN ratio of Nusselt Number.

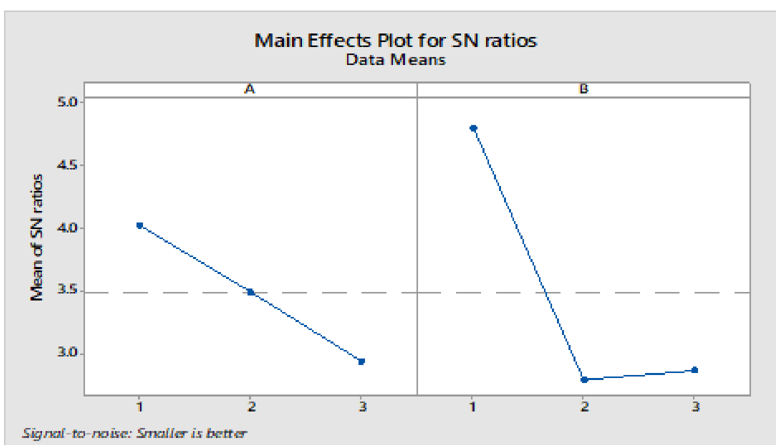

Fig 17. SN ratio of Thermal resistance

Table1.indicates L9 orthogonal array which is designed for the optimization of different parameters like coefficient of heat transfer, Nusselt number and thermal resistance.Figures 15 and 16. Shows the Signal Noise ratio for heat transfer coefficient

and Nusselt number respectively. It is clear from the SN ratio that the honey comb shaped heat sink and lower voltage input is more optimized as larger heat transfer coefficient and higher Nusselt number are comparatively better. Figure 17. Shows the Signal Noise ratio for thermal resistance. It is noted from the SN ratio that the radial shaped heat sink and higher voltage input is more optimized as lower thermal resistance is required.

Table 2. Taguchi Analysis.

Heat Transfer Coefficient			Nusselt Number			Thermal Resistance		
Level	A	B	Level	A	B	Level	A	B
1	27.82	27.97	1	39.50	39.88	1	4.027	4.803
2	27.29	26.59	2	39.28	38.97	2	3.497	2.792
3	26.11	26.66	3	39.11	39.07	3	2.941	2.869
Delta	1.71	1.38	Delta	0.40	0.91	Delta	1.085	2.011
Rank	1	2	Rank	2	1	Rank	2	1

Table 2. indicates the analysis for coefficient of heat transfer, Nusselt number and thermal resistance for optimization using Taguchi method. From this analysis it is clear that voltage input parameter is more important for heat transfer coefficient. Where as in case of Nusselt number and Thermal resistance shape of heat sink is more important parameter compared to voltage Input.

Table 3. Comparison related to past studies.

Sl.No	Authors	Title of the work	Study/ Description	Observations
1.	Alhassan Salami Tijania, Nursyameera Binti Jaffria	Thermal analysis of perforated pin-fins heat sink under forced convection condition	This research experimentation aims at studying the effect of perforated pin fins on heat sinks thermal performance under forced convection. Results of perforated pin fins and flat plate heat sink is compared to solid pin fins and solid flat plate heat sink.	In this study, the experimental analysis shows that with the increase in Reynolds number, increases the Nusselt number and heat transfer coefficient. Figure 13 and 14 from the experimental analysis exhibits the same trend.
2.	Nabeel Abdulhadi Ghyadh, Sahib Shihab Ahmed, Maher A.R. Sadiq Al-Baghdadi	Enhancement of Forced Convection Heat Transfer from Cylindrical Perforated Fins Heat Sink-CFD Study	Three-dimensional, non-isothermal CFD model is studied to notice the thermal performance of heat sink having perforated fins. The arrangement of fins is also studied. Results obtained from CFD are compared with available experimental results.	In this study, CFD analysis shows that the Nusselt number and thermal transmittance increases with increase in Reynolds number for all the samples. Figure 1 and 14 from the experimental analysis exhibits the same trend.
3.	Emad M.S. El-Said , Gamal B. Abdelaziz , Swellam W. Sharshir , Ammar H. Elsheikh, Ashraf Mimi Elsaid	Experimental investigation of the twist angle effects on thermo-hydraulic performance of a square and hexagonal pin fin array in forced convection	Experimentations were conducted on two pin fin section on a square and hexagonal shaped with four twist angles of 0o, 30o, 60o, and 90o with air as working medium at constant heat flux and Reynolds number (Re) ranging from 3182 to 9971. The thermo-hydraulic performance of the heat sink under forced convection at various operating conditions and design factors are found.	From this experimental investigation of pin fin array under forced convection, it is observed that the increase in Reynolds number increases the Nusselt number and decreases the thermal resistance. Figure 5 and 14 from the experimental analysis exhibits the same trend.
4.	Ayush Gupta, Vishwjeet Choudhary, Varun Singh, Rahul Chamola	Heat Transfer Characteristics through Plate-Pin Heat Sink with Dimples	Plate fins having dimples are placed in between the pin fins. Experimental investigation is carried out under forced convection by varying pin-pitch ratio and plate-pitch ratio. The experiment is carried out at constant heat flux and by varying the Reynolds number from 6500 to 15000.	The trend of increase in Nusselt number and decrease in friction factor are observed with the increase in Reynolds number for all the samples. Figure 14 from the experimental analysis exhibits the same trend.

