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Numerical and Experimental Study of Notched Aluminum V-Fin Arrays under Different Inclinations and Heat Input Conditions

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ABSTRACT

Efficient thermal management is essential for reducing overheating and improving the performance of engineering systems. This study investigates the natural convection heat transfer performance of cast aluminium V-shaped fin arrays with different notch configurations and inclination angles using experimental and computational fluid dynamics (CFD) approaches. Fin arrays with 0, 10, 20, and 30 mm notch sizes were evaluated at 0°, 30°, 60°, and 90° inclinations under different heat input conditions. The CFD analysis was used to examine temperature distribution, velocity contours, velocity vectors, and streamlines around the fin array. The results show that inclination angle and notch size significantly influence thermal performance. The 20 mm notch at 60° inclination provided the optimum CFD performance, achieving a maximum heat transfer coefficient of 12.24 W/m²K and a Nusselt number of 177.57. The combined experimental and CFD investigation demonstrates the potential of optimized V-shaped fin arrays for enhanced natural convection cooling applications.

Keywords: V-shaped fins; Natural convection; Aluminium; Notch size; Inclination angle; CFD; Heat transfer; Nusselt number.

1. INTRODUCTION

Heat generation is a common problem in industrial products and systems, leading to reduced performance and efficiency (Hashnayne and Podder, 2024). Excessive overheating may even result in system failure; therefore, effective heat dissipation techniques are required (Alfellag et al., 2024). Heat transfer can be achieved through convection, which may be either forced or natural. Among these, natural convection is widely preferred because it is economical, simple, and does not require external power for fluid circulation (Ghandouri et al., 2020). However, the effectiveness of finned systems depends on proper selection of fin geometry, orientation, number, and material (Ghazarian et al., 2024).

Fins are extensively used in heating and cooling applications because they increase the surface area available for heat transfer between a solid surface and the surrounding fluid (Huang et al., 2015). However, excessive fin density can restrict airflow and increase flow resistance, resulting in a reduction in heat transfer performance (Jeong et al., 2024). Therefore, an optimum fin arrangement is necessary to achieve effective thermal performance while minimizing additional weight and volume. Natural convection heat transfer is driven by buoyancy forces, which enhance fluid motion and improve heat exchange around heated surfaces (Raheem et al., 2024).Among various fin geometries, rectangular fins are the most commonly used, while triangular, diamond, and V-shaped fins have also been investigated for thermal enhancement (Rahmani et al., 2014). Lee et al. (2022) performed a CFD analysis of V-shaped fin configurations with different notch geometries and reported that the introduction of notches enhanced vortex

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formation and improved convective cooling performance. Their numerical results showed good agreement with experimental temperature distributions.

Rahman et al. (2024) conducted a comparative experimental and numerical investigation on inclined V-fin heat sinks for passive cooling applications. Their study demonstrated that fin inclinations between 45° and 60° provided improved buoyancy-driven airflow and enhanced thermal performance. The CFD simulations accurately predicted temperature contours and flow behaviour around the fins. Chen et al. (2026) developed an experimental-CFD model to analyse natural convection heat transfer in aluminium cast fin arrays under different heat input conditions. Their results indicated that increasing power input and optimizing fin spacing significantly improved heat dissipation. The numerical predictions showed less than 5% deviation from experimental measurements, confirming the reliability of CFD for thermal analysis. Among various fin configurations, V-shaped fin arrays have been recognized as an effective geometry for improving heat transfer performance. Fin arrays can be manufactured through machining, welding, bonding, and casting processes using materials such as cast iron, aluminium, and aluminium alloys (Taamneh et al., 2018).

In the present study, V-shaped fin arrays were fabricated from aluminium LM-16 using the sand-casting process. Aluminium LM-16 was selected because of its good thermal conductivity, castability, and widespread availability. The objective of this work is to investigate natural convection heat transfer from V-shaped fin arrays with and without notches. The thermal performance of these configurations is evaluated at different inclination angles and compared through experimental investigation and CFD analysis (Tijent et al., 2024).

