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EFFECT OF GROOVED PIN-FIN DESIGNS ON HEAT TRANSFER AND FLUID FLOW CHARACTERISTICS

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ABSTRACT

Enter abstract (an abstract is a brief, comprehensive summary of the contents of the article). The grooved technique enhances thermal dissipation by increasing the heat exchange surface area and promoting efficient heat transfer in high-performance electronic devices. The primary objective of this study is to investigate the impact of grooved pin-fin heat sinks on both heat transfer performance and turbulent fluid flow behavior. The results demonstrate that the novel configuration significantly improves the thermal performance of the heat sink. Specifically, the geometry with seven rectangular grooves improved the heat transfer coefficient by 17% versus the conventional design, with a corresponding pressure drop increase of only 7%. This configuration also achieved the highest hydrothermal performance factor (HTPF = 1.15) and reduced the heat sink mass by 7.33%, offering a promising solution for advanced thermal management applications.

Keywords: heat transfer, fluid flow, grooved technique, heat sink, pin fin.

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1. INTRODUCTION

The first subtitle opens with an introduction that presents the specific problem under study and describes the research strategy. The first subtitle opens with an introduction that presents the specific problem under study and describes the research strategy. The first subtitle opens with an introduction that presents the specific problem under study and describes the research strategy. The first subtitle opens with an introduction that presents the specific problem under study and describes the research strategy [1]. Effective thermal management presents a major challenge in modern electronic devices due to increasing size and power densities. Among the various cooling strategies, finned heat sinks are widely used to improve convective heat transfer by increasing the surface area in contact with the fluid. In this context, the integration of geometric modifications into the fin structure, such as grooves, holes, or other techniques, improves heat transfer, which has attracted considerable interest from researchers.

The perforation technique allows for a higher heat transfer rate by varying different parameters such as the shape, size, and number of perforations. However, several studies [1-3] have indicated that the Nusselt number and pressure difference improve with an increase in the number and size of perforations. This occurs due to a larger heat exchange surface area and a reduced blocking effect on the flow. Haque et al. [4] and Zohora et al. [5] conducted numerical studies on various pin fin designs, including twisted, grooved, airfoiled and wavy configurations. The geometries were optimized by integrating different shapes of perforations. These geometric modifications increased the heat exchange surface area, altered the flow structure, and improved the hydrothermal performance of the heat sinks. On the other hand, after a specific increase in the size and number of perforated fins, the heat transfer rate gradually decreases with the increase in the number and size of the holes and leads to excessive reduction in the fin material, which reduces the conduction rate of the fins [1-3]. Bencherif et al [6] conducted a numerical study to investigate the effect of combining perforation technique and splitter inserts on the heat dissipation and turbulent flow characteristics of pin fin heat sinks (PFHS). Their new geometries show a 34.91% increase in Nusselt number and a 24.22% reduction in thermal resistance compared to the conventional configuration. Under the same conditions, the volume occupied and the mass of this case are also reduced by 70% and 47.5%, respectively. Sahel et al. [7] conducted a numerical study on the impact of combining separators, transverse fins, and the number of holes in pin fins. The results showed that combining the above configuration can improve the performance of heat sinks while reducing their size and weight.

The addition of grooves (axial, helical, etc.) in pin fins increases heat transfer due to a larger heat exchange surface area and the creation of secondary turbulence, although it may also slightly increase pressure loss [8]. Eren and Caliskan [9] experimentally studied the effect of grooved pin fin in a rectangular channel on heat transfer enhancement and friction factor

using the Taguchi method. They studied the effect of cylindrical and triangular grooved pin fin. It was observed that the best heat transfer intensification was achieved with triangular grooved pin fin. Moreover, an experimental study on deep-grooved fins was conducted by Al-Karagoly et al [10]. They found that increasing the length and width of the grooves produces a higher heat transfer coefficient. In addition, they also observed that the position of the groove plays a very important role in improving heat transfer. Furthermore, Zhu et al. [11] reported that the microchannel heat sink with grooves improves thermal efficiency through the mixing of cold and hot fluids and the destruction of the thermal boundary layer.

In this article, a numerical study was conducted to analyze the effect of rectangular grooved pin fin on heat transfer and fluid flow characteristics of heat sinks (HS). For a turbulent air flow regime, the study was performed using COMSOL v.6.2 CFD-Multiphysics software. Promising results were obtained for the design of future heat sinks.

