Numerical Simulation of Hybrid Passive Heat Sink for On-Board EV Charger

Pranali Gole, Mahendra Sable and Vishal Bhalla
Department of Mechanical Engineering
College of Engineering, Pune, India
Golepp20.mech@coep.ac.in, mjs.mech@coep.ac.in, vbhalla.mech@coep.ac.in

Abstract

The Battery chargers are an important component in electric and plug-in hybrid vehicles and various other clean energy systems. The thermal management in the battery charger is a crucial aspect that influences its overall performance and cyclic stability. Passive cooling technology using heat sinks is preferred in developing battery chargers due to its reliability, quietness, and efficiency. In the present work, new hybrid passive heat sinks with various fin geometries namely inclined interrupted fins, pin fins, and straight interrupted fins, have been developed by adding a phase change material layer to passively cooled bare fin heat sinks. The developed heat sinks have the same geometric footprint as that of the battery charger; IC650 was built by the industrial partner of the project Delta-Q Technologies. Simulations were carried out to analyze the effects of PCM quantities for thermal loads on the heating-cooling performance of the HPHS using Ansys fluent 19.1 commercially available software to validate the experimental results from the literature study. Inclined interrupted fin design found more effective in terms of thermal performance among all considered configurations.

Keyword

PCM, Hybrid passive Heat sink, Thermal management, Passive cooling

1. Introduction

The electric vehicle and plug-in hybrid vehicle markets are developing rapidly to reduce dependence on fossil fuels, with a projected reduction of 200 million tons of oil equivalent by 2030. (Alawadhi and amon 2000) Demand for EVs is expected to increase by 20% in the coming decades. (Ali et al. 2018) This requires technological advances in the design of electric drive units and improved charging infrastructure. In recent years, the miniaturization of electronic components, as well as the improvement of their performance, have led to the emergence of high-performance devices with high packing density.(Benyamin et al. 2021) Therefore thermal management of electric vehicles is an important issue which is needed to be addressed as not the only battery but other components E-motors, controllers, and onboard Ev chargers generate numerous amounts of heat.(Bunsen et al. 2019) hence there is a need to develop an effective cooling system for thermal management of onboard Ev chargers.

Notable research work has been carried out using different passive and active cooling systems i.e. air cooling, liquid cooling, heat pipe cooling, refrigeration, thermoelectric, and the use of thermal conductivity enhancers in finned cooling is done. However, PCM cooling remains the foremost selection based on its high-energy storage density. (Farzanehnia et al. 2019) The key selection for a proper PCM requires both high latent heat and thermal conductivity in order to store and reject with facility the heat. Phase change materials-based heat sinks are emerging as one the effective techniques for the removal of heat from electronic devices. Current research focuses on improving the thermal performance of heat sink models using PCM as a thermal conductivity improver. The effect of various parameters influencing the performance of TCE-PCM-based heat sinks needs to be studied in systematic order.

1.1 Objectives

In literature different fin configurations were investigated where it is found that most of the work has been done by use of PCM on microprocessor chips, fin submerged in PCM is used as Thermal conductivity Enhancers to improve the heat transfer characteristics of PCM enclosed in containers and use of PCM-Air hybrid heat sink design which combines the effect of fin interaction with the PCM & ambient. This design facilitates continuous heat dissipation from the heat sink to the ambient via natural/forced convection. From the research study, it’s found that the following gaps in the literature are required to be addressed in order to develop a heat sink for the battery charger. Only a few studies have been discussed about the performance of heat sinks during intermittent operation. Lack of an investigation on the performance of heat sink on small-scale real industrial applications has been done. Very few researchers have studied the influence of varying the PCM quantity on the performance enhancements in heat sinks during the complete heating-cooling operation. So objectives of the research are

1. To develop a heat sink, by adding a PCM layer to the fined heat sinks of a battery charger to extend its operation at high load conditions.
2. Numerical analysis of heat sink designs with various fin geometries, including (a) inclined interrupted fins; (b) pin fins; and (c) straight interrupted fins.
3. To study the effect of varying PCM quantity on the performance enhancements in the heat sink.