2. Experimental Methodilogy And Apparatus

The study was conducted to investigate natural convection heat transfer from aluminum LM16 V-shaped fin arrays with different notch sizes (0 mm, 10 mm, 20 mm, and 30 mm) under various inclination angles. The fin arrays were heated electrically and tested at heat inputs of 75 W, 100 W, 125 W, and 150 W. Temperature measurements were recorded after achieving steady-state conditions. The average base temperature and ambient temperature were used to calculate the heat transfer coefficient and Nusselt number. Experimental results were subsequently validated using CFD simulations.

The experimental setup consisted of:

Aluminum LM16 V-shaped fin array mounted on an adjustable inclination frame.

- Base plate dimensions: 400 mm × 200 mm.
- Fin height: 20 mm.
- Fin thickness: 5 mm.
- Uniform fin spacing: 20 mm.
- Embedded electrical resistance heater for heat generation.
- Type-K thermocouples (±0.5°C accuracy) for temperature measurement.
- Data acquisition system operating at 1 Hz sampling frequency.
- Precision power supply (±1% accuracy) for maintaining constant heat input levels.
- Ambient thermocouple positioned 0.5 m away from the fin array.

2.1 Meshing

The CFD model was developed in ANSYS Fluent. The computational domain was created around the fin array to simulate natural convection airflow. An unstructured mesh was generated using a combination of tetrahedral and hexahedral elements. Inflation layers were applied near the fin and base surfaces to capture thermal and velocity boundary layers accurately.Mesh quality was maintained to ensure accurate numerical results.

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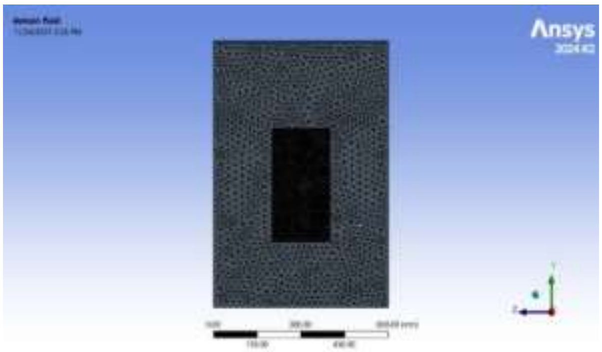

Figure 2.1 Domain Enclosure

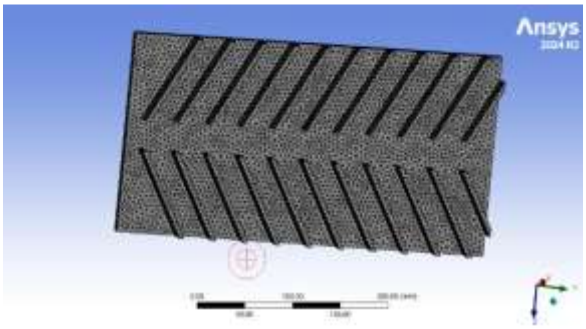

Figure 2.2 Meshing of Fin

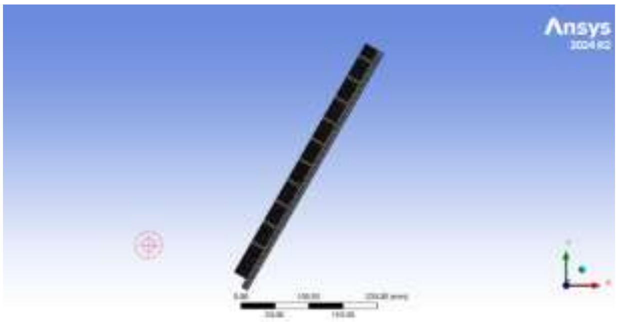

Figure 2.3 Meshing of Fins (Cross sectional view)