2. PROBLEM DESCRIPTION

A set of three-dimensional Computational Fluid Dynamics (CFD) simulations was conducted to study the hydro-thermal efficiency of rectangular grooved pin-fin heat sinks (G-PFHSs). The pin fins were arranged in a staggered configuration on a square base plate with dimensions of 100 × 100 × 3 mm³, as depicted in Fig. 1 The channel dimensions were 240 × 100 × 50 mm³. The pin height was set to 50 mm, while the thickness of the base plate was fixed at 3 mm. The geometrical parameters presented in this study are the same as those used for the validation task by Chin et al. [3]. Both the base plate and fins were made of A8350P aluminum. To simultaneously enhance the heat exchanger surface area and reduce the mass of the heat sink, the study was carried out to investigate the effect of the number of grooves (Fig. 2).

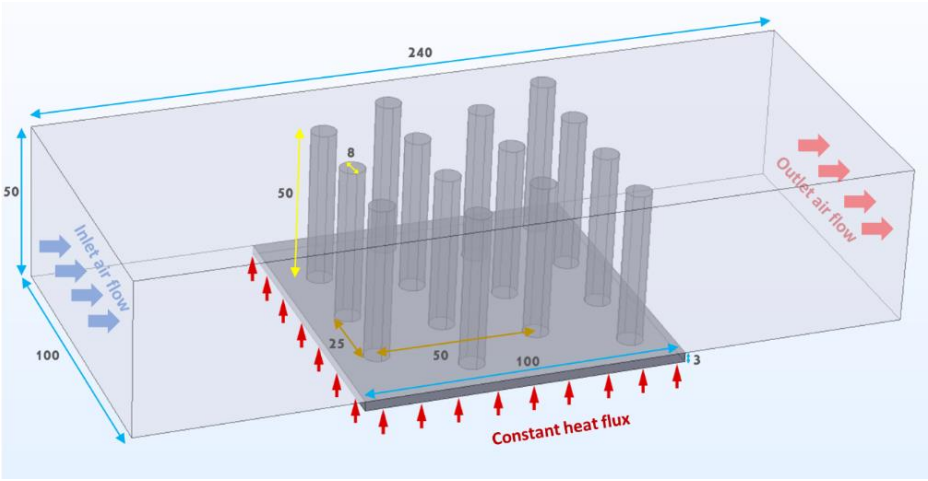


Fig.1. Configurations and detailed dimensions (in mm) of the cylindrical pin-fin heat sink (CPFHS) and the airflow channel.

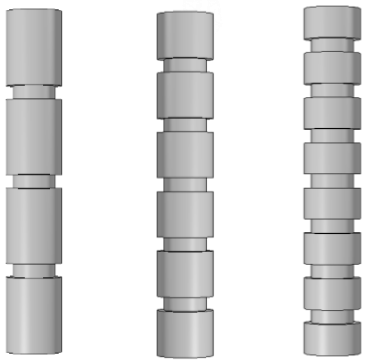


Fig. 2. Pin fins with different numbers of grooves.

3. MATHEMATICAL FORMULATION AND GOVERNING PARAMETERS

The governing equations for steady-state, incompressible fluid flow are defined as follows:

Continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Momentum Equation

$$\frac{\partial (u_i u_j)}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \nu \nabla^2 u_i + \frac{\partial}{\partial x_j}\left(-\overline{u_i' u_j'}\right) \tag{2}$$

Energy equation

$$\frac{\partial (u_j T)}{\partial x_j} = \alpha \nabla^2 T + \frac{\partial}{\partial x_j}\left(-\overline{u_i' \theta}\right) \tag{3}$$

Heat conduction equation

$$\nabla(\lambda_s \nabla T_s) = 0 \tag{4}$$

Where, λs is the thermal conductivity of A8350P-Aluminum (λs =167 W/m. K), Ts is the temperature field in the solid heat sink.
The governing parameters used in this paper are summarized as follow:

