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Numerical Simulation of Heat Transfer Performance in Novel Biomorphic Pin-Fin Heat Sinks

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Abstract – Pin-fins are effective strategies to enhance heat sink performance; moreover, bio-inspired designs present endless geometrical potential. In this work, a comparative investigation of two biomorphic pin-fin-based heat sinks was carried out via ANSYS CFD simulations. The results showed that the heat transfer performance of the pentagonal and sharp-edged design reported approximately 14% higher Nusselt number compared to a circular and smoother-edged design. Furthermore, the pressure drops or variations within both heat sinks were minimal. The findings from this research provide a baseline for future bio-inspired heat sink designs and heat transfer improvement strategies.

***Keywords*:** heat sinks; heat transfer; thermal management; CFD; mini-channels; pin-fins; bio-inspired design

1. Introduction

Miniaturised electronic gadgets have sparked a revolution in the electronics industry. These electronic devices heat up immensely from constant operation in the microscales — lowering their performance, efficiency, and potentially damaging the overall components/system. The design of miniature heat transfer systems with high heat flux has become crucial as ineffective thermal management can reduce device lifespan, waste energy, and produce unsustainable impacts. Thus, the cooling mechanism of electronic gadgets is one of the key engineering challenges with current-generation technology. As a result, various investigations have been carried out to offer an integrated efficient cooling system. Hence, due to their outstanding potential to efficiently cool electronics, pin-fin-based heat sinks have gained interest in many applications [1].

Despite that, recent research has highlighted a lack of consensus regarding optimum strategies, mechanisms to cope with future heat transfer requirements, and underlying physics within microscale heat transfer [2]. Whilst CFD simulations to determine flow and heat transfer characteristics have been explored, further design analysis and studies are required to provide novel insights, knowledge on optimal heat transfer, and thermal management solutions. Additionally, authors have explored bio-inspired designs to provide unique shapes and understandings into heat transfer improvement; however, further exploration and experiments are warranted in this area as well [3]. Therefore, this paper aims to investigate heat transfer characteristics in novel mini heat sinks with biomorphic pin-fins, emphasising design, heat transfer, flow characteristics, and CFD analysis. Acknowledging extant literature and adopting a biomimetic/biomorphic technology approach, this paper appraises bio-inspired shapes to improve understanding of flow dynamics and provide enhanced heat transfer. The term biomimetic relates to solving complex problems whilst adopting systems that occur in nature; on the other hand, biomorphic designs are inspired by naturally occurring shapes or living organisms.

This short paper is divided into sections and organised around the research aim. The design process that helped to shape this work is described in Section 2. The model simulation, results and an evaluation of the findings are covered in Section 3. The closing parts of this paper include discussions, conclusions, and recommendations for further research.

2. Numerical Methods and Materials

In this paper, two designs have been created inspired by parasol fungus/mushrooms. The first design had smoother circular stems/pin-fins and flat tops (CSFT), but the second design maintained sharp edges, pentagonal stems, and diamond-shaped tops (PSDT). Next, a numerical study was performed to analyse the heat transfer and flow characteristics and compare the designs using CFD. The geometry of the parasol-inspired pin-fin heat sinks can be seen in Fig. 1. A sample of 30 pin-fins was selected to reduce simulation time and cost. Both designs had identical sizes, pin-fin spacing, and dimensions.

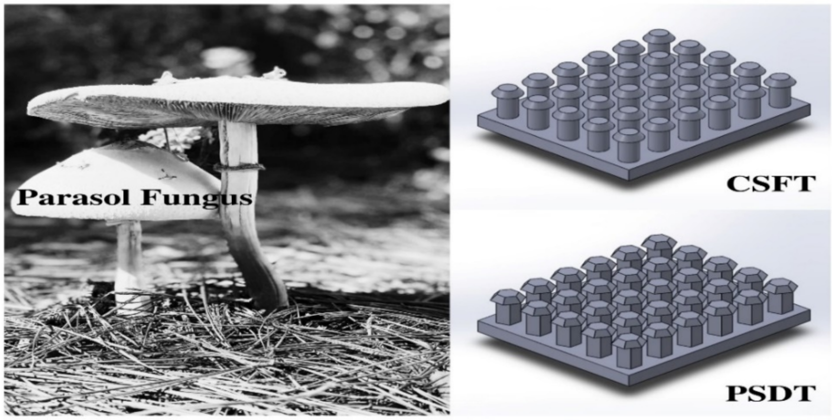

Fig. 1: Bio-inspired/biomorphic heat sink designs

2.1. Model Pre-processing

ANSYS Fluent Mesh software was employed to create three distinct mesh sizes for fluid and solid domains. The mesh grid independence test/validation was done using a velocity metric. Table 1 provides the mesh statistics.