Mesh Details

Types of Mesh	Unstructured Mesh
Nodes	132111
Element	668683
Element Size	10 mm
Growth Rate	1.2

Table 1 Meshing Details

Experimental Procedure

For each power level and notch configuration, the following procedure was implemented:

- Power level set to desired value and maintained for ≥45 minutes
- Temperature readings recorded continuously after 30-minute stabilization
- Mean base plate temperature calculated as average of three measurement points
- Ambient temperature recorded as reference
- Heat transfer coefficient calculated using:

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$$h = Q / (A \cdot \Delta T) \quad (1)$$

Where, Q = Heat input (W), A = Fin surface area (m²), $\Delta T = T_{mean} - T_{ambient}$ (K)

• The characteristic fin surface area was calculated based on geometric measurements of the fin assembly. Mean temperature (Tmean) was computed as:

$$T_{mean} = (T_{base} + T_{ambient}) / 2 \quad (2)$$

3. EXPERIMENTAL DESCRIPTION

The Computational Fluid Dynamics (CFD) analysis was carried out to investigate the thermal performance of an aluminium V-shaped fin array under natural convection conditions. The study focused on evaluating the effect of different notch sizes and inclination angles on the heat transfer coefficient and Nusselt number.Four fin configurations were considered:Fin array without notch,10 mm notch,20 mm notch and 30 mm notch with the fin arrays were analyzed at four different inclination angles: 0°, 30°, 60° and 90° The CFD simulations were performed using air as the cooling medium under steady-state natural convection conditions. The thermal performance was evaluated using the following parameters: Heat transfer coefficient (h) and Nusselt number (Nu).The obtained CFD results are graphically represented in the plots of: Heat Transfer Coefficient vs Inclination Angle and Nusselt Number vs Inclination Angle

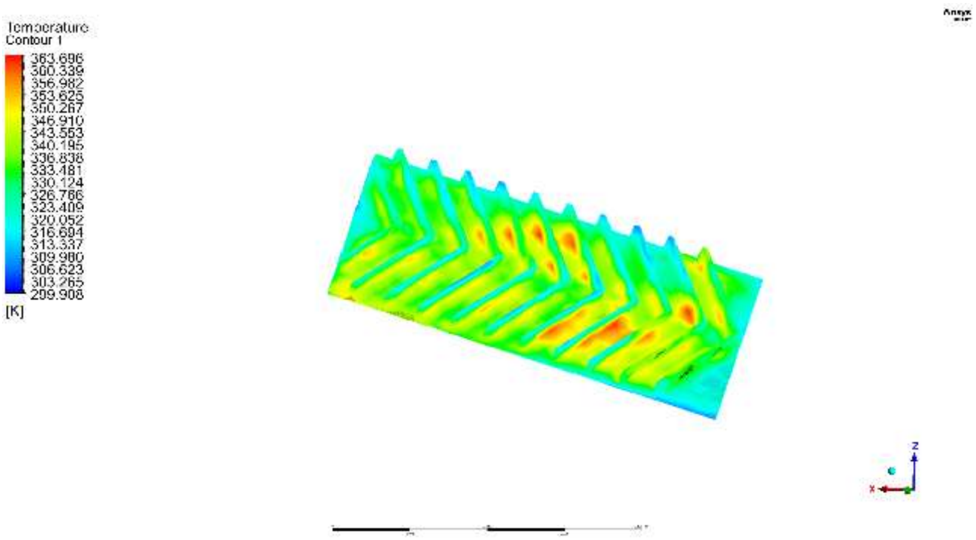

Figure 3.1 Temperature contour

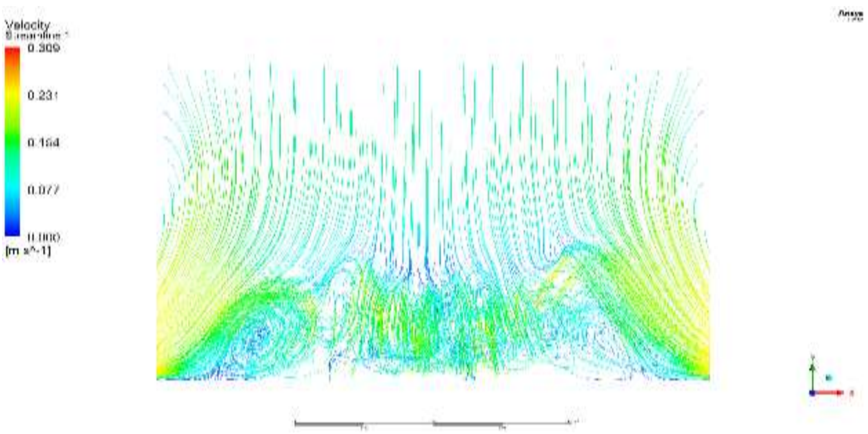

Figure 3.2 Streamline Velocity

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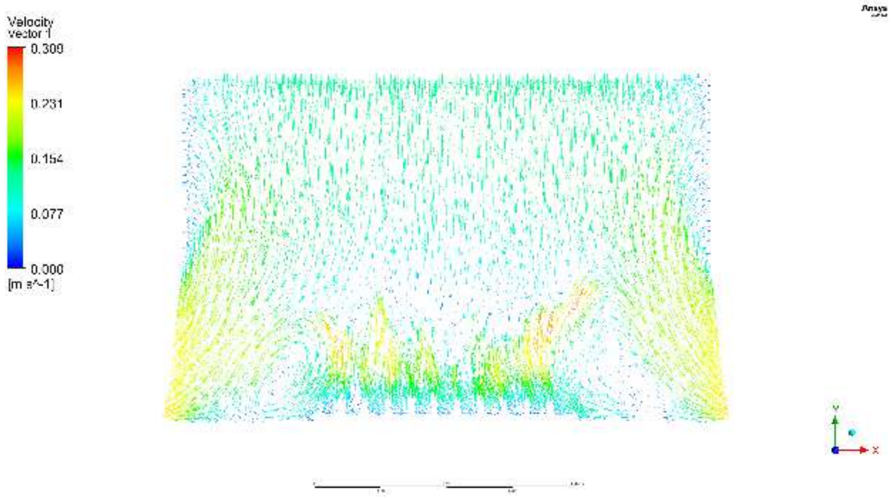

Figure 3.3 Vector Velocity

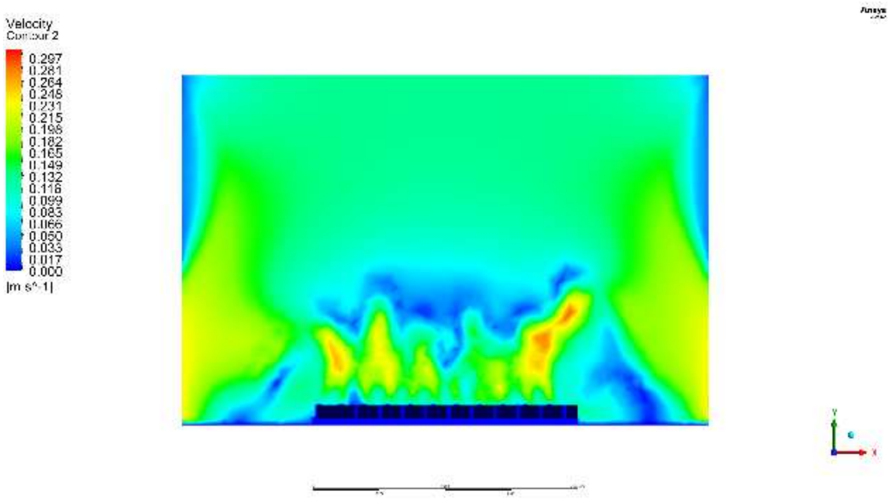

Figure 3.4 Velocity

3.1 Configuration without Notch

The V-shaped fin array without notch was used as the base configuration for comparison. Since there were no openings in the fins, airflow circulation was limited, resulting in lower natural convection heat transfer. The thermal boundary layer developed continuously over the fin surfaces, reducing cooling effectiveness. This configuration showed the lowest heat transfer coefficient and Nusselt number among all cases.

3.2 Configuration with 10 mm Notch

In this configuration, a 10 mm notch was introduced in the fins to improve airflow movement. The notch allowed heated air to escape more effectively and promoted entry of cooler air into the fin channels. As a result, natural convection heat transfer improved compared to the no-notch configuration. Moderate enhancement in heat transfer coefficient and Nusselt number was observed.

3.3 Configuration with 20 mm Notch

The 20 mm notch configuration provided larger airflow passages inside the fin array. This improved air circulation and reduced the thermal boundary layer thickness more effectively than the 10 mm notch. Enhanced mixing of air increased the heat dissipation rate from the fin surfaces. Consequently, higher heat transfer coefficient and Nusselt number values were obtained.

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3.4 Configuration with 20 mm Notch

The 30 mm notch configuration provided the largest airflow passage within the fin array, resulting in strong air circulation and enhanced natural convection. The larger notch improved the removal of heated air and promoted better mixing of cooler air around the fins. However, further increase in notch size also removed more fin material, which reduced the effective heat transfer surface area. Due to the reduction in fin surface available for conduction and convection, the rate of heat transfer through the fin tends to decrease beyond an optimum notch i e 30 mm size**.**

3.5 Comparative Analysis

A comparative summary of thermal performance across all three configurations is presented The lack of significant variation suggests that the notch geometries tested in this study do not produce the anticipated boundary layer disruption effects in natural convection environments. This contrasts with some computational predictions suggesting enhancement potential for interrupted fin geometries. Possible explanations for the null effect include:

- The notch dimensions may require larger relative proportions (ratio to fin height or spacing) to induce measurable effects
- Alternative fin inclination angles (0°, 30°, 90°) or fin materials may produce different results
- Higher power levels beyond 150 W may reveal geometric effects not apparent in the current range