2. Literature Review

In the literature study, three different fin configurations were investigated in which the first configuration was found to be employing PCM materials on microprocessor chips in its cavities but due to its low thermal conductivity and heat dissipation rate they are restricted in use only with adhesives (Alawadhi et al., 2000, Ali et al. 2018). In the second configuration use of fins made as a thermal conductivity enhancer so as to improve the heat dissipation in PCM-enclosed containers. Ali et al (2018) made a comparison between cylindrical and square fin configurations for equal fin volume and found better thermal management using cylindrical pin fin configuration. Ali and Arshad (2018) studied the impact of fin thickness on the performance of hybrid heat sink design and found its optimum at 3 mm in thickness. Fok et al. (2010) investigated the effect of different fin orientations and a number of fins and found no effect of orientation but significant improvement in the performance due to the addition of fins. Baby and Balaji (2018) studied pin fin and plate-fin geometries and defined a modified Stefan number as a basis for performance comparison in which lowering Stefan numbers better fin performance was observed. An open-air active cooling design with pipe fins filled with PCM to improve heat transfer rate as compared to a system with simple PCM containers. From the study, it is found that there is no fin interaction with ambient it giving a lower heat dissipation rate which leads to slow restoration of the system (Farzanehnia et al. 2019, Fok et al. 2010, Hasan et al. 2018, Kandasamy et al. 2007). Proposed the design of a heat sink submerged in PCM containers in which fins are used as baffles so as to improve the cooling rate significantly. In the third configuration investigation of a hybrid model of the heat sink is done which employed the interaction of fin with PCM and ambient by natural or forced convection cooling method. Also, Ghanbarpour et al (2020) investigated the effect of analysis of hybrid heat sinks using heat pipes and observed a significant reduction in the maximum heat

Sink temperature was mainly influenced by the heat transfer dissipation capacity of the fins exposed to the ambient air. Based on the literature review following gaps need to be addressed in order to develop an effective cooling system for onboard EV charger application. A lack of investigations is done for real industrial applications. Only a few studies have been done for small-scale applications with varying fin geometries for a given PCM quantity (Murshed et al. 2018). In the present study, numerical analysis is carried out using the following research gaps. As per the works of literature combined numerical hybrid heat sink design for real industrial application by employing a combined air-PCM heat sink model was not proposed previously. So the objective of the current research is to analyze the Hybrid heat sink model numerically using Ansys fluent and validate the results with literature work for further improvements.

3. Methods

An experimental study was carried out. It consists of a finned heat sink filled with Phase change Material and provided with insulation (having a thermal conductivity of 0.037 w/mk. The 100 mm x 150 mm Polyamide heater which generates maximum of 120 W of heat was attached to the base of heat sink and was connected to power source which is programmable DC output. Temperature was measured using thermocouples attached at different locations: six attached at the base of sink, six were at the tip of fin at the same location as that of the base and six were distributed within pcm to measure temperature distribution and liquid fraction over a period of time. DAS system was used to record average temperature values of thermocouples located at base and within PCM. Experimentation carried out till steady state achieved i.e. change in the average base temperature dropped to 0.5^{0}c.
Enhancement factor (ε) is used as the ratio of time taken by the HPHS to the time taken by the BFHS to reach the PCM melting temperature during heating as shown by equation (1).

$$\varepsilon = \mathrm{tHPHStFHS} \tag{1}$$

The overall thermal performance of different heat sink samples is calculated based on the thermal conductance (G) given in Equation (2).

$$G=PTmax\text{-}Ta \qquad (2)$$

4. Data Collection

Three different heat sink models were considered in the analysis having the same footprints as that of the onboard battery chargers made by delta-Q technologies. The models were analyzed by considering different parameters viz. thermal load, PCM Materials, and PCM quantity. The schematic showing the heat sink samples and dimensions with different fin geometries is shown in Figure 1. The size of the base for all the heat sinks is 160 mm (L) × 180 mm (W) and the height (H) is 60 mm. The inclined interrupted fin design is considered based on benchmarked product configuration whereas straight interrupted and pin fin configuration is considered for analysis due to its rare use found in the literature (Kandasamy et al. 2007, Khattak et al. 2019, Ling et al. 2017). The heat transfer surface area of all the heat sinks is approximately the same (~0.25-0.26 m^2) with a maximum relative difference of ±1.25%.