Table 1: Grid independence test results.

Mesh Type	Nodes	Mean Velocity	Maximum Velocity	Refinement Ratio
Mesh (I)	128016	1.349	1.494	--
Mesh (II)	278333	1.352	1.505	2.174
Mesh (III)	534609	1.352	1.496	1.921

Based on the minimal deviations between the velocity results, Mesh (I) was chosen as the suitable option; Mesh (I) orthogonal quality ranged from 0.75 on average to 1 at its highest. Furthermore, the refinement ratio of Mesh (II)/(I) and (III)/(II) were both above 1.3 providing additional validation to the grid independence results [4].

2.2. Equations

Flow on the micro-scale exhibits dissimilar properties from the flow on the macro scale; albeit, some disagreements amongst researchers exist regarding this. Nevertheless, the governing equations used for modelling the simulation of the novel heat sinks and standard k-epsilon flow turbulence assumptions were adapted from previous works [5], [6].

$$Continuity\ equation: \frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$Energy\ equation\ (fluid): \rho_f\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)= \mu\cdot \mathrm{Pr}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+S_t(fluid) \tag{2}$$

$$Nusselt\ Number: Nu=\left(\frac{D_h}{k}\right)\ln\left[\frac{(T_s-T_i)}{(T_s-T_o)}\right]\left(mC_p/A_{ht}\right) \tag{3}$$

Where, u, v, w - velocity components; x, y, z - directions; ρ_f – fluid density; μ - dynamic viscosity; Pr - Prandtl number; S_t - energy equation source term; T, T_s, T_i, T_o are fluid, bottom wall, inlet, and outlet temperatures, respectively; m - mass flow rate; A_{ht} - base area where heat is applied; D_h - hydraulic diameter; k – thermal conductivity; C_p – specific heat.

3. Results and Discussion

Fig. 2 exhibits the findings from the CFD simulations. The initial temperature and inlet velocity were 300K and 1 m/s. m/s. For exploratory purposes, the initial heat source term was given a high value of 100 MW/m^3. PSDT had a higher temperature saturation region/heat distribution near the outlet with some low temperature region on the bottom right edge. edge. However, due to the potential influence of the laminar boundary layer, CSFT design showed lower temperature saturation regions but had a small high temperature zone on the bottom right edge — in contrast to the other design.

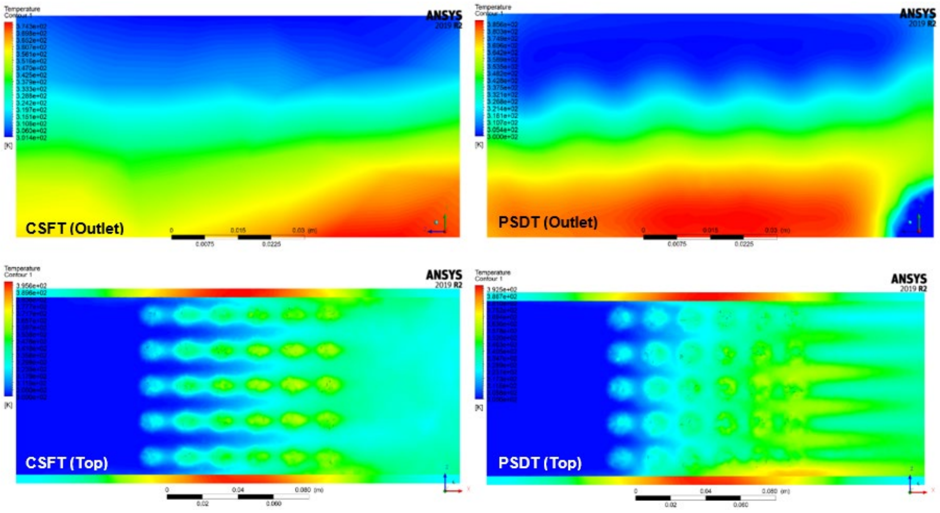

Fig. 2: Temperature distribution from the top view and outlets

Fig. 3 shows the pressure distribution of CSFT and PSDT. Compared to CSFT, the sharp-edged PSDT had a lower pressure zone at the outlet. Nevertheless, the difference between the inlet to outlet pressure in both the designs was minimal.