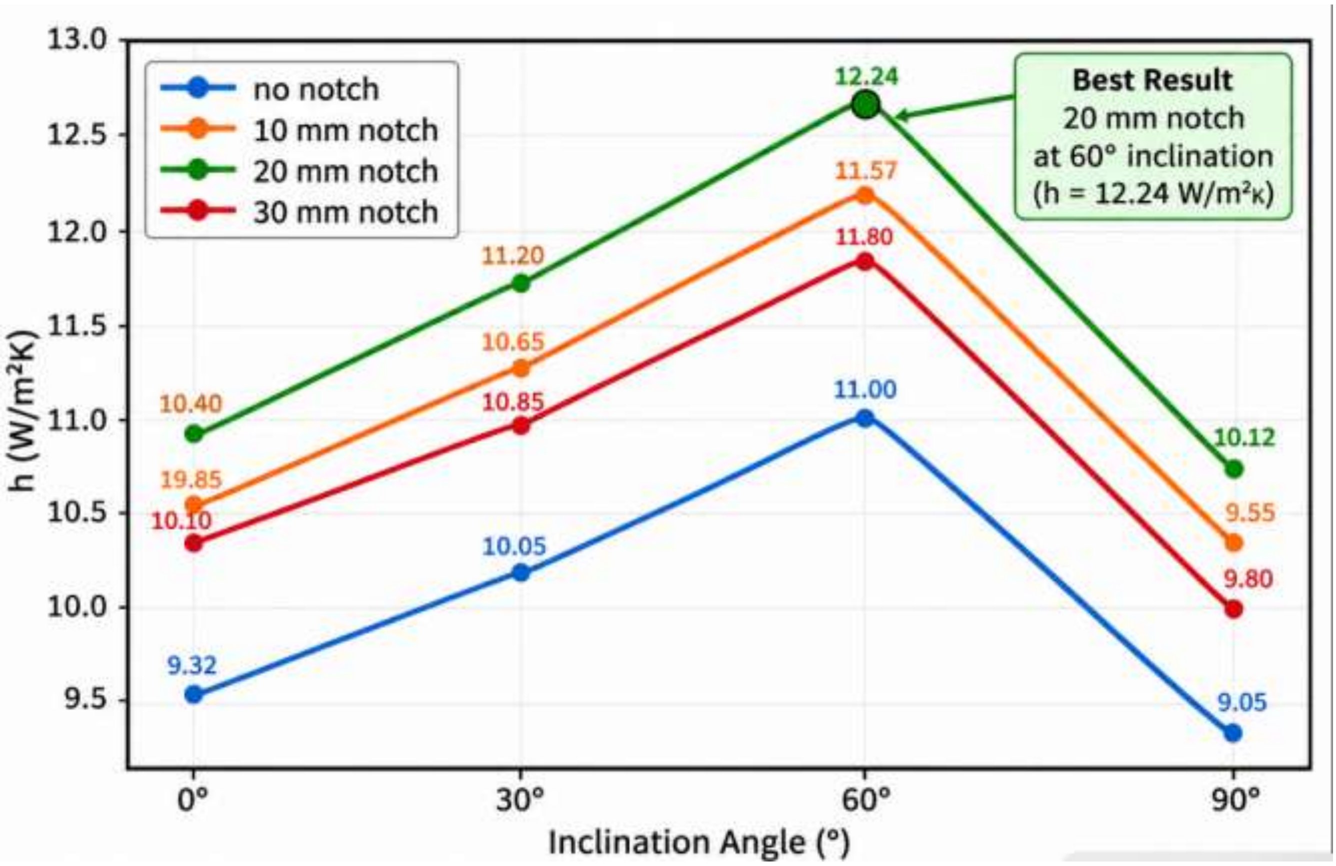

Figure 3.5 Heat Transfer Coefficient vs Inclination Angle

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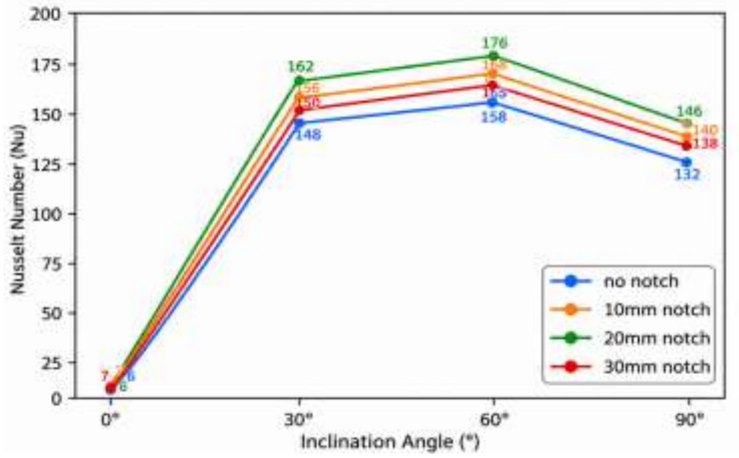

Figure 3.6 Nusselt Number vs Inclination Angle

The table shows that the different notch size and for inclinations the heat transfer coefficient and the Nusselt number is mentioned.

Notch Size	Inclination Angle	h (W/m²K)	Nusselt Number (Nu)
no notch	0°	9.32	6
no notch	30°	10.05	148
no notch	60°	11.00	158
no notch	90°	9.05	132
10mm notch	0°	10.85	7
10mm notch	30°	11.05	156
10mm notch	60°	12.05	168
10mm notch	90°	10.75	140
20mm notch	0°	11.10	8
20mm notch	30°	11.70	162
20mm notch	60°	12.12	176
20mm notch	90°	10.06	146
30mm notch	0°	10.10	7
30mm notch	30°	10.85	150
30mm notch	60°	11.80	165
30mm notch	90°	9.80	138

Table 2 Comparative thermal performance summary for the notch and Inclinations.