Continued on next page

Table 3 continued

5.	Osot Khonsue	Enhancement of the forced convective heat transfer on mini pin fin heat sinks with micro spiral fins	Experimental investigation on aluminium pin fins of rectangular, cylindrical and spiral shaped using air as working medium under constant heat flux and by varying Reynolds number from 322 to 1982. This experimental study is done to find the characteristics of heat transfer and pressure drop-in mini heat sinks.	The average heat transfer coefficient and Nusselt number increases with increase in Reynolds number for all the variations of rectangular, cylindrical and Spiral pin fins. Figure 13 and 14 from the experimental analysis exhibits the same trend.
6.	Ambarish Maji, Dipankar Bhanja, Promod Kumar Patowari, and BalaramKundu	Thermal Analysis for Heat Transfer Enhancement in Perforated Pin Fins of Various Shapes with Staggered Arrays	This work finds the heat dissipation through staggered different shaped pin fins with varying perforated geometries. To examine the effects on the fin geometry and perforated dimension along the shape of fin, 3 dimensional CFD simulation has been carried out. Also, enhancement of heat transfer rate against pressure loss is studied.	Fin geometry of perforated fin influences the pressure drop. It is also noted that Nusselt number, Heat transfer and pressure drop grows with the rise in Reynolds number. Figure 6,13 and 14 from the experimental analysis exhibits the same trend.

Table 3. compares the previous related works. Heat sinks with different shapes and by varying conditions are studied through different methods like experimentation, CFD analysis to find the enhancement of heat transfer. From the studies it is observed that the coefficient of heat transfer and Nusselt number grows with the rise in Reynolds number for most of all the samples.

From Figure. 8 and 3, it is clear that the Reynolds number and the coefficient of heat transfer decreases with the increase in voltage input. From this it is clear that the heat transfer coefficient and Nusselt number grows with rise in Reynolds number. Figures 18 and 19 shows that the heat transfer coefficient and Nusselt number grows with rise in Reynolds number respectively for Honey comb shaped heat sink. Also, the same trend holds good for both radial and flared heat sink.

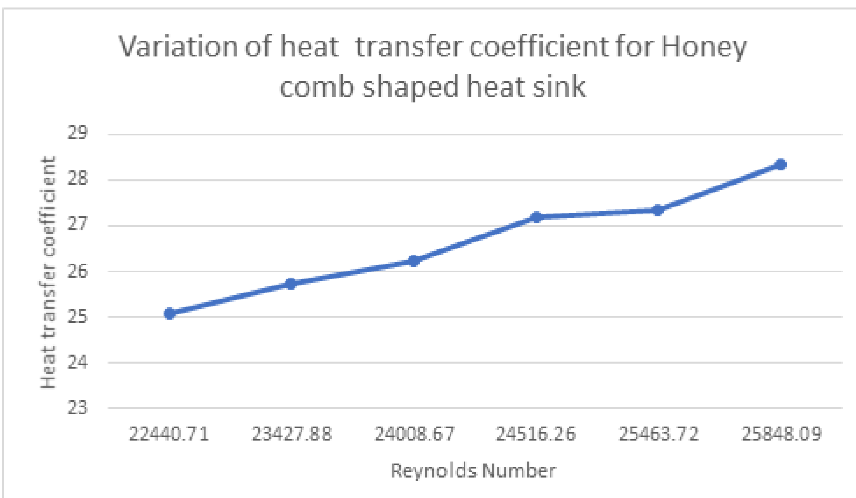

Fig 18. Variation of heat transfer coefficient with respect to Reynolds Number for honey combshaped heat sink.

