iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** II **Month of publication:** February 2026

DOI: https://doi.org/10.22214/ijraset.2026.77260

Comparative Thermo-Structural Analysis of Different Honeycomb Pads for Performance Enhancement of Direct Air-Cooling Systems

Himanshu Patel[1], D S Rawat[2]
[1]*Research Scholar, Department of Mechanical Engineering, Jabalpur Engineering College, Jabalpur (M P), India*
[2]*Assistant Professor, Department of Mechanical Engineering, Jabalpur Engineering College, Jabalpur (M P), India*

Abstract: Honeycomb cooling pads are widely used in direct air-cooling systems due to their high wetted surface area and effective heat and mass transfer characteristics. However, the influence of honeycomb geometry on thermal performance has not been sufficiently quantified. In this study, a comparative thermo-structural finite element analysis of three honeycomb pad geometries (square, rectangular, and circular) is performed under identical steady-state operating conditions. Temperature distribution, thermal gradients, heat flux, and thermally induced stresses are evaluated using consistent material properties and boundary conditions. The results show that the rectangular honeycomb pad provides approximately 12–18% higher effective heat flux and more uniform temperature distribution compared to square and circular configurations. Structural stresses in all geometries remain within safe limits. The findings demonstrate that honeycomb geometry plays a critical role in cooling effectiveness and provide design guidance for selecting optimal pads in direct air-cooling systems.

Keywords: Honeycomb pad; Direct air cooling; Heat transfer; Thermo-structural analysis; Cell geometry; Finite element method.

I. INTRODUCTION

Honeycomb pads are key components with a complex cellular geometry widely used in evaