CFD Analysis and Experimental Validation of Al6063–SiC Composite Heat Sinks under Forced Convection

[1]Harichandra K. Chavhan' [2]Dr. Pradeep M. Solanki

[1] Research Scholar in Mechanical Engineering, Shram Sadhana Bombay Trust College of Engineering and Technology Jalgaon Maharashtra 425001 India; hkcmech@gmail.com,

https://orcid.org/0009-0007-0048-8260

[2]Associate Professor in Mechanical Engineering, Shram Sadhana Bombay Trust College of Engineering and Technology Jalgaon Maharashtra 425001 India; solanki.pradeep@sscoetjalgaon.ac.in,

https://orcid.org/0000-0001-8949-9562

ABSTRACT: A three-dimensional numerical simulation of flowing fluids by the use of CFD analysis was performed to test forced convection thermal performance of Al6063-SiC composite plate-fin heat sink with SiC reinforcement level of 47 wt.%, 49 wt.%, and 51 wt.%. The simulations were performed assuming a constant heat input of 50W and inlet air velocities of 2-4m/s. The outcomes suggest that a rise in airflow speed shows a significant reduction of the base and fin surface temperatures as well as an increase of the heat transfer coefficient due to convection and a decrease of the thermal resistance for all the composite configurations.

The effect of SiC reinforcement was found significant. Under the same conditions of air flow it was found that heat sinks having higher SiC content always had lower operating temperatures and showed better thermal performance. The heat transfer coefficient due to convection of the 51 wt.% SiC composites was the highest (up to 111.01 W/m^{2}degC) and the thermal resistance was the lowest (0.38 degC/W). This improved performance is explained by an effect on heat spreading and distribution in the composite despite the decrease in bulk thermal conductivity experimentally observed.

Flow analysis was used to demonstrate uniform airflow through the fin channels with localised areas of recirculation which increase convective heat transfer. The pressure drop rose with the velocity of airflow, which shows the trading-off between the thermal performance and power for pumping while material composition has negligible effects on the flow resistance. The numerical results are compared with experimental data which proves the reliability of the developed model. The results demonstrate the prospects of the use of Al6063-SiC composites in the design of advanced electronic cooling systems.

Keywords: Al6063–SiC composite; CFD validation; Heat sink; Forced convection; Thermal resistance; Heat transfer coefficient.

I. INTRODUCTION

The high rate of development of high power and miniaturised electronic devices has led to a significant rise in the heat generation density that poses a significant challenge to thermal management systems (Li et al., 2023; Kim et al., 2022). Efficient dissipation of heat is necessary to maintain optimal operating temperatures, reliability and lifespan of electronic components (Zhang et al., 2023; Lee et al., 2021). Inadequate thermal management may cause thermal runaway, performance degeneration and eventually system failure as in number of the cases such as microprocessors, power electronics, light emitting diodes (LEDs) and communication systems (Singh et al., 2023; Kumar et al., 2021).

Among various kinds of cooling methods, air-cooled plate fin heat sinks are one of the widest applications owing to their simplicity, low cost of manufacturing, and ease of integration (Kumar et al., 2021; Wang et al., 2022). The thermal performance of such thermal sinks is dependent on a mix of conductive heat transfer, taking place in the solid material, and convective heat transfer, which will be to the surrounding fluid (Patel et al., 2022). The efficiency of a convective heat transfer is often characterised by dimensionless parameters like the Reynolds number (Re) which determines the flow regime and the Nusselt number (Nu) which determines the enhancement of the heat transfer due to convection relative to conduction (Incropera et al., 2020). These parameters depend strongly on the average velocity of the airflow, on the geometry of the fin and the material properties (Sharma et al, 2024).

Traditionally, heat sinks are made with monolithic materials such as aluminium, copper owing to their relatively high thermal conductivity (Reddy et al., 2020). Among them, Al6063 is used widely due to its favourable combination of thermal conductivity, corrosion resistance, formability and cost-effectiveness (Verma et al., 2021). However, conventional aluminium alloys have certain shortcomings, especially with regarding thermal expansion mismatching with semiconductor materials while additionally limiting improvement of the thermal performance below excessive heat flux conditions (Ali et al., 2023). Therefore, these limitations have driven the search for advanced materials with better thermophysical properties (Gupta et al., 2021).

Aluminium Matrix Composites (AMCs) reinforced by ceramic particles are recognised as potential candidates for the next-generation thermal management systems (Chawla et al., 2020; Surappa, 2020). In particular, silicon carbide (SiC) reinforced aluminium composites have received much attention because of their strong mechanical properties, superior resistance to thermal effects and minimum coefficient of thermal expansion (CTE) (Ramesh et al., 2021; Khan et al., 2022). The addition of SiC particles in the aluminium matrix can improve the dimensional stability and lower the thermal stresses, and hence make them suitable for high performance and high reliability application (Singh et al., 2023).

Several experimental and numerical studies were carried out on the thermal behaviour of Al-SiC composites (Kumar et al., 2022; Mehta et al., 2021). Previous works have shown the general trend that as the content of SiC increases, the mechanical properties improve and CTE is reduced (Surappa, 2020; Chawla et al., 2020). However, it is more complicated how SiC reinforcement effect on thermal conductivity and convective heat transfer performance (Ali et al., 2023). While SiC is characterized by relatively high intrinsic thermal conductivity, the composite thermal conductivity may be affected by interfacial thermal resistance between matrix and reinforcement, particle distribution, agglomeration and porosity (Khan et al., 2022; Das et al., 2020). As a result, it is not possible to equate an increase of reinforcing content with a corresponding increase of thermal conductivity.

From a heat transfer point of view, the overall thermal performance of a heat sink is not determined by the conductivity of the material used, but also by the heat transfer efficiency through convection (Wang et al., 2022). This brings up the importance of viewing material properties and flow characteristics at the same time. Computational Fluid Dynamics (CFD) has become an important means to analyse such coupled phenomena to get detailed visualisation of the temperature field, velocity distribution and pressure variations associating complex geometry (Chen et al., 2021; Deshmukh et al., 2022). Numerous researches have been using CFD to examine the impact of the airflow speed, fin arrangement, and boundary condition on the performance of the heat sink (Kumar et al, 2021; Zhang et al, 2023). However, one of the major drawbacks of many of the already available CFD studies is the absence of any rigorous experimental validation, which raises some concerns about the accuracy and reliability of the predicted results (Kulkarni et al., 2023).

Furthermore, most of the literature information available on Al-SiC composites focused on comparatively low to moderate reinforcement loads, usually less than 45 wt.% SiC (Singh et al., 2023). There is evident dearth of systematic investigations seeking to answer the high reinforcement fractions (greater than 45 wt.) which are especially important under forced convection conditions discussed for practical electronic cooling applications (Verma et al., 2024). The combined thermodynamic conditions of SiC content and angle of flow combine to impact key thermal parameters such as convective heat transfer coefficient, thermal resistance and temperature distribution properties and these aspects of thermal parameter as a function of SiC content and flow angle are insufficiently explored.

In addition, few studies have been carried out on the validation of CFD models with experimentally tested thermal properties of high SiC reinforced composites in the same operating conditions (Kulkarni et al., 2023; Hussein et al., 2025). Such validation is important to establish a level of confidence in numerical predictions to make it possible to use CFD as a reliable design and optimization tool.

In this context, the present study is aimed at filling these research gaps by a comprehensive and validated CFD analysis of Al6063-SiC composite plate-fin heat sink with high SiC reinforcement levels of 47 wt%, 49 wt% and 51 wt%. A three-dimensional numerical model was developed by using ANSYS Fluent as software to simulate forced convection heat transfer under a controlled condition with the parameters and inlet air velocities from 2 to 4 m/s and a constant heat input of 50 W.

The numerical model is verified against previously published experimental data collected under exactly the same geometric and thermal parameters providing the accuracy and robustness of the simulation framework (Chavhan and Solanki, 2025). Key performance parameters, e.g. base temperature, average surface temperature, convective heat transfer coefficient, thermal resistance and pressure drop are systematically evaluated. In addition, the research offers understanding of the interaction between material composition and flow behavior, with special focus on the effect of the high SiC reinforcement on the improvement of the thermal performance.

The presented contributions of this work are threefold: (i) establishment of a validated CFD model for high SiC reinforced Al6063 composite heat sinks, (ii) in-depth consideration of compounding effects of airflow velocity and reinforcement fraction on the heat sink thermal performance, and (iii) determination of optimal material composition for enhanced heat dissipation. The results of this study would be expected to aid in the design of advanced thermal management systems for high performance electronic applications.

II. LITERATURE REVIEW

A considerable amount of work has been conducted to boost the thermal performance of heat sinks and ADC models for use in electronic cooling applications (Li et al., 2023; Kumar et al., 2021). This section provides a critical review of past experimental and numerical studies including a focus on the reinforcement level of silicon carbide (SiC) and its thermal properties and heat transfer performance.

Plate-Fin Heat Sinks under Forced Convection

Fundamental studies by Bar-Cohen and Kraus laid out the theoretical basis for air-cooled heat sink design which covered the important design, optimizing the fin geometry, air flow and surface area augmentation (Bar-Cohen and Kraus, 1983). Their work proved that convective heat transfer can be very much dependent on flow behaviors that are generally expressed in terms of dimensionless numbers such as Reynolds number (Re) and Nusselt number (Nu) (Incropera et al., 2020).

Subsequent experimental and numerical investigations have proved the fact that an increment of airflow velocity can greatly improve the heat transfer performance by decreasing the thermal boundary layer thickness and the heat transfer coefficient due to convection (Kumar et al., 2021; Wang et al., 2022). Plate fins heat sinks under forced convection conditions were studied and showed that the heat transfer coefficient was increased by up to 40-60% with increases in the air flow rate from 2 to 4 m/s, although this was accompanied by corresponding increases in pressure drop and pumping power requirements (Singh et al., 2020; Sharma et al., 2024).

Thermal Behavior of Al–SiC Composites

Aluminium-silicon carbide (Al-SiC) composites have been extensively studied because of their enhanced thermomechanical properties (Gupta et al., 2021; Chawla et al., 2020).

Comprehensive reviews of SiC reinforcement for upgraded stiffness, wear resistance, and thermal stability of aluminium alloys were pointed out by Gupta and Wong (2021).

Experimental studies have been done to investigate the effect of SiC content at a broad range of compositions. For example, Ramesh et al conducted investigations on Al6063-SiC composites with reinforce levels as large as 10-20 wt% which proved the improvement of mechanical strength and moderate changes of thermal properties (Ramesh et al., 2021). A review of aluminium matrix composites was conducted by Surappa and it was stated that the reinforcement levels in aluminium matrix composites generally range from 5 wt.% to 30 wt.% for conventional applications based on balancing the processability and performance [Surappa, 2020].

Studies reported by Chawla and Chawla indicated that at higher levels of reinforcement (20-40 wt.%) results in significant reduction of the coefficient of thermal expansion (CTE), which improves the dimensional stability, whilst the level of thermal conductivity may not increase in the same magnitude due to formation of interfacial thermal resistance (Chawla et al., 2020; Khan et al., 2022).

Further experimental work suggested that the thermal conductivity also may show a declining pattern beyond ~30 wt.% SiC due to increased interfacial resistance, and particle agglomeration and formation of micro-voids and porosity (Das et al., 2020; Ali et al., 2023). These findings agree well with those from classical composite theory and from observations made experimentally and reported in the literature of materials science.

However, most of these studies are restricted to ~ 40 wt.% SiC, and few studies are conducted on high reinforcement loading (>45 wt.% SiC), especially for thermal management applications in which the convective heat transfer mode is concerned (Verma et al., 2024).

CFD Studies on Heat Sink Performance

Computational Fluid Dynamics (CFD) has become an essential tool to analyse the heat transfer of complex systems (Chen et al., 2021; Deshmukh et al., 2022). Studies with the mesh models by turbulence models like k-e and k-o-SST have shown the performance of predicting the air and heat flow in plate fin heat sinks (Mishra et al. 2021).

A series of previous CFD studies have found that the increasing of the Reynolds number significantly improves Nusselt number and heat transfer coefficient, while the heat transfer coefficient due to convection increases about 30 to 50% as the air flow velocity rises from 2 to 4 m/s and thermal resistance decreases accordingly with the improvement of air flow conditions (Wang et al., 2022; Kumar et al., 2021; Zhao et al., 2023).

In spite of the above advancements, most of the CFD studies use homogeneous material properties and are confined mainly to the traditional materials such as aluminium. There is still very limited work done to incorporate experimentally measured composite properties into CFD simulations (Patel et al., 2022).

More importantly, many research works are not actively validated by experimental data, which is crucial for always ensuring the verifiability of the numerical models especially with complex materials such as particle reinforced composites (Kulkarni et al 2023; Hussein et al 2025).

Research Gaps

Based on the above literature, the following research gaps are recognized:

- Most of the research studies of Al-SiC composites are limited to low and moderate reinforcement content (≤40 wt. %).
- Limited research is available on high SiC reinforcement (>45 wt.%) in heat sink applications.
- Lack of validated CFD studies by experimentally measured composite properties.
- Lack of analysis of combined effects of velocities of the airflow and composition of materials in forced convection.

III. METHODOLOLOGY

Geometry and Computational Domain

A three-dimensional computational model of plate-fin heat sink with forced convection was set up to study the thermal performance of Al6063-SiC composite materials. The geometric configuration of the fins such as height, thickness, distance and the base was designed to mirror the experimental configuration provided in the previous study of the authors, thus permitting to validate directly the numerical results (Chavhan and Solanki, 2025).

The computational domain is a wind tunnel in the form of a rectangular air channel that encloses the heat sink. Adequate upstream and downstream lengths were included in order to determine fully developed flow conditions, and minimize inlet and outlet boundary effects (Versteeg and Malalasekera, 2020).

The geometry has been made and optimized in Space Claim. Necessary cleaning operations were performed to eliminate geometric inconsistencies such as gaps, overlaps and unnecessary edges that would guarantee a watertight domain ready for high quality mesh generation (ANSYS Inc., 2023).

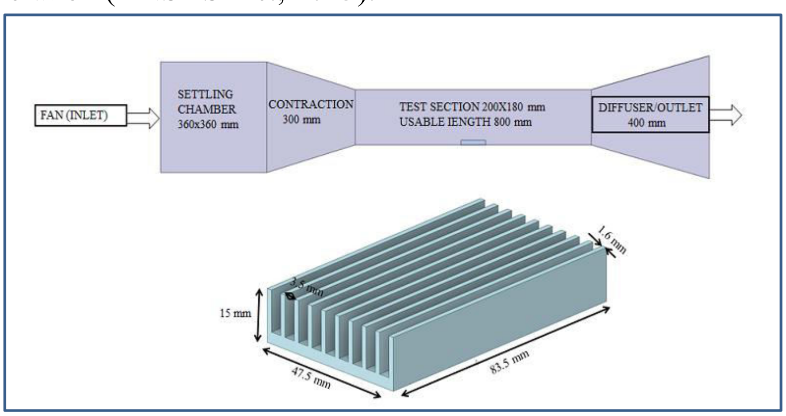

Figure 3.1Wind Tunnel and Heat Sink Geometry

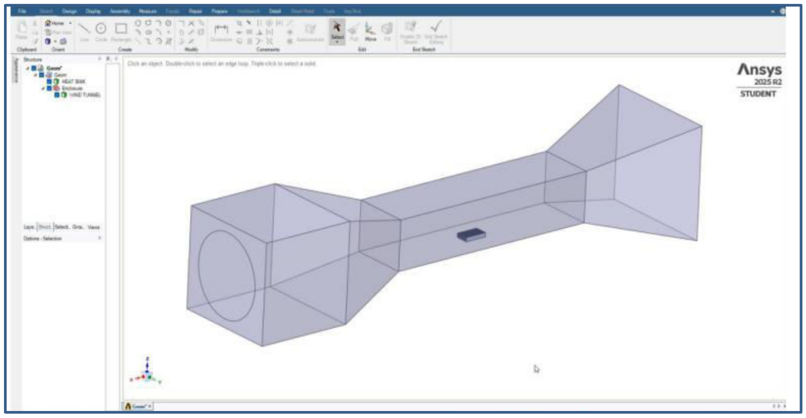

Figure 3.2 Transparent Geometric Model of heatsink and Wind-tunnel assembly ready for CFD meshing

Model Assumptions

To secure balancing between the computational efficiency and physical accuracy, the below assumptions were made. The analyses were carried out in steady-state conditions while the air flow was treated as three-dimensional and completely turbulent (Versteeg and Malalasekera, 2020). Air was considered incompressible Newtonian fluid with constant thermophysical properties evaluated at mean temperature that is a common assumption for forced convection air cooling applications at a moderate temperature range (Incropera et al., 2020).

Radiative heat transfer was disregarded because this mode of heat transfer is relatively small compared to the heat transfer by convection under the current operating conditions (Incropera et al., 2020). Heat generation within the fins was assumed to be negligible, having the thermal input applied only at the heat sink base, which is consistent with the usual electronic cooling setups (Kumar et al., 2021).

Perfect thermal contact between the base and fins was assumed (eliminating the thermal resistance at the interface between them), as it is common practice in numerical analysis of heat sinks, to reduce model complexity (Patel et al., 2022).

Governing Equations:

The flow and the heat transfer in the computational domain are governed by the basic conservation equations of mass, momentum and energy. Under the assumption of steady state, incompressible and turbulent flow, the governing equations are as follows:

Continuity Equation

$$\nabla . \vec{V} = 0$$

Momentum Equation

$$\rho\left(\vec{V} . \nabla\right)\vec{V} = -\nabla P + \mu \nabla^2 \vec{V}$$

Energy Equation

$$\rho C_p\left(\vec{V} \nabla T\right) = k \nabla^2 T$$

Where $\rho, C_p, \mu and k$ represent density, specific heat, dynamic viscosity, and thermal conductivity respectively.

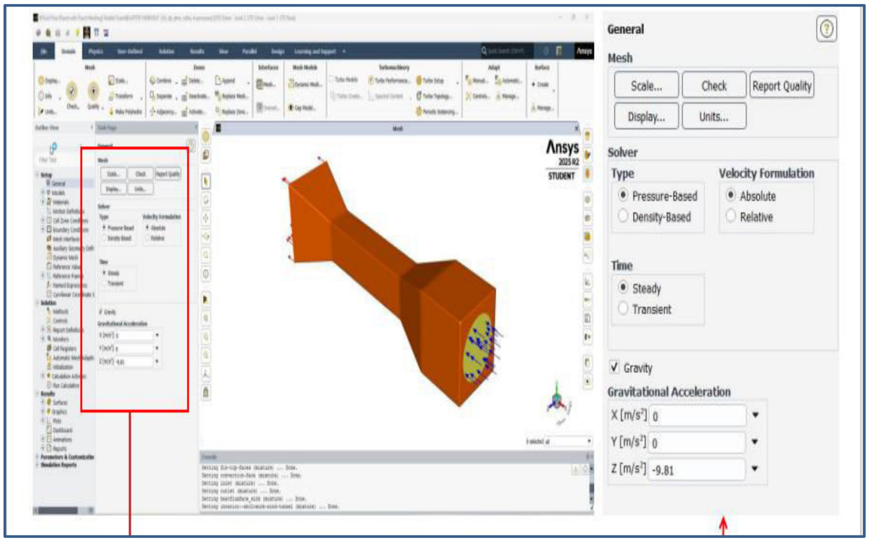

Figure 3.3 A pressure-based, steady-state solver with the gravity enabled to allow this analysis to resolve perfectly numerical the buoyancy-affected airflow and heat transfer behaviour.

Turbulence Modeling

To properly obtain the turbulent flow features in the air channel, the Reynolds-Averaged Navier-Stokes (RANS) approach was implemented (Versteeg and Malalasekera, 2020). The standard k-e turbulence model was implemented because of its robustness, numerical stability and computational efficiency for internal flow applications such as plate fin heat sinks (Launder and Spalding, 1974; Mishra et al., 2021).

The transport equations for turbulent kinetic energy (k) and dissipation rate of this energy (e) are solved together with the conservation equations. The model introduces the concept of eddy viscosity to account for better momentum and heat transfer that occur due to turbulence (Incropera et al., 2020).

Standard wall functions were used near solid boundaries in order to effectively model the near-wall region generally without having to compute extremely fine mesh resolutions. This approach is a good compromise between computationally expensive and accurate solution of high-Reynolds number flows for engineering applications (ANSYS Inc., 2023; Versteeg and Malalasekera, 2020).

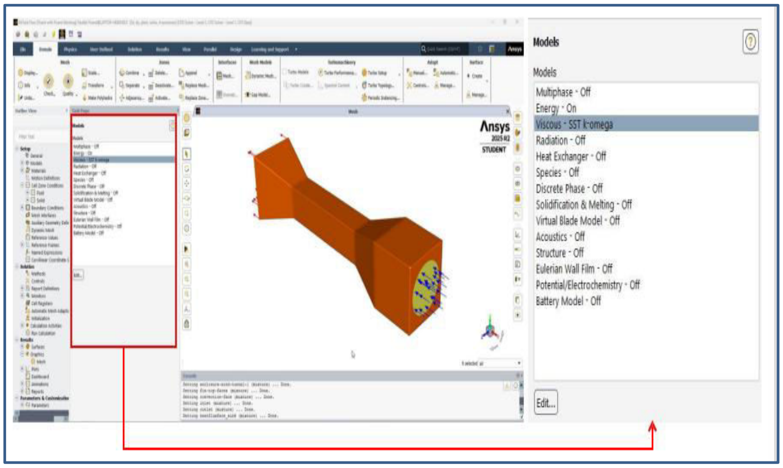

Figure 3.4 k-Omega SST turbulence model used for resolving the airflow behaviour over fins with stable convergence behavior.

Mesh Generation and Grid Independence Study

A high-quality computational mesh was created based on a hybrid structure using poly-hexcore strategy in order to achieve good balance between numerical accuracy and computational efficiency. Local mesh refinement was carried out in areas of high gradients such as back of heat sink fins and base to resolve the flow and thermal fields. In addition, inflation layers have been introduced along all solid-fluid interfaces in order to resolve the near-wall velocity and thermal boundary layers with adequate layer numbers. In order to guarantee the reliability and mesh-independence of the numerical results, a systematic grid independence study of the results was conducted by three gradually refined mesh configurations, i.e., coarse, medium, and fine mesh. Key performance parameters, namely, base temperature and convective heat transfer coefficient were monitored and compared at these mesh levels.

The results showed that the difference between medium and fine mesh was less than 2% showing that the solution is practically independent of increasing the mesh. Based on this observation, this medium mesh was used for all following simulations, because it offers a good balance between solution accuracy and computational cost.

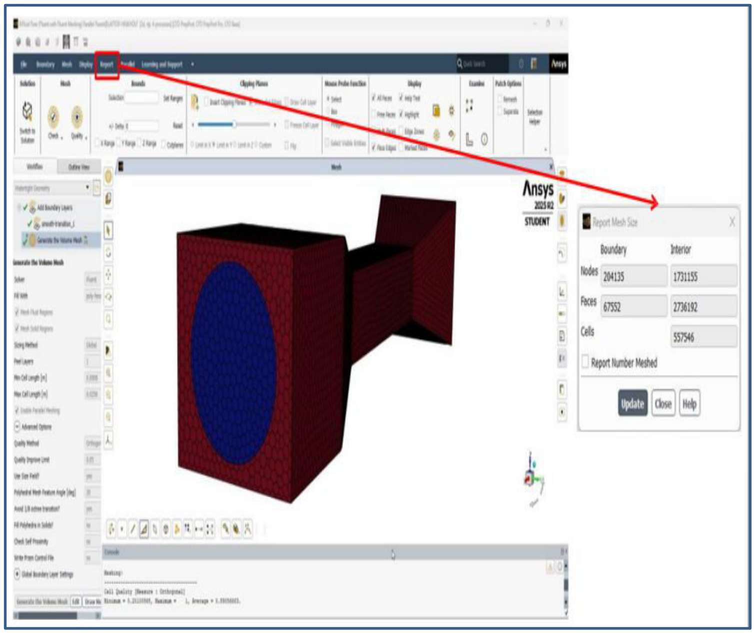

Figure 3.5 Poly-hexcore mesh resulting from suitable cell density

Boundary Conditions and Material Properties

A uniform velocity inlet boundary condition was imposed at the channel entrance having air velocities of 2, 3, and 4 m/s matching the experimental operating conditions. A pressure outlet condition was prescribed at the exit.

A constant heat applied at the foot of the heat sink was used (50 W). All of the solid surfaces were imposed with no-slip boundary conditions and conjugate heat transfer was implemented for the solid-fluid interface. The temperature of the ambient air was therefore kept in the range 25-26 degC.

The thermophysical properties of the samples of Al6063-SiC composites were acquired experimentally. For each composition thermal conductivity was measured thrice and the average number is chosen as a representative input for numerical simulations which ensures improved accuracy and consistency of the results (Chavhan and Solanki, 2025).

The averaged values of the thermal conductivity were found to be 143.15, 128.58, and 119.49 W/mK for Samples 1, 2, and 3, respectively. The associated experimental uncertainty was within ± 8% which shows good reliability and repeatability of the measurements, necessary for the validation of numerical models (ASTM E1225-13, 2020).

Table 1: Material Properties
(Chavhan and Solanki, 2025; Incropera et al., 2020; Callister and Rethwisch, 2020).

Sample	Density of material ρ (kg/m^3)	Specific heat of material C_p (J/kg K)	Average thermal conductivity of material K (W/m^0C)
Sample 1 (Al6063:53% & SiC: 47%)	2932	830	143.15
Sample 2 (Al6063:51% & SiC: 49%)	2947	828	128.58
Sample 3 (Al6063:49% & SiC: 51%)	2963	826	119.49

Numerical Solution Procedure

The governing equations were solved by finite volume method (FVM) in a pressure-based solver framework. Pressure-velocity coupling was done by the SIMPLE algorithm. For spatial discretization, a second order upwind scheme was used to increase numerical accuracy.

The solution was initialized using hybrid initialization and iterative calculations were carried out until convergence was achieved. The convergence criteria were defined so that the residuals of the continuity, the momentum and energy equations were less than 10^{-6} Additionally, significant physical parameters, such as the base temperature and pressure drop were monitored in order to ensure stability of the solution and convergence.

Validation Methodology

The validation of the present numerical model was performed using the outcomes of this numerical model with experimentally measured data from the previous study carried out by the authors (2025). The validation was done under identical operation conditions such as inlet air velocities (2 m/s to 4 m/s), heat input (50 W) and ambient temperature, to ensure the consistency between experimental and numerical investigations.

Key performance parameters such as heat sink base temperature and convective heat transfer coefficient were selected for comparison which is the indicators of the thermal performance of the system. The thermophysical properties used in the simulations for the Al6063-SiC composite materials were identified by experimental results and average values were used to represent the effective material behaviour.

To quantify the agreement between scientific predictions and the experiments, the percentage deviation was calculated by the following expression (Versteeg and Malalasekera, 2020; Coleman and Steele, 2018).

$$\% \text{ error} = \frac{|X_{CFD} - X_{EXP}|}{X_{EXP}} \times 100$$

Where,

X_{CFD} and X_{Exp} represent the numerical and experimental values, respectively.

The comparison showed decent result between the numerical and experimental results and with the deviations mostly within plus or minus 5-8%, which can be regarded as acceptable results for conjugate heat transfer simulations involving composite materials which are complicated. The observed discrepancies may be attributed to experimental uncertainties, assumptions of constant thermophysical properties as well as to limitations of the turbulence model.

Overall, the close agreement validates the CFD model developed, which is able to predict with good accuracy the thermal performance of the plate-fin heat sink and it can be reliably used to further analyse the results with more CFD parametric analysis.

IV. ANALYSIS AND DATA PRESENTATION

Temperature Contour:

Figure 4.1 to 4.3 present the temperature contours of the Al6063-SiC composite heat sinks having 47 wt.%, 49 wt.%, and 51 wt.% SiC subjected to forced convection of entrance velocities of air 2, 3, and 4 meter per sec. The contours are plotted according to the same color scales in order to allow direct comparison between various compositions of the composite and different flow conditions. These figures show the conduction of the heat from the heat sink base to the fins and its subsequent dissipation to the air all around. The maximum temperatures are detected on the base of the heat sink, and lower temperatures are spread on the surfaces of the fins, indicating a good heat spreading and convective heat removal.

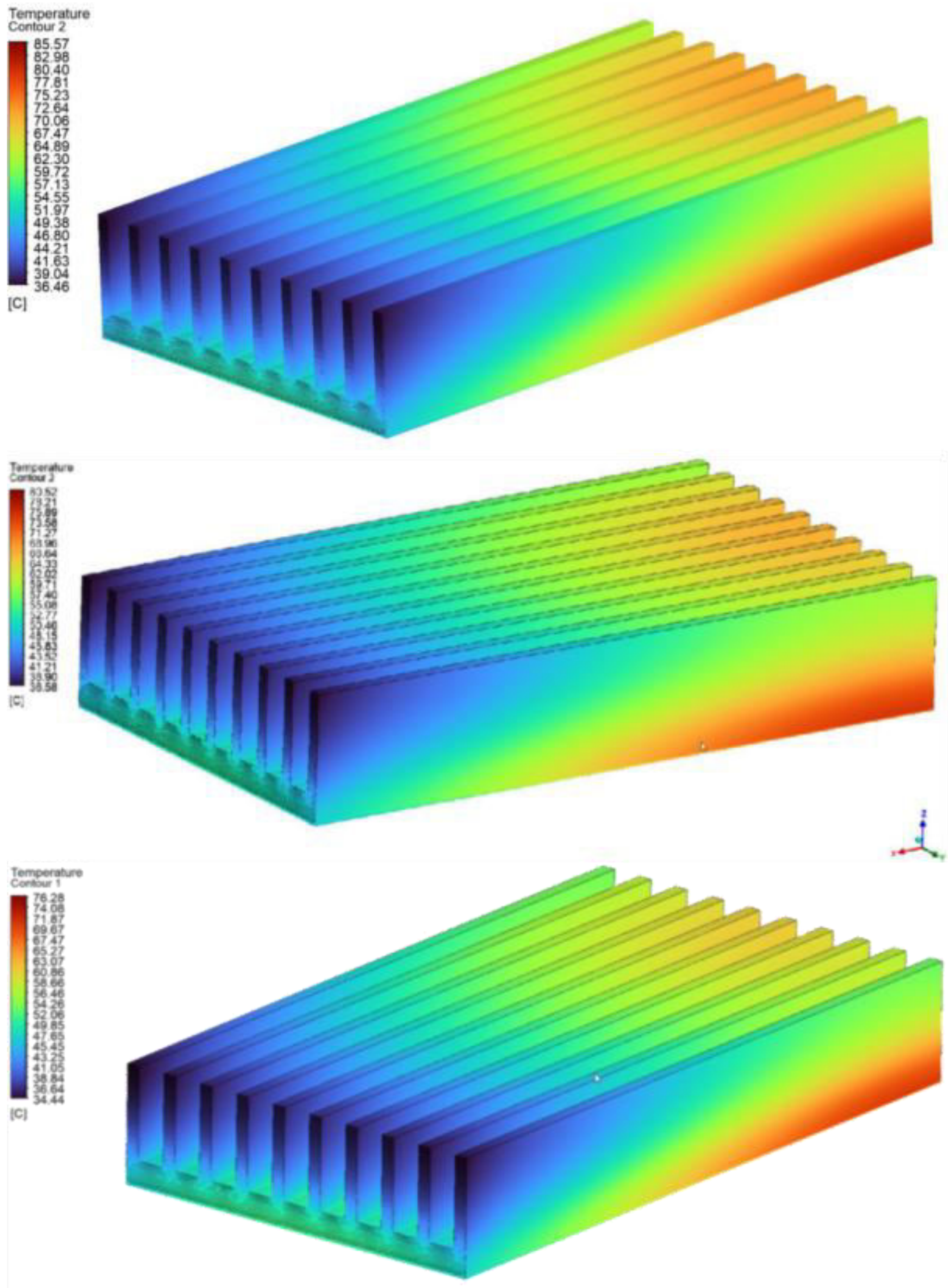

Figure 4.1 Temperature contour of Sample 1

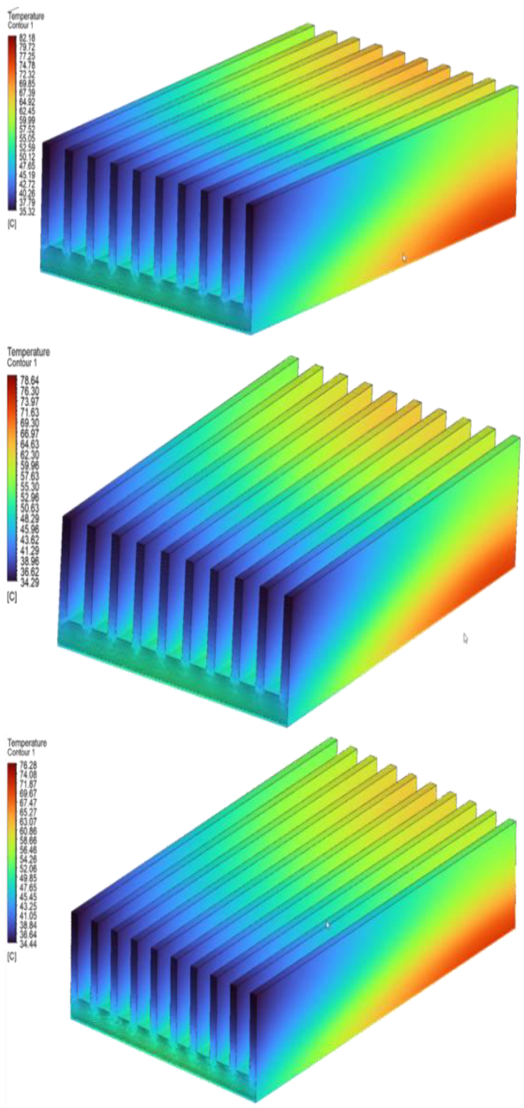

Figure 4.2 Temperature contour of Sample 2

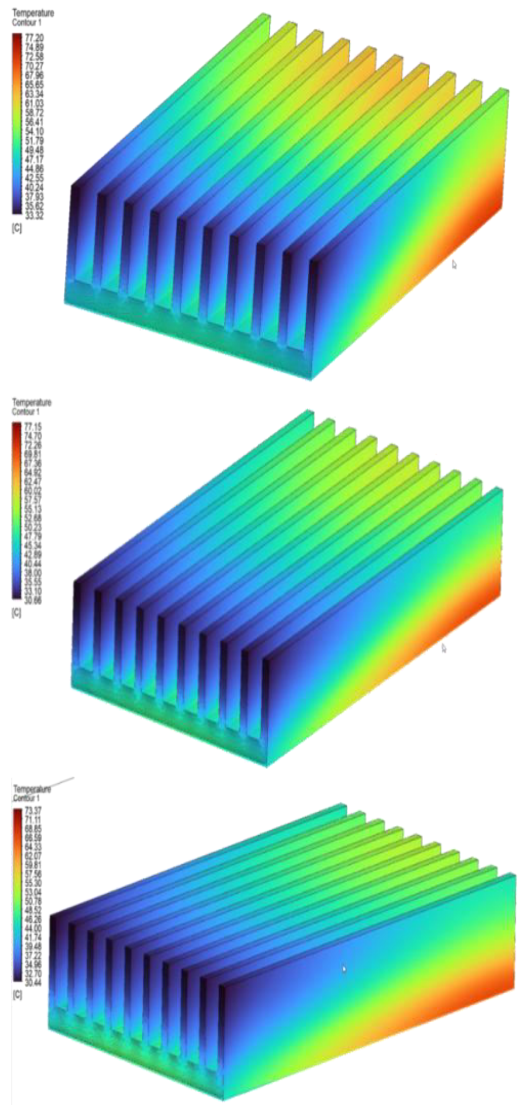

Figure 4.3 Temperature contour of Sample 3

Velocity Contour

The velocity vectors and streamlines in the fin passages for the sample 3 are illustrated in figure 4.4. The air flow is still mostly homogeneous throughout the flow direction with local areas of recirculation that occur near the base and trailing edges of the fins. These flow features through the augment the mixing of the fluid and promote the convective flow of heat from the sides of the fins.

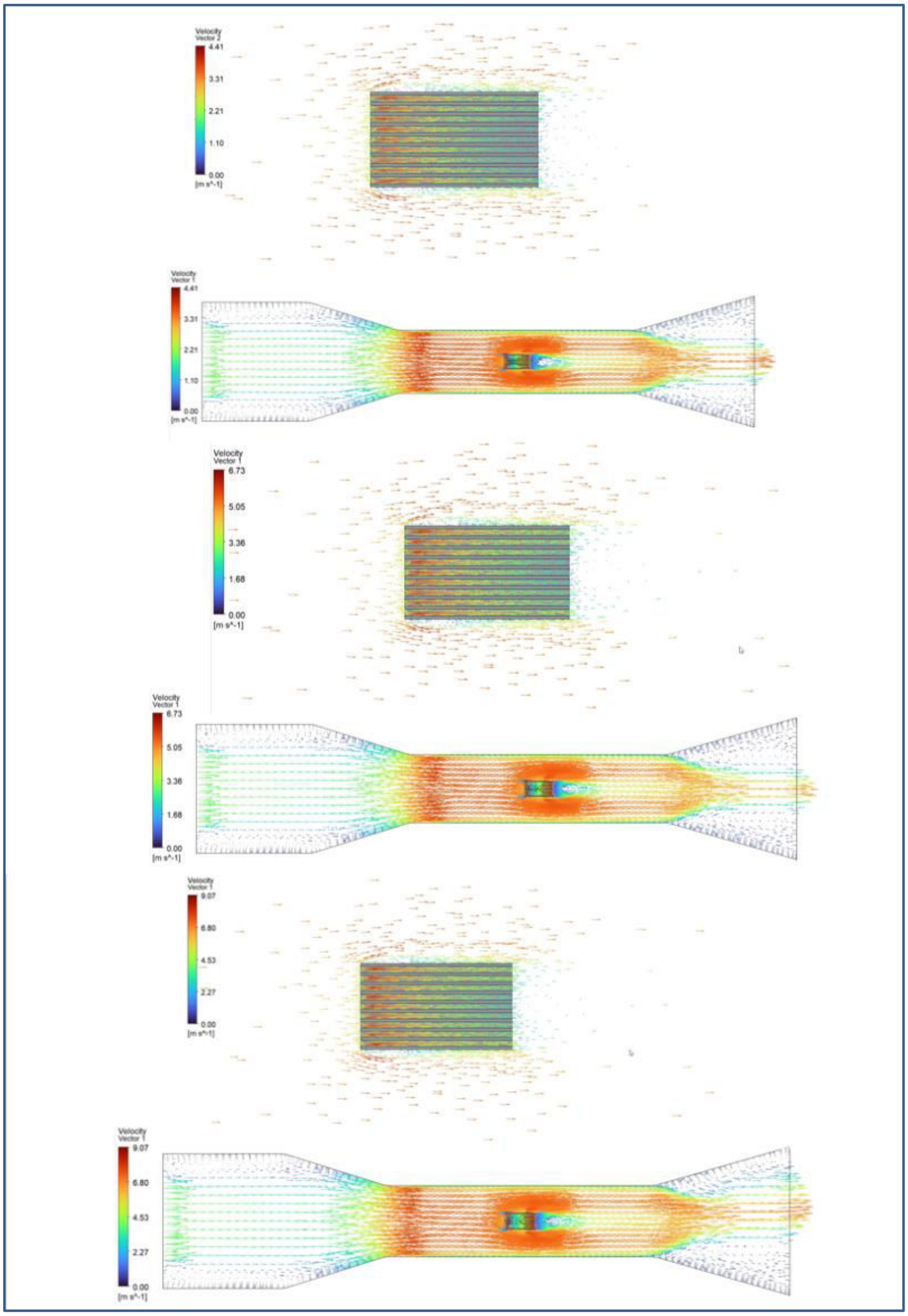

Figure 4.4 Velocity Contour of Sample 3 having velocity 2-4 m/s

Pressure Contour

Pressure variations over the heat sink for different inlet velocities for the sample 3 is shown in Figure 4.5. The drop of pressure across the all-heat sinks samples increases with the velocity of airflow, as it varies from about 11 Pascal at 2 meter per sec to 20 Pascal at 4 meter per sec, proving that the forced convection nature of the flow is verified.

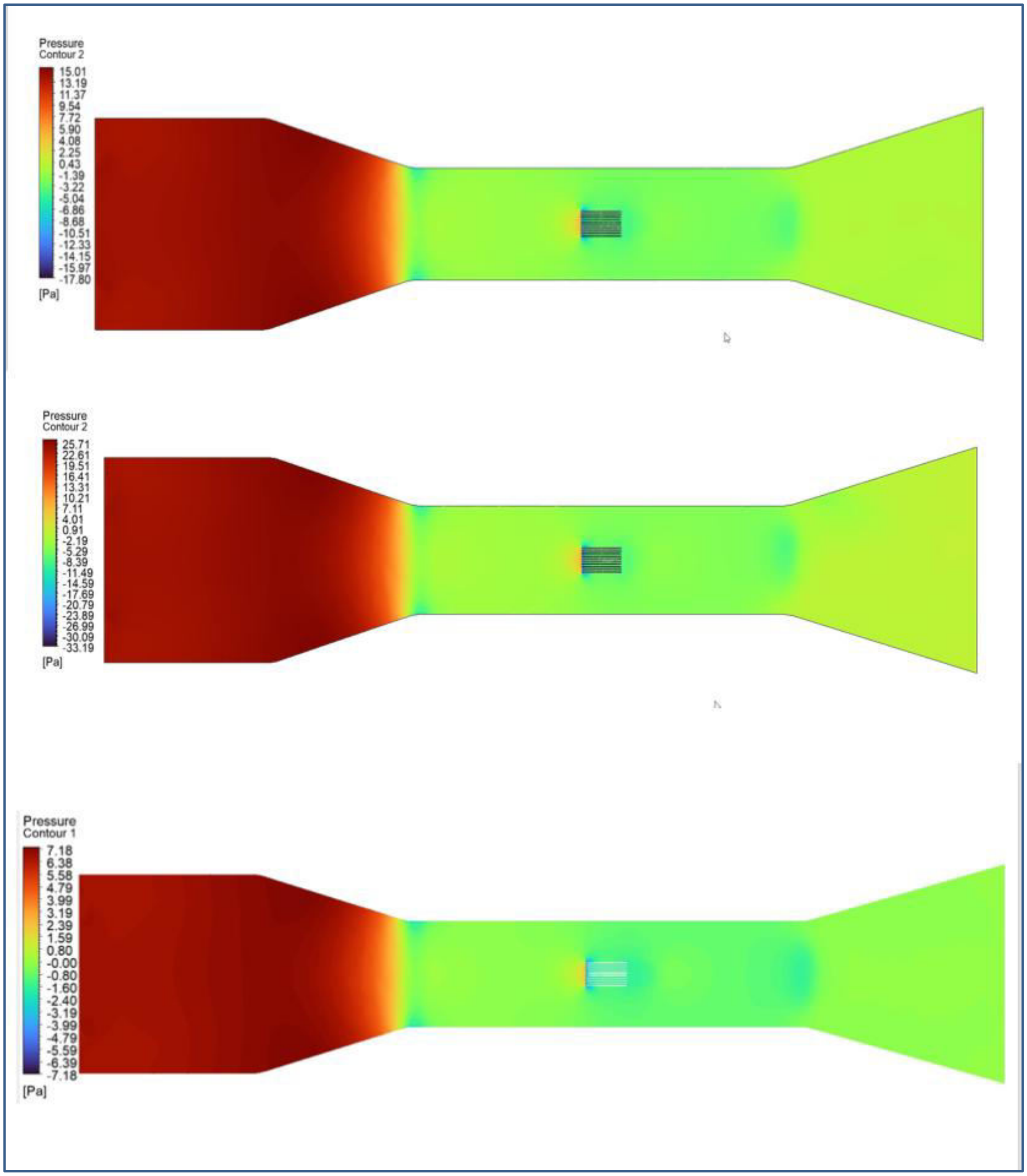

Figure 4.5 Pressure Contour of Sample 3 having velocity 2-4 m/s

Quantitative data of thermal information is extracted from the CFD results by area-weighted averaging. Tables 2-4 are a summary of the base temperature, average fin-surface temperature, entrance and outlet air temperatures, and pressure decrease of all the composite samples for the investigated airflow conditions.