Nusselt number (Nu) :

$$Nu = \frac{q'' D_h}{\lambda_{air}(T_W - (T_{in} - T_{out})/2)} \tag{5}$$

Thermal resistance (R_{th}) :

$$R_{th} = (T_W - T_{in})/q'' \tag{6}$$

Pressure drop (Δp) :

$$\Delta p = p_{in} - p_{out} \tag{7}$$

Hydrothermal performance factor (HTPF) :

$$HTPF = \frac{Nu}{Nu_{CPFHS}} \Big/ \frac{\Delta p}{\Delta p_{CPFHS}} \tag{8}$$

4. NUMERICAL MODEL

4.1. Boundary conditions

The conjugate heat transfer (conduction/convection) and turbulent flow through a grooved pin-fin heat sink was investigated with the help of COMSOL Multiphysics v.6.2. Convergence was achieved using symmetry conditions and minimization of calculation time. A uniform velocity and temperature (T_{in} = 300 K) were applied at the inlet, while atmospheric pressure was imposed at the outlet. The channel walls and pin fins were treated with no-slip conditions, and the channel was assumed to be thermally insulated except for the base plate, where a constant heat flux of 5903 W/m² was applied. The working fluid was assumed to be air, and both the pin fins and the base plate were made of aluminum A5083 (k = 167 W/m·K) [3].

4.2. Mesh selection and solver settings

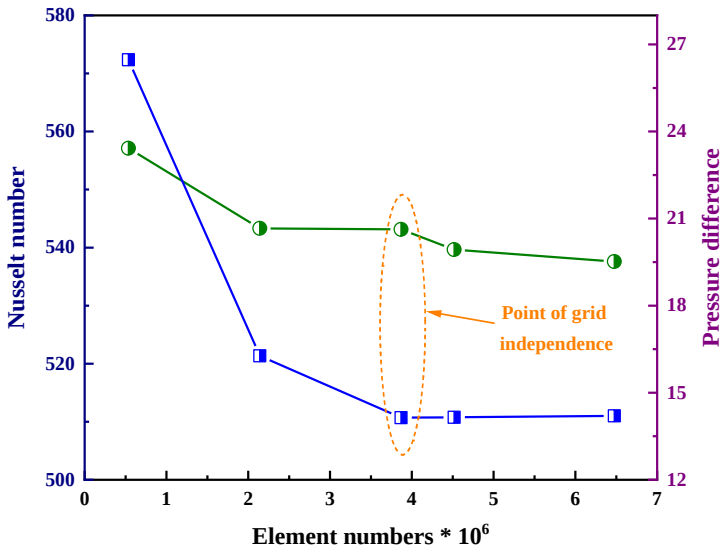


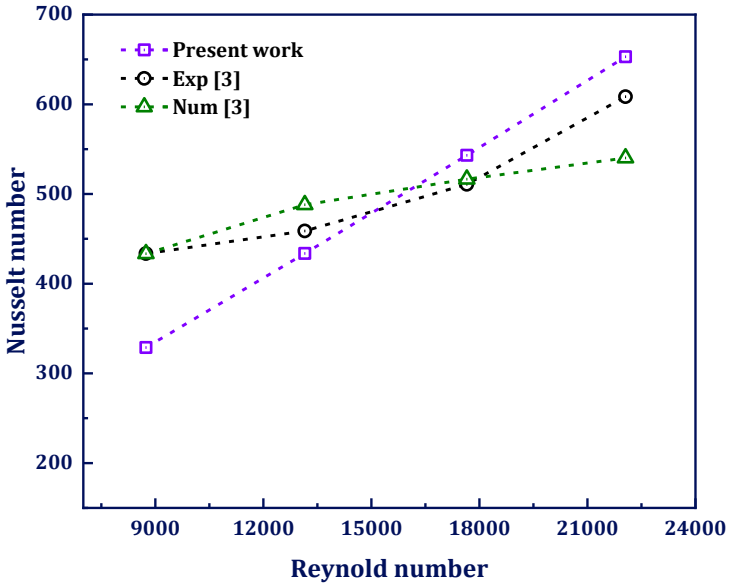
Fig. 3. Test of grid sensibility for CPFHS.

A free tetrahedral mesh was used to mesh the computation domain in COMSOL Multiphysics v.6.2. A test of mesh independence was conducted with grids ranging from 535,216 to 6,476,647 elements. In the elements beyond 3,868,518, the deviation in Nusselt number and pressure drop were less than 0.64% and 0.45%, respectively, ensuring numerical stability.