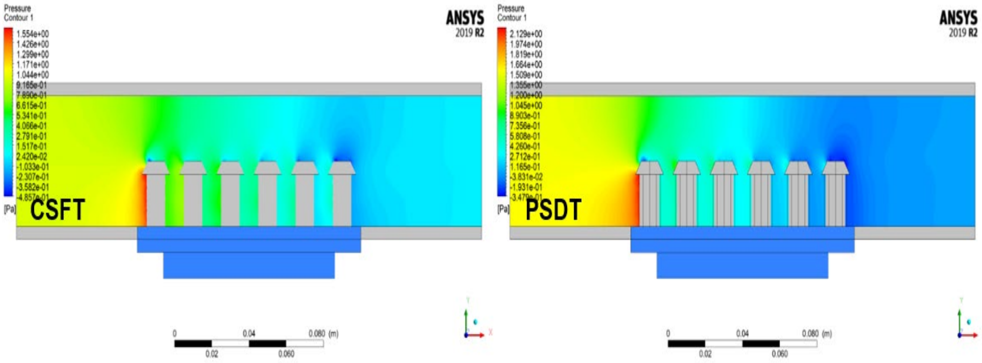

Fig. 3: Pressure distribution in the heat sinks

Fig. 4 shows localised Nu variation using points along the pin-fin tops. PSDT had approximately 14% higher Nu on average — the highest Nu coming at the first row/set of pin-fins in both designs. The model simulations were validated against previous work [7]; the Nu and pressure change values were in acceptable ranges. Nevertheless, further experimental verification is required to assess the feasibility of such sharp-edged pin-fin designs. Therefore, subsequent experiments could include topological optimisation of pin-fin numbers and pin-fin surface treatment. It should be noted that it was challenging to utilise past experimental data from the literature due to the vastly different geometrical configurations and setup. Hence, the authors acknowledge the limitations of the findings. However, the current research output is arguably still valuable.

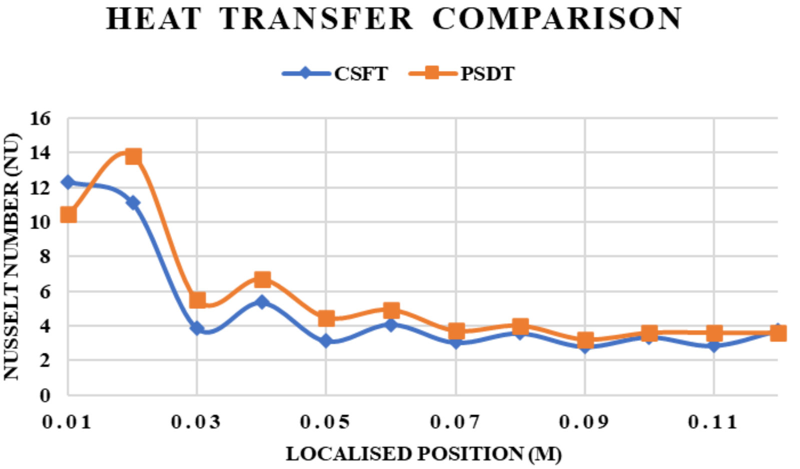

Fig. 4: Heat transfer comparison

4. Conclusion

In this paper, comparative analyses of two bio-inspired pin-fin heat sinks were conducted. The geometric structures, flow and heat transfer characteristics were studied using CFD simulations. The following conclusions could be drawn: (a) A sharp-edged pentagonal design showed superior heat transfer performance over a circular design (b) The pressure drop in both the designs was minimal; however, a higher portion of low-pressure region exists in the design showing better heat transfer performance.

Acknowledgements

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