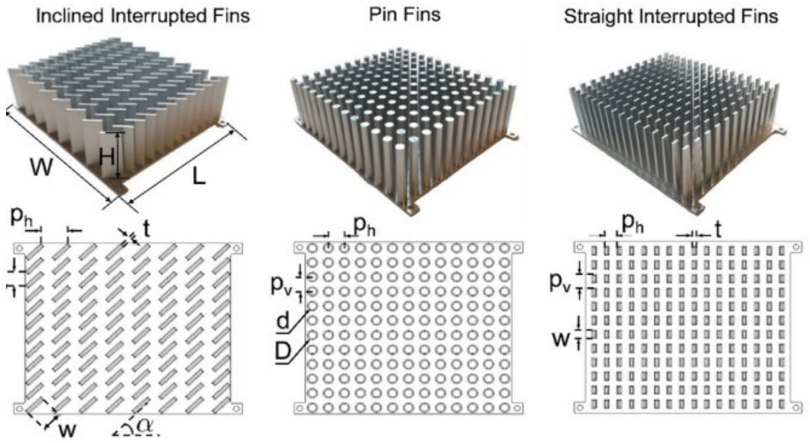

Figure 1. Heat sink samples and their dimensions

A commercial-grade paraffin wax was used as the PCM in HPHS designs (Table 1) the selection is based on the desired isothermal phase change temperature range of the PCM suitable for the device operation. The volume fraction of the PCM is calculated as the ratio of the liquid PCM volume used to the total heat sink volume (160 mm × 200 mm × 60 mm) using Equation (1).

$$\emptyset=VpcmVtotal$$

(3)

Table 1. Properties of Phase change material

Material	Paraffin Wax
Thermal conductivity (W/m.K)	0.3
Specific heat (kJ/kg.K)	2.8
Density (kg/m^3)	880
Temp. (°C)T_s	56
Temp. (°C)T_L	58
Melting heat solidification (kJ/kg)	146.1
Melting heat melting (kJ/kg)	145.3
Viscosity for liquid (kg/m.s)	0.0063

5. Results and Discussion

5.1 Numerical Results

5.2 Graphical Results

Simulations were carried out for the finned heat the sink design with PCM and without PCM conditions. To investigate the thermal performance of the heat sink was analyzed without PCM conditions for three configurations at different thermal loads. Figure 2. 3, and 4 Illustrates the difference in temperature variation with time at various power levels 80W, 100W, and 120 W. The temperature used is the average base temperature of the heat sink.

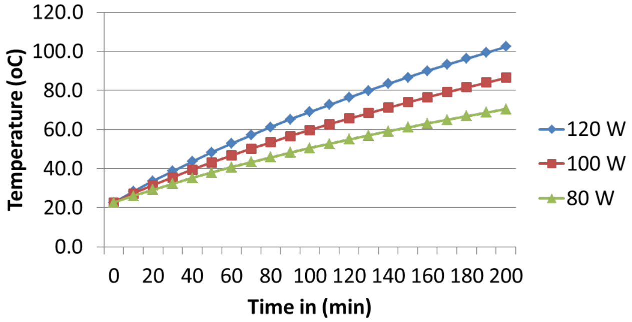

Figure 2. Variation in the base temperature profile for straight Interrupted Fins (HS-1)

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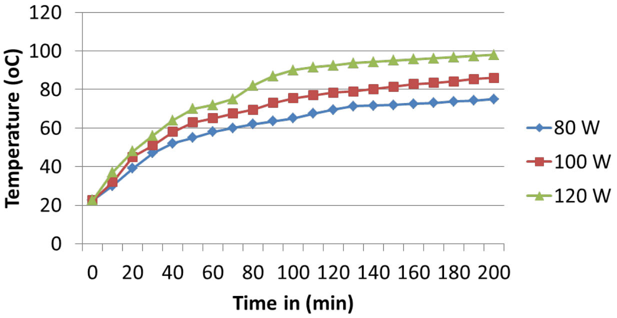


Figure 3. Variation in the base temperature profile for Circular Fins (HS-2)

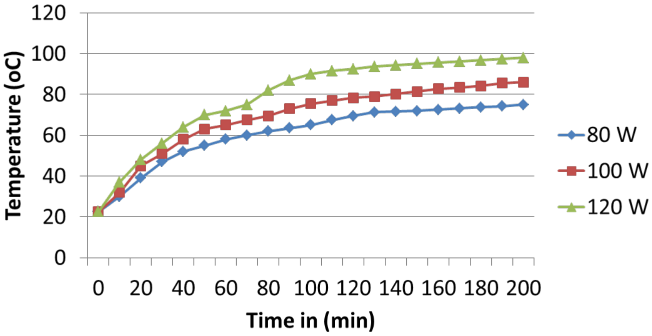


Figure 4. Variation in the base temperature profile for Inclined Interrupted Fins (HS3)