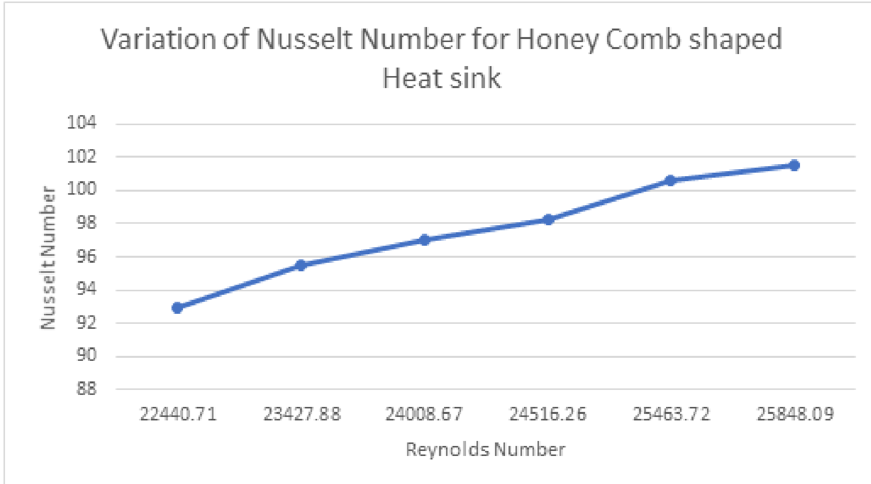

Fig 19. Variation of Nusselt number with respect to Reynolds Number for honey comb shaped heatsink

The results obtained from the experiment are inline when compared with the literature survey results obtained by analytical and numerical methods. The above results are obtained from the actual experimentation. This experiment has led the way to find different parameters like coefficient of heat transfer, Nusselt number, Reynolds number, pressure drop and effectiveness of fins. Further the results of this work can be compared with the results obtained from either analytical or numerical method.

5 Conclusions

Experimentation and Taguchi analysis shows that the Honey comb shaped heat sink is better to enhance heat transfer in electronic devices compared to radial and flared heat sink as the heat transfer coefficient of honey comb shaped heat sink for 100V of voltage input is more by 20.01% and 22.73%, also shows higher Nusselt number by 9.7% and 8.9% along with decrease in thermal resistance by 20.1% and 22.73% with respect to radial and flared heat sinks respectively. Designing of new heat sink to reduce the pressure drop and thermal resistance can be considered as a suggestion for future studies. Studies can also be extended by varying the fin design parameters like number of fins, fin spacing and thickness of fins. This experimental study manifest that the heat dissipation is more in honey comb shaped heat sink when compared with radial and flared heat sink.