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4. RESULTS AND DISCUSSION

The thermal performance of the aluminium LM16 V-shaped fin arrays was evaluated using both experimental measurements and CFD simulations for different notch sizes (0, 10, 20, and 30 mm) and inclination angles (0°, 30°, 60°, and 90°). The performance was assessed in terms of heat transfer coefficient (h) and Nusselt number (Nu). The CFD analysis further provided temperature contours, velocity contours, velocity vectors, and streamline patterns to understand the airflow behaviour around the fin arrays.

4.1 Temperature and Flow Characteristics

The temperature contours indicate that the highest temperatures occurred near the heated base plate, while lower temperatures were observed away from the fin surfaces. The streamline and velocity vector plots show the formation of buoyancy-driven airflow around the fins. As the notch size increased from 0 mm to 20 mm, improved airflow circulation was observed due to the easier passage of heated air through the fin channels. The 20 mm notch configuration exhibited stronger air circulation and thinner thermal boundary layers, resulting in enhanced heat dissipation.

For the 30 mm notch configuration, airflow circulation further increased; however, excessive removal of fin material reduced the effective heat transfer area. Consequently, the improvement in heat transfer performance was lower than that achieved with the 20 mm notch configuration.

4.2 Effect of Inclination Angle on Heat Transfer Coefficient

The variation of heat transfer coefficient with inclination angle is shown in Figure 3.5. For all fin configurations, the heat transfer coefficient increased as the inclination angle changed from 0° to 60°. This behaviour is attributed to improved buoyancy-driven airflow and more effective removal of heated air from the fin passages.

The fin array without a notch exhibited the lowest performance, with the heat transfer coefficient increasing from 9.32 W/m^2K at 0° to 11.00 W/m^2K at 60°. The introduction of notches enhanced thermal performance by promoting airflow through the fin channels. The 10 mm notch achieved a maximum heat transfer coefficient of 12.05 W/m^2K at 60°, while the 20 mm notch produced the highest value of 12.12 W/m^2K at the same inclination angle. Beyond 60°, the heat transfer coefficient decreased for all configurations because the airflow pattern became less effective for natural convection heat transfer.

4.3 Effect of Inclination Angle on Nusselt Number

The Nusselt number followed a trend similar to that of the heat transfer coefficient. At 0° inclination, all configurations exhibited relatively low Nusselt numbers. As the inclination angle increased to 60°, a significant improvement in convective heat transfer was observed. The highest Nusselt number of 176 was obtained for the 20 mm notch configuration at 60° inclination, whereas the no-notch configuration reached only 158 under the same condition.

The enhancement achieved by the 20 mm notch can be attributed to the optimum balance between increased airflow circulation and sufficient fin surface area. Although the 30 mm notch improved airflow movement, the reduction in heat transfer area limited its overall effectiveness, resulting in a lower Nusselt number of 165 at 60°.

4.4 Comparative Performance Analysis

A comparison of all configurations shows that notch geometry and inclination angle significantly influence natural convection heat transfer. The 20 mm notch consistently outperformed the other configurations due to improved airflow distribution and enhanced mixing of ambient air within the fin passages. The optimum operating condition was observed at 60° inclination, where both the heat transfer coefficient and Nusselt number reached their maximum values. The CFD results were consistent with the observed experimental trends, demonstrating the capability of numerical analysis to predict thermal behaviour in notched V-shaped fin arrays.