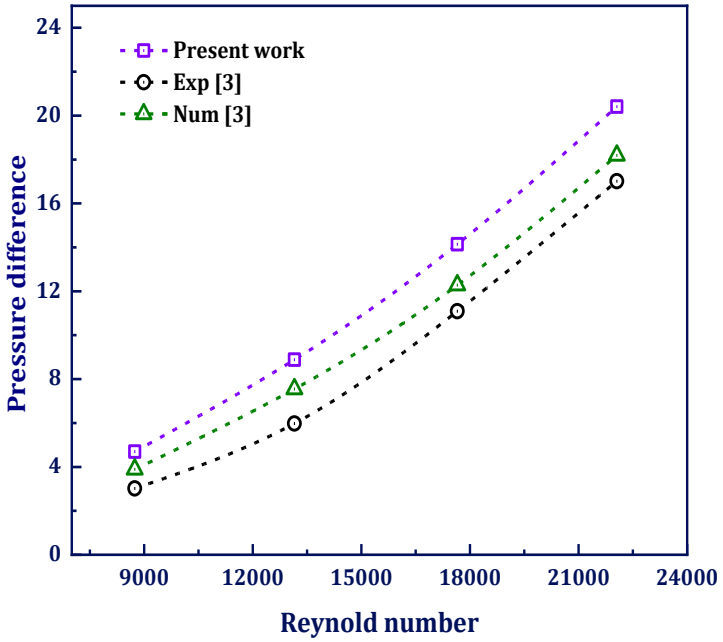
Thus, a grid of approximately 3.9 million elements was chosen, with a maximum error of 1% (Fig. 3). The iteration method of GMRES was utilized with a relative tolerance of 10^{-5} and the linear systems were solved using PARDISO.

5. RESULTS AND DISCUSSION

5.1. Validation of the numerical model



a) Nusselt number (Nu) results.



b) Pressure difference (Δp) results.

Fig. 4. Validation of results for CPFHS.

The validation was done by making the results consistent with available experimental and numerical data [3]. Fig 4 (a) and (b) are used to show how Nu and Δp change with Re respectively. The comparison of the Nusselt number indicates a maximum deviation of 22.56 % and 22.53 % as compared to the experimental and numeric values given by Chin et al. [3]. The same was also the same with the deviations of 19.95% and 12.21% with regard to the pressure drop.

5.2. Heat Transfer and Thermal Resistance

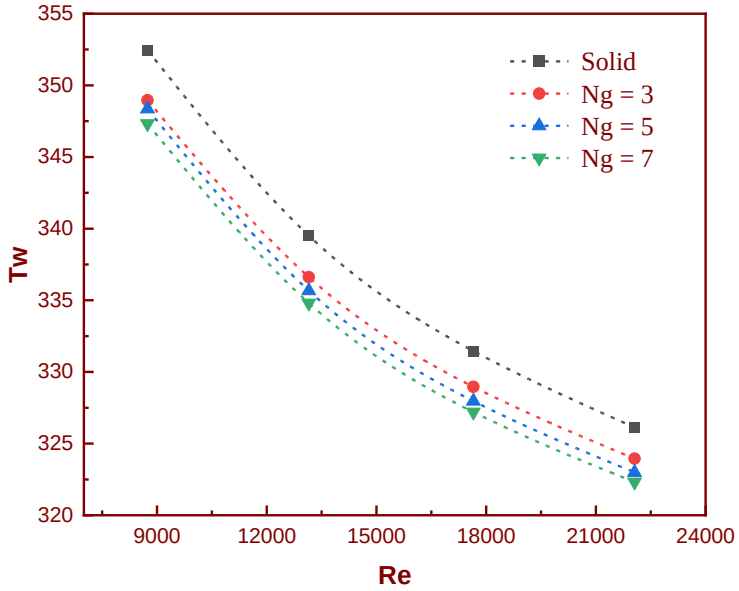


Fig. 5. Variation of the wall temperature (TW) versus Re.