Table 2: Simulation Results for sample 1 [Al6063 (53%) & SiC (47%)]

Test No.	Air Velocity (meter per sec)	Heat Input (W)	Ambient Temp. (°C)	Base Temperature (°C)	Average Surface Temp. (°C)	Pressure Drop (Pa)
	v	Q	T_a	T_b	T_S	ΔP
1	2	50	25	73.1	59.3	11
2	3	50	25	69.8	56.6	15
3	4	50	25	68.2	53.1	18

Table 3: Simulation Results for sample 2 [Al6063 (51%) & SiC (49%)]

Test No.	Air Velocity (meter per sec)	Heat Input (W)	Ambient Temp. (°C)	Base Temperature (°C)	Average Surface Temp. (°C)	Pressure Drop (Pa)
	v	Q	T_a	T_b	T_S	ΔP
1	2	50	26	69.03	54.9	12
2	3	50	26	68.6	51.4	13
3	4	50	26	66.2	47.4	19

Table 4: Simulation Results for Sample 3 [Al6063 (49%) & SiC (51%)]

Test No.	Air Velocity (meter per sec)	Heat Input (W)	Ambient Temp. (°C)	Base Temperature (°C)	Average Surface Temp. (°C)	Pressure Drop (Pa)
	v	Q	T_a	T_b	T_S	ΔP
1	2	50	25	68.7	51.3	11
2	3	50	25	65.4	46.6	15
3	4	50	25	61.5	43.9	20

Sample calculation for the Sample No. 1; Test No.1

By applying Newton's Law of cooling (Incropera et al., 2020),

$$Q = h\, A_{surface\ area} (T_S - T_a)$$

Where,

Q = Heat supplied to heat sink in watt

h= Convective heat transfer coefficient, $w/m^2\ °C$

$A_{surface\ area}$= Surface area of the heat sink, m^2

T_S= Average surface Temperature, °C

T_a= Ambient Temperature, °C

Test No. 1

$$Q = h_1 \times 0.02383 (59.3\text{-}25)$$

$$50 = h_1 \times 0.02383 (59.3\text{-}25)$$

$$h_1 = 61.17\ w/m^2\ {}^0C$$

Thermal Resistance (Incropera et al., 2020),, °C/W

$$R_\theta = \frac{T_S - T_a}{Q}$$

Test No. 1

$$R_\theta = \frac{59.3-25}{50}$$

$$R_\theta = 0.68\ °C/W$$

The heat transfer coefficient due to convection and thermal resistance obtained by calculating based on the standard heat transfer relations using the CFD-predicted temperature fields are presented in table 5 for all the samples and test numbers.

Table 5: Simulation Results for 'h' and 'R_θ'

Sample No.	Test No.	Convective heat transfer coefficient (h) $w/m^2\ °C$	Thermal Resistance **(R_θ)** °C/W
Sample 1 Al6063 (53%) & SiC (47%)	1	61.17	0.68
	2	66.39	0.63
	3	74.66	0.56
Sample 2 Al6063 (51%) & SiC (49%)	1	70.17	0.60
	2	79.47	0.53
	3	93.66	0.45
	1	79.77	0.53

Sample 3 Al6063 (49%) & SiC (51%)	2	97.13	0.43
	3	111.01	0.38

V. RESULT AND DISCUSSION

The computed result developed in this work is also qualitatively compared with those experimentally observed trends found by the authors in their earlier work on Al6063-SiC composite heat sinks. The predicted values of base temperature, assessed convective heat transfer coefficient and resultant pressure-drop are found to be in line with experimentally measured values under similar working conditions (Chavhan and Solanki, 2025). This agreement proves the adequacy of the adopted turbulence model, mesh strategy and conjugate heat transfer formulation for the CFD simulations.

Effect of Airflow Velocity on Thermal Performance:

Figures 4.1-4.3 show the dependence of the airflow velocity on the thermal characteristics of the heat sinks with Al6063-SiC composite. For all three of the composite samples, a consistent decrease in base temperature and average fin surface temperature occurs with increasing inlet air velocity over the range of 2 m/s to 4 m/s.

For the 47 wt.% SiC composite, the temperature base starts out at 73.1 degC for 2 m/s and drops to 69.8 degC for 3 m/s and further to 68.2 degC for 4 m/s. A similar trend is found for the 49 wt.% SiC composite, with a decrease in the base temperature from 69.03 degC to 66.2 degC for the same velocity range. The biggest reduction is noted for the 51 wt.% SiC composite with the base temperature reducing from 68.7degC to 61.5degC with a velocity increase from 2 m/s to 4 m/s.

This behavior can be explained by the improved convective heat transfer theory at higher velocities of the airflow. Increasing the velocity gives higher Reynolds number which increases turbulence and reduces thickness of thermal boundary layer over the fin surfaces. As a result, the heat transfer coefficient due to convection increases and more efficient heat removal from the heat sink is achieved.

Overall, the results clearly show that airflow velocity is a dominating parameter to control the thermal performance of plate-fin heat sinks. However, the improvement of the thermal performances is accompanied by the expected increase in pressure drop, which indicates the trade-off between cooling effectiveness and flow resistance.

Effect of SiC Reinforcement Percentage on Thermal Performance:

Figures 4.1-4.3 show the effect of SiC reinforcement percentage on the thermal performance of Al6063-SiC composite heat sinks under the same conditions of airflow. At all of the inlet velocities investigated, an increase in the SiC content leads to a constant decrease in the base and average fin-surface temperature.

At an inlet velocity of 2 m/s, the base temperature changes from 73.1 degC for the 47 wt.% SiC composite to 69.03 degC and 68.7 degC for the 49 and 51 wt.% SiC composites, respectively. This trend increases with higher values for the airspeed. At 4 m/s the base temperature decreases from (at 47 wt.% SiC) 68.2 degC to (at 49 wt.% SiC) 66.2 degC to a minimum of (at 51 wt.% SiC) 61.5 degC.

Temperature contour analysis also shows an increase in the thermal uniformity of the heat sink as the SiC content is increased. The temperature gradients of the 51 wt.% SiC composites are smoother and hot-spots near the heat source are reduced, which means the heat-spreading ability is improved. This behavior is attributed to the improved values of effective thermal conductivity of the composite, which leads to more efficient conduction of the heat from the base to the fin surfaces.

The variation of convective heat transfer coefficient with SiC content. is given in Table 5. At the constant flow velocity of stream, 3 m/s, the value of heat transfer coefficient is increased from 66.39 W/m^2C for 47 wt.% SiC composite to 79.47 W/m^2C for 49 wt.% SiC composite and last to 97.13 W/m^2C for 51 wt.% SiC composite. This enhancement suggests that an increase in SiC reinforcement enhances the thermal transport in the solid domain which then increases the available heat at the solid-fluid interface promoting the convective heat transfer mechanism.

Overall, the results prove that the enhanced thermal performance of heat sinks based on Al6063 with increased SiC reinforcement. The combined result of increased thermal conductivity and airflow velocity results in higher heat dissipation characteristics thus higher SiC content composites are more suitable for thermal management applications.

Convective heat transfer coefficient and Thermal Resistance Characteristics

The result of the variation of convective heat transfer coefficient and thermal resistance with contractual air velocity and SiC content are presented in Table 5. For all composite samples, the heat transfer coefficient due to convection (h) is monotonically increased with increasing airflow velocity which is consistent with the behavior of forced convection which is described in the literature. As the inlet velocity is increased the Reynolds number will increase which leads to increase of the turbulence intensity and thermal boundary layer thickness and thus convective heat transfer will be improved.

It can be seen that for the 47wt.% SiC composite, h increases from 61.17 W/m^2degC at 2 m/s to 74.66 W/m^2degC at 4 m/s. A similar trend is observed for 49 wt.% SiC composite with h increases from 70.17W/m^2degC to 93.66 W/m^2degC for the same velocity range. The best enhancement is found for the 51 wt.% SiC composite material with h increasing from 79.77 W/m^2C (2 m/s) to 111.01 W/m^2C (4 m/s).