Table 2. Thermal conductance at different fin configurations

Type of configuration	Thermal conductance (G) at given thermal power levels		
	80 W	100 W	120 W
Pin fin	0.72	0.65	0.66
Straight interrupted fin	0.62	0.65	0.69
Inclined interrupted fin	0.68	0.63	0.65

HS-3 delivered the best performance followed by HS-2 and HS-1 at thermal load of 80 W. At higher thermal loads of 100 W and 120 W the shape of temperature profiles for HS-1, HS-2, and HS-3 is similar to that at 80 W, except that the slope of the temperature profile is higher. The time delays for HS-3 and HS-2 to reach 85^0C are higher than HS-1 by 45% and 7% respectively (Table 2).

Similarly, at a 120 W load the time delays for HS-3 and HS-2 to reach 85^0C are higher than for HS-1 by 8.5 % and 6.5 %. Overall, the thermal performance of HS-3 at all the thermal loads was found to be higher compared to HS-2 and HS-1.

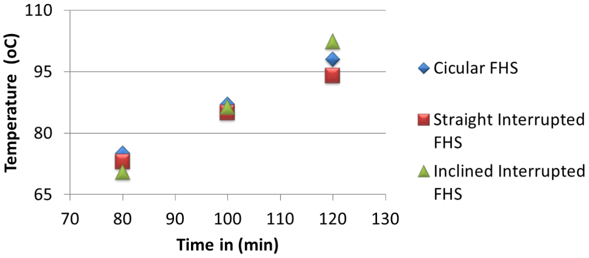
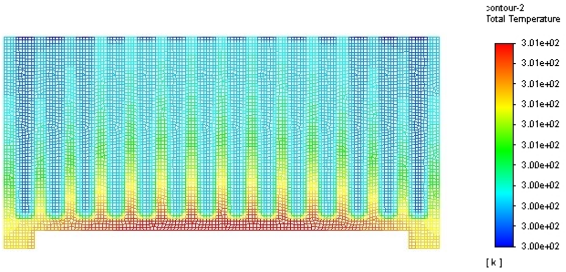


Figure 5. The steady-state temperature achieved by HS1, HS2 & HS3 for Thermal loads of 80 W, 100W & 120W

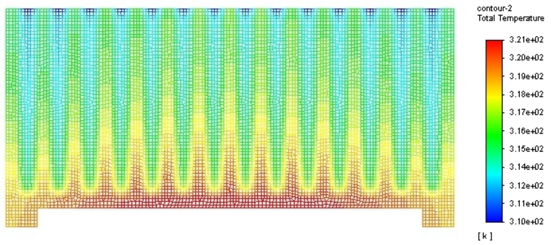
Figure 5. Illustrates the steady-state temperature achieved by all the heat sink configurations without PCM conditions for Thermal power levels of 80 W, 100W & 120W. The steady-state temperature of HS-1 for a thermal power level of 120 W was higher than 80 W by ~20 ^{0}C. The steady-state temperatures of HS-3 were lower than HS-2 and HS-1 at all thermal power levels.

5.3 Proposed Improvements

From the numerical analysis it is found thermal conductivity enhancer thermal conductivity enhancers in heat sink configuration give a poor thermal performance, so Phase change material is used as thermal conductivity enhancers in finned heat sink. The Contours of Average temperature and liquid fraction shown in Figures 6-8.