Fig. 5 displays the variation of the of the wall temperature (Tw) versus Reynolds number (Re) for various numbers of grooves. The wall temperature decreases as the Reynolds number increases, due to improved convective heat transfer at higher flow rates. An increase in the number of grooves (Ng) causes the wall temperature to decrease at the same Reynolds number, which indicates that grooved geometries enhance heat dissipation. The classic configuration (CPFs)

shows the highest wall temperatures, confirming its lower thermal efficiency compared to novel configurations. In line with these observations, Fig. 6 depicts the variation of Nu versus Re with different numbers of grooves. The Nusselt number increases with Reynolds number, which indicates an intensification of convective heat transfer. Higher groove numbers yield higher Nu values at the same Reynolds number, with Ng = 7 presenting a 17 % higher Nu compared with CPFs. This is due to the increased heat exchange surface, and the grooves disrupting the boundary layer and promoting fluid mixing.

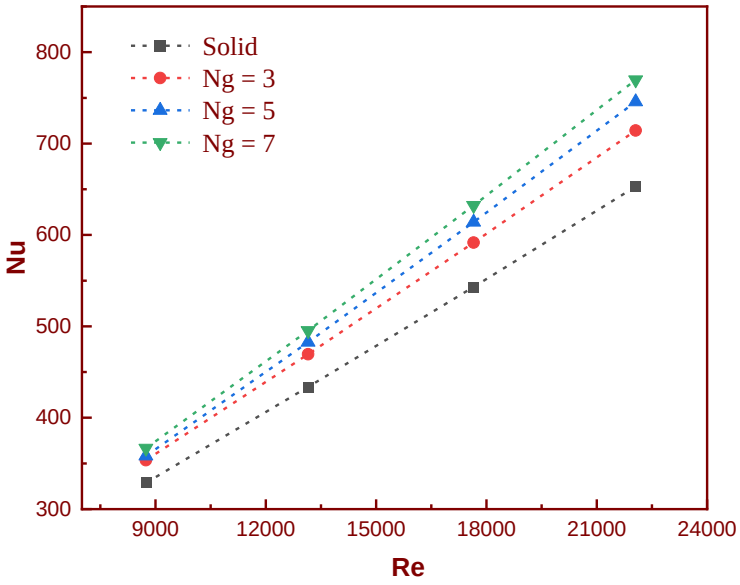


Fig. 6. Variation of the Nusselt number (Nu) versus Re.

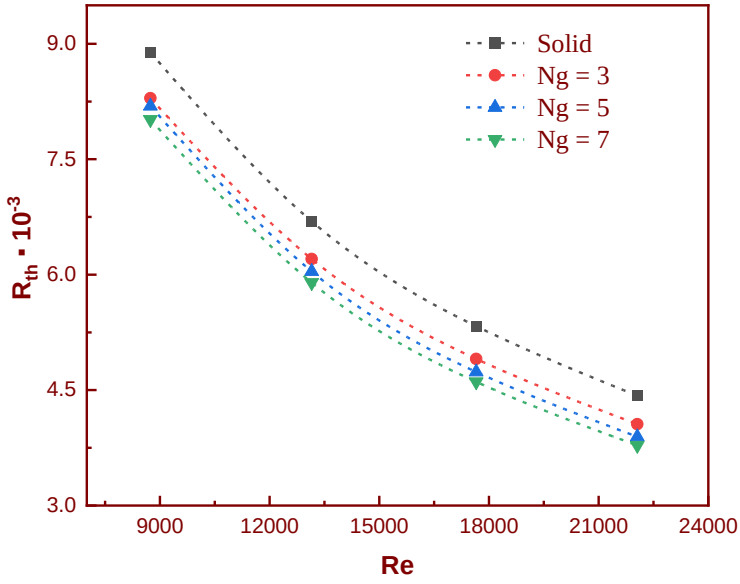


Fig. 7. Variation of the thermal resistance (R_{th}) versus Re.

The variation of the thermal resistance (Rth) versus Reynolds number (Re) is depicted in Fig.7. Thermal resistance decreases with increasing of Re, as expected from the enhanced convective cooling. For any Re, grooved pin fins achieve lower thermal resistance than conventional ones. The reduction becomes more pronounced with a larger number of grooves, with Ng = 7 being most effective, showing an 17% decrease compared with the classic geometry.