Correspondingly the increase in the heat transfer coefficient due to convection causes a decrease in the thermal resistance (R_{th}). For the composite with 47 wt.% SiC, the thermal resistance is lower from 0.68 degC/W at a primitive velocity of 2 m/s to 0.56 degC/W at 4 m/s. For the 49 wt.% SiC composite, the thermal resistance decreases from 0.60 degC/W to 0.45 degC/W while the thermal resistance for the 51 wt.% SiC composite is the lowest, going from 0.53 degC/W to 0.38 degC/W.

These results show that with increasing airflow velocity, the convective heat transfer is greatly enhanced with reduced thermal resistance and better overall cooling performance is achieved. Furthermore, the apparent improvement in performance with increases in the SiC content is indicative of the improved heat transfer effectiveness of the composite heat sinks. As a note, even though the bulk thermal conductivity of the composite decreases with increasing the SiC content (as observed experimentally), the comprehensive thermal performance results from many other factors such as particle dispersion, interfacial characteristics, and facilitating heat distribution in the fin surfaces.

The result of the increased convection of the end parts of the blades at increased airflow velocities combined with the improved heat spreading within the heat sink provides for superior thermal performance, especially for the 51 wt.% SiC composite. These results are in line with classical forced convection heat transfer principles and show the value of material modification in the optimization of heat sink performance.

Flow Characteristics and Pressure Drop Analysis

The velocity vectors and the streamlines in the fin passages of the heat sinks at various air flow velocities are shown in Figure 4.4. The flow field shows smooth formation along the fin channels and some of the localized recirculation areas are identified around the base and trailing edges of the fins. As the inlet air velocity is increased from 2m/s to 4m/s, the intensity of these recirculation regions becomes more pronounced resulting in enhanced mixing of the fluid and disruption of the thermal boundary layer. This behavior contributes to better convective heat transfer, as there is more interaction between the stream of air and heated surfaces as a result.

Figure 4.5 shows the corresponding pressure drop through the heat sink for while the investigated airflow velocities are. A monotonic pressure drop increase is observed with increasing inlet velocity for all the composite samples varying from about 11 Pa at 2 m/s to about 20 Pa at 4 m/s. This trend is in agreement with the laws of classical fluid dynamics where the loss of pressure is proportional to flow velocity squared, because of increased inertial action effects and resistance to flow distribution within confined passages.

The results further show that the pressure drop is a function of airflow velocity and geometrical parameters such as fin spacing and channel length with little dependence on the material composition of the heat sink. This is not unexpected, since pressure losses are mostly related to the behavior of fluid flow, and not so much to thermal properties of the solid material.

The measured rise in the pressure drop, therefore highlights the inherent tradeoff between thermal performance and pumping power of forced convection cooling systems. While higher airflow velocities increase the heat transfer processes and the reduction of thermal resistance, they also increase the required fan power needed to overcome the flow resistance. Therefore a balance between thermal efficiency and energy consumption in an optimum operating condition needs to be found, especially in the case of practical heat sink design and electronic cooling applications.

Validation with Experimental Results

To determine the accuracy and the predictive power of the current numerical model, a systematic validation was conducted by comparing the CFD results with experimentally measured data available for exactly the same operating conditions. The comparison was conducted for key thermal performance parameters, i.e. heat sink base temperature and convective heat transfer coefficient, for the investigated range of airflow velocities (2-4 m/s).
The experimental data were obtained from the previously reported study of the authors which were conducted with the same heat sink's geometry and boundary conditions. In order to obtain consistency, thermophysical properties for the numerical simulations were obtained from experimentally measured values, in which averaged properties were used to represent the composite materials.
A quantitative comparison between the numerical and experimental results is presented in Table 6. The quality of the agreement between test predictions from the CFD software and the experimental data was analyzed by simulation of the percentage error as defined earlier.

Table 6: Validation of CFD Results with Experimental Data

Velocity (m/s)	**Sample**	**Base Temp (Exp) (°C)**	**Base Temp (CFD) (°C)**	**Error (%)**	**h (Exp) (W/m²·C)**	**h (CFD) (W/m²·C)**	**Error (%)**	**R_{th} (Exp) (°C/W)**	**R_{th} (CFD) (°C/W)**	**Error (%)**
2	47% SiC	70	73.1	4.43	67.68	61.17	9.62	0.62	0.68	9.68
3	47% SiC	69	69.8	1.16	72.35	66.39	8.24	0.58	0.63	8.62
4	47% SiC	67	68.2	1.79	83.92	74.66	11.03	0.50	0.56	12
2	49% SiC	68	69.03	1.51	80.69	70.17	13.04	0.54	0.60	11.11
3	49% SiC	67	68.6	2.39	87.42	79.47	9.10	0.50	0.53	6
4	49% SiC	64	66.2	3.44	104.90	93.66	10.71	0.42	0.45	7.14
2	51% SiC	65	68.7	5.69	91.22	79.77	12.54	0.46	0.53	15.22
3	51% SiC	63	65.4	3.81	104.90	97.13	7.41	0.40	0.43	7.50
4	51% SiC	62	61.5	0.81	123.42	111.01	10.05	0.34	0.38	11.76

As it can be seen from Table 6, the base temperature predicted by CFD agrees to a good extent with the experimental values with deviation ranging from 0.81% to 5.69%. This suggests that the numerical model is a good representation of the overall thermal behaviour of the system.
For the heat transfer coefficient, the deviation is between 7.41% and 13.04%. The CFD values are always slightly less than experimental values, which could be explained by the

simplifications used in the modelling of turbulence, treatment of the near-wall regions, and the assumptions for ideal boundary conditions.

Similarly thermal resistance deviation is in the range of 6.00% to 15.22%. The greater deviation between thermal resistance is related to its sensitivity to both the temperature difference and the heat transfer rate which amplifies small discrepancies in measurement and modelling.

Overall, the difference between predictions by the CFD and experimental results stays within an acceptable range of ± 15%, which is typical for the convective heat transfer studies. Therefore, the numerical model is regarded as validated and reliable for the future analyses and parametric studies.

VI. CONCLUSION

This paper conducted an overall computational and experimental analysis of the thermal performance of Al6063-SiC composite plate-fin heat sinks under forced convection conditions. A successful validated three-dimensional CFD model was developed and successfully compared with experimental data to an acceptable level of agreement (±15%).

The results clearly indicate that not only the airflow velocity, but also the SiC reinforcement has a great influence on the thermal performance. The heat transfer is increased by a substantial reduction in base temperature and thermal resistance when the inlet air velocity is increased from 2 m/s to 4 m/s, i.e., convective heat transfer is increased. This improvement is mostly explained by the higher intensity of turbulence and decreased thickness of the thermal boundary layer.

Furthermore, the results are improved, even with a low bulk thermal conductivity, by a higher SiC content from 47 wt.% to 51 wt.% in heat dissipation performance. The 51 wt.% SiC composites showed the best performance in terms of their highest convective heat transfer ability in the measurement (111.01 $W/m^{2o}C$) and lowest thermal resistance of 0.38 $^oC/W$. This behaviour is important to put in perspective the significance of heat spreading mechanisms and interfacial heat transfer processes in composite materials.

Flow analysis showed that there are localised recirculation zones which contributes to increased mixing and improved convective heat transfer. However, an enhancement in the airflow velocity also leads to an enhancement in pressure drop, meaning that a trade-off exists between the thermal performance and the pumping power requirements.

Overall, the validated CFD model is a reliable tool in predicting the performance of heat sinks, and it can be successfully used for design optimization. The results of this study have shown that Al6063 composites reinforced with a high SiC content are good candidates for high-power electronic application in high-power systems in advanced thermal management technologies.

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