5. CONCLUSION

The present study investigated the natural convection heat transfer performance of sand-cast aluminium LM16 V-shaped fin arrays with different notch sizes and inclination angles using experimental and CFD approaches. The results demonstrated that both notch geometry and fin inclination significantly affect thermal performance. For all configurations, the heat transfer coefficient and Nusselt number increased as the inclination angle increased from 0° to 60°, indicating improved buoyancy-driven airflow and enhanced heat dissipation. The introduction of notches promoted better air circulation within the fin passages, resulting in higher convective heat transfer compared with the fin array without a notch.

Among the configurations studied, the 20 mm notch exhibited the best overall thermal performance, achieving a maximum heat transfer coefficient of 12.12 W/m²K and a Nusselt number of 176 at 60° inclination. Although the 30 mm notch enhanced airflow movement, the reduction in effective heat transfer area limited its performance improvement. The CFD temperature contours, streamlines, velocity vectors, and velocity contours supported the experimental observations by illustrating the enhanced airflow and heat transfer mechanisms associated with the optimized notch configuration. The findings indicate that a 20 mm notch combined with a 60° inclination provides an optimum design for improving natural convection cooling in V-shaped fin arrays.

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Reviewer 1 Comments (Original)	Author Responses
1. The authors should strengthen the manuscript by clearly defining the research gap and explaining what is novel about the particular combination of V-fin geometry, notch size, inclination angle, and heat input investigated.	The previous experiments were conducted by many reseachers like Rectangular, triangular, perforated fins, pin fin, trapezoidal fins etc. The novelty of the present work lies in the combined experimental and CFD investigation of cast aluminium LM16 V-fin arrays incorporating different notch sizes and inclination angles under multiple heat input conditions.
2. The experimental methodology should provide sufficient details to ensure reproducibility, including specimen dimensions,fin spacing	Material- Alluminum alloy LM16,Base Plate Length- 400mm, Base Plate Width-200mm, Base Plate Thickness-10mm, Fin Height-20mm, Fin Thickness-5mm,Fin Spacing-20mm.
3. Heating method, thermocouple locations, ambient conditions,	The thermofoil heater present with K-type thermocouples were mounted uniformly on the base plate surface to measure the average base temperature. One thermocouple was positioned in the ambient environment at a distance of 0.5 m from the fin array to avoid thermal interference.
4. Measurement uncertainty, and calculation procedures for heat transfer coefficient and Nusselt number.	Overall uncertainty in heat transfer coefficient and Nusselt number was estimated using the Kline and McClintock method and was found to be approximately ±5%. Thermocouple ±0.5°C, Voltmeter ±0.5 V Ammeter ±0.01 A Power Supply ±1%
5. For the CFD component, the authors should report mesh independence, governing equations, boundary conditions, convergence criteria, solver settings, and the assumptions used in the simulation.	The Governing Equations used were Continuity Equation, Momentum Equation and Energy Equation The CFD assumptions were Steady state , Laminar flow, Incompressible air ,Boussinesq approximation ,Constant properties except density
6. The authors should also provide a systematic comparison among the four notch sizes and four inclination angles	Why 20 mm is Optimum Small notch (10 mm) → limited airflow

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and explain the physical mechanisms responsible for the observed optimum at 20 mm and 60°.	improvement. Medium notch (20 mm) → optimum balance between: o airflow enhancement o thermal boundary layer disruption o retained fin surface area. Large notch (30 mm) → excessive material removal reduces heat transfer area. Why 60° is Optimum Explain: Better alignment with buoyancy flow. Reduced stagnant zones. Stronger chimney effect. Maximum fresh air entrainment. Improved boundary-layer thinning.
7. A baseline comparison with an un-notched V-fin or another conventional fin geometry would further demonstrate the actual enhancement achieved by the proposed design.	The optimum 20 mm notch at 60° increased the heat transfer coefficient by approximately 10.2% compared with the un-notched V-fin configuration.
8. The manuscript should also be carefully proofread to improve English grammar, technical terminology, citation formatting, and overall presentation.	Done