5.3. Pressure Drop

Fig. 8 presents the Variation of the pressure difference (Δp) as a function of Re. It can be seen that for all configurations when the Re increases, the Δp increases due to the increase in the blocking flow near fins. at lower Re, all cases present the same Δp, while for greatest Reynolds number (Re=22060) and compared with old geometry the Δp increase by 6.59%, 7.72%, 7.61%, for the configurations with Ng = 3,5,7 respectively.

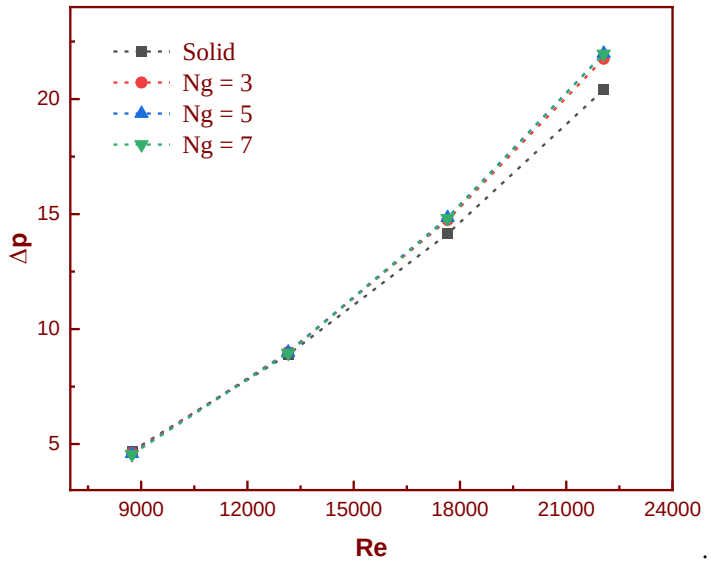


Fig. 8. Variation of the pressure difference (Δp) versus Re.

5.4. Thermal performance optimization

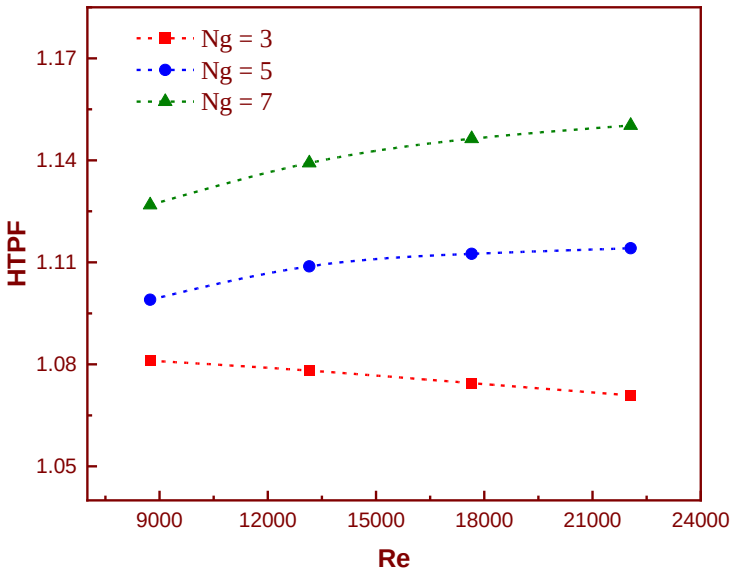


Fig. 9. Variation of hydro-thermal performance factor (HTPF) versus Re.

Fig. 9 presents the evolution of the hydro-thermal performance factor (HTPF) versus Re. It evident from the figure, that HTPF is superior to unity for all novel configurations. From these outcomes, it is concluded that the configuration with Ng = 7 ensures the most HTPF, which gets to 1.15 at Re = 8740. Thus, this geometry benefits to considering in the heat sink conception.

6. CONCLUSION

The effect of the rectangular grooves on the heat transfer and fluid flow characteristics through the pin fin heat sink was analyzed in this paper. Different numbers of grooves were tested for Reynolds numbers ranging from 8,547 to 21,367. The results showed that for the geometry with seven rectangular grooves, the heat transfer coefficient increased by 17% compared with CPFs. This increase was accompanied by a moderate pressure drop of 7%. In addition, the novel configuration achieved the highest hydrothermal performance factor (HTPF) of 1.15, while reducing the heat sink mass by 7.33% compared to the conventional geometry. This case was selected as a recovered configuration for the heat sink design.

7. REFERENCES

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