20 minutes



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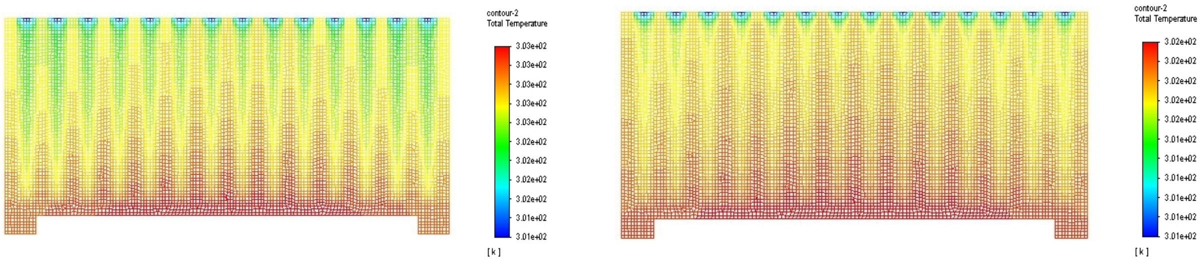
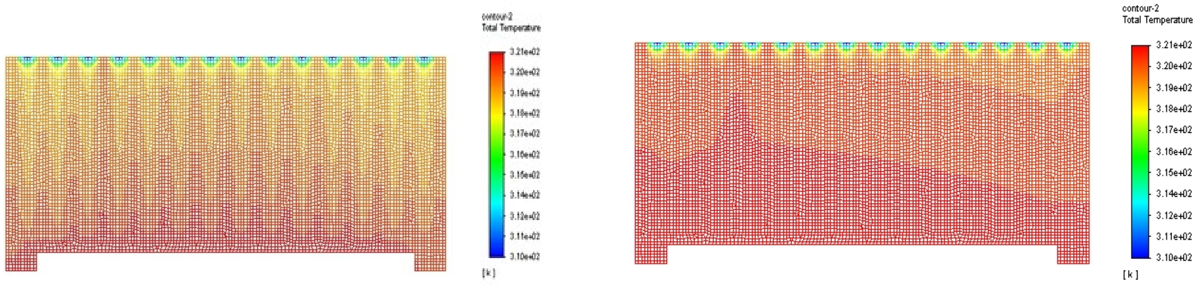


60 minutes

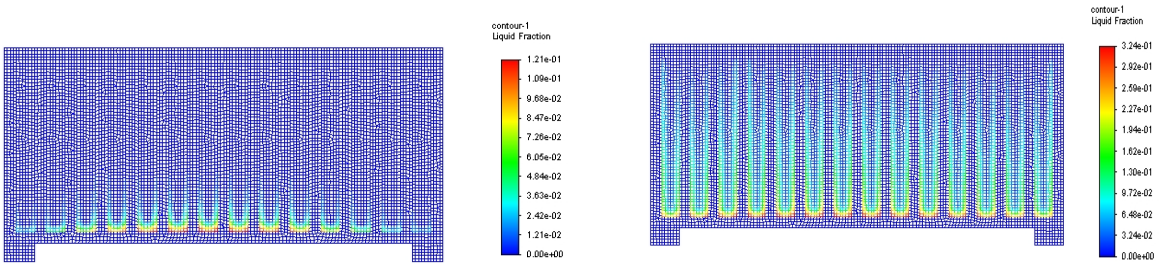
80 minutes



100 minutes

120 minutes

Figure 6. Contours of the average temperature



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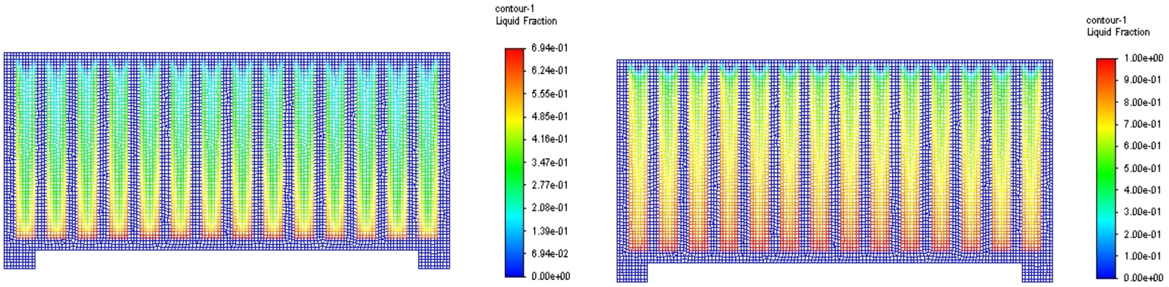