References

1) Khomane SG, Pise AT, Udare AR. Enhancement of Heat Transfer by Natural Convection from Discrete Fins. *International Engineering Research Journal* . 2015;p. 73–77. Available from: http://www.ierjournal.org/sveri/14.Enhancement%20of%20Heat%20Transfer%20by%20Natural%20Convection%20from%20Discrete%20Fins.pdf.
2) Zoman AV, Palande DD. Heat Transfer Enhancement Using Fins with Perforation: A Review. *International Journal Of Engineering Sciences & Research Technology*. 2016;5(7). doi:10.5281/zenodo.57869.
3) Hameed VM, Khaleel MA. A study on the geometry and shape effects on different aluminum fin types of a vertical cylindrical heat sink. *Heat and Mass Transfer*. 2020;56:1317–1328. Available from: https://dx.doi.org/10.1007/s00231-019-02750-7.
4) Zaidshah S, Yadav V. Heat transfer from different types of fins with notches with varying materials to enhance rate of heat transfer a Review. *International Journal of Applied Engineering Research*. 2019;14(9). Available from: http://www.ripublication.com/ijaerspl2019/ijaerv14n9spl_30.pdf.
5) Shah IS. Effect of Geometry and Arrangement of Pin Fin in Heat Exchanger: A Review. *Journal of Emerging Technologies and Innovative Research*. 2016;3. Available from: http://www.jetir.org/papers/JETIR1602008.pdf.
6) Hatem M, Abdellatif H, Hussein W. Enhancement of Perforated Pin-Fins Heat Sink under Forced Convection. *International Research Journal of Engineering and Technology (IRJET)*. 2020;7(10). Available from: https://www.irjet.net/archives/V7/i10/IRJET-V7I10245.pdf.
7) Gayadh SNA, Ahamed S, Mehar A, Al-Baghdadi S. Enhancement of Forced Convection Heat Transfer from Cylinder Perforated Fins Heat Sinks-CFD Study. *Journal of Mechanical Engineering Research and Developments*. 2021;44:407–419.
8) Maji A, Bhanja D, Patowari PK, Kundu B. Thermal Analysis for Heat Transfer Enhancement in Perforated Pin Fins of Various Shapes with Staggered Arrays. *Heat Transfer Engineering*. 2019;40(3-4):295–319. Available from: https://dx.doi.org/10.1080/01457632.2018.1429047.
9) Hemant C, Pisal A, Ranaware. Heat Transfer Enhancement by Using Dimpled Surface. *IOSR Journal of Mechanical and Civil Engineering*;p. 7–15. Available from: http://www.iosrjournals.org/iosr-jmce/papers/sicete(mech)-volume6/54.pdf.
10) Nimesh M, Limbasiya DAB, Harichandan. Enhancement of Heat Transfer in Heatsinks Using Aerodynamically Shaped Fins. *2nd International Conference for Convergence in Technology (I2CT)*. 2017;p. 786–789.
11) Jasim HH. Heat transfer enhancement from heat sources using optimal design of combined fins heat-sinks. *Propulsion and Power Research*. 2020;9(4):372–382. Available from: https://dx.doi.org/10.1016/j.jppr.2020.11.002.

12) Moorthy P, Oumer AN, Ishak M. Experimental Investigation on Effect of Fin Shape on the Thermal-Hydraulic Performance of Compact Fin-and-Tube Heat Exchangers. *IOP Conference Series: Materials Science and Engineering*. 2018;318:012070. Available from: https://dx.doi.org/10.1088/1757-899x/318/1/012070.
13) Jha NK, Kailash BA. Heat Transfer Enhancement and Thermal Performance of Extended Surfaces with Cavity. *International Journal of Innovative Research in Science, Engineering and Technology*. 2015;4(10):9792–9797. doi:10.15680/IJIRSET.2015.0410043.
14) Zaharaddeen A, Bello P, Rao, Nabilisyakumu, Ahmad UG. Experimental Analysis on Pin Fin Heat Exchanger Using Different Shapes of the Same Material. *International Journal of Engineering Science and Computing*. 2016;6(4). doi:10.4010/2016.890.
15) Pankaj N, Shrirao R, Sambhe. Enhancement of Heat Transfer Characteristics using Aerofoil Fin over Square and Circular Fins. *International Journal of Recent Technology and Engineering (IJRTE)*. 2019;8(3). Available from: https://www.ijrte.org/wp-content/uploads/papers/v8i3/C4027098319.pdf.
16) Ayatollahi SM, Ahmadpour A, Hajmohammadi MR. Performance evaluation and optimization of flattened microchannel heat sinks for the electronic cooling application. *Journal of Thermal Analysis and Calorimetry*. 2021. Available from: https://dx.doi.org/10.1007/s10973-021-10589-6.
17) Bondareva NS, Ghalambaz M, Sheremet MA. Influence of the Fin Shape on Heat Transport in Phase Change Material Heat Sink with Constant Heat Loads. *Energies*. 2021;14(5):1389. Available from: https://dx.doi.org/10.3390/en14051389.
18) El-Said EMS, Abdelaziz GB, Sharshir SW, Elsheikh AH, Elsaid AM. Experimental investigation of the twist angle effects on thermo-hydraulic performance of a square and hexagonal pin fin array in forced convection. *International Communications in Heat and Mass Transfer* . 2021;126:105374. Available from: https://doi.org/10.1016/j.icheatmasstransfer.2021.105374.