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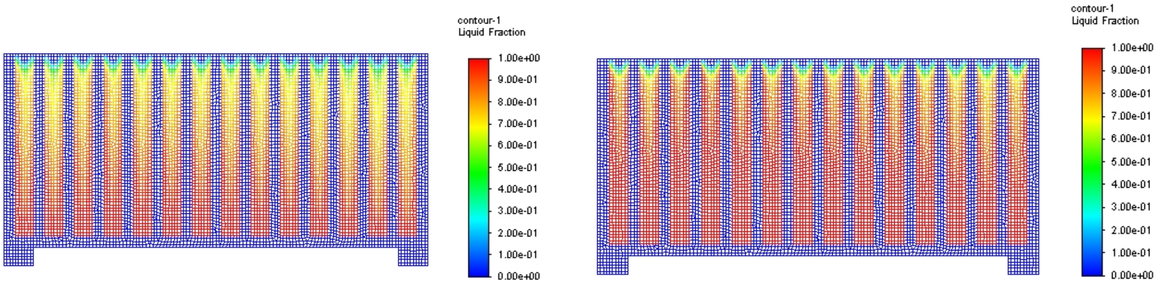

100 minutes 120 minutes

Figure 7. Contours of the liquid fraction

5.4 Validation

Validation of the numerical model is shown in Figures 7 and 8. The simulation is carried out without PCM conditions on the Heat sink model available in the literature. The straight interrupted finned heat sink model is analyzed for the same boundary conditions which were used for experimentation. From the graph it is found that results are matching closely with an accuracy of 10-15%.

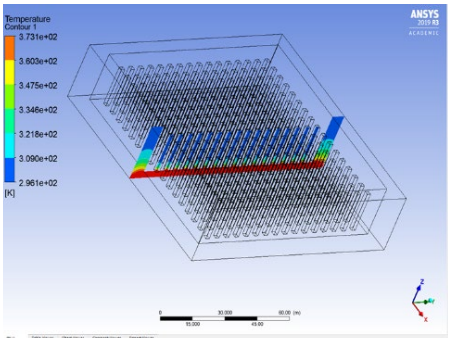

Figure 8. Simulation for with fins condition

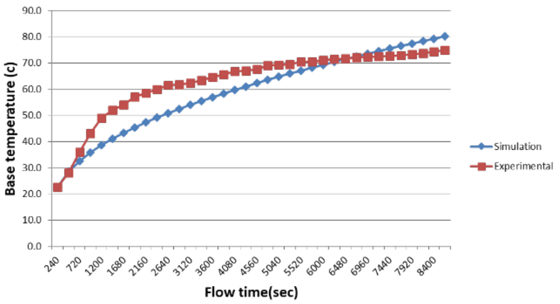

Figure 9. Comparison of Base temperature Profiles

6. Conclusion

In the present study hybrid design of heat sink is developed for real industrial onboard Ev charger using paraffin wax as a PCM. The effect of PCM quantity over different geometries is compared with the finned heat sink design. Viz. inclined interrupted, straight interrupted, and pin fin was analyzed at different thermal loads. The following conclusions were drawn from the study:

For finned heat sink without PCM condition Inclined interrupted FHS delivered the best performance followed by Circular and Straight interrupted FHS for a thermal load of 80 W. At higher thermal loads of 100 W and 120 W, the shape of the temperature profiles for Inclined interrupted, Circular, and Straight interrupted FHS is similar to that at 80 W, except that the slopes of the temperature profiles are higher. Overall, the thermal performance of inclined interrupted FHS at all the thermal loads was found to be higher than for Circular and Straight interrupted FHS.

Using Phase change Materials based hybrid heat sink design offers potential in cooling electronic devices compared to traditional methods.so by using PCM as a thermal conductivity enhancer in finned heat sink design reduce heating rate and peak temperatures of the heat sink thus electronic devices can have longer usage. It is concluded that less peak is observed in the contours of temperature with PCM as a TCE for a given time period. So, maximum thermal performance is achieved and reduce thermal stresses in heat sink.

Thermal conductance calculated at different thermal power levels for three different configurations was higher for pin fin configuration at 80 W i.e. 0.72 and for straight interrupted fin configuration at 100 W i.e. 0.69

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Biographies

Pranali Gole graduated in Mechanical Engineering from Maharashtra institute of technology, Pune in 2019. Presently, pursuing her post-graduation in Automotive Technology from the College of Engineering, Pune.

Dr. M.J.Sable is presently working as Professor at, the Mechanical Engineering Department, College of Engineering, Pune.

Dr. Vishal Bhalla is presently working as Associate Professor at, the Mechanical Engineering Department, College of Engineering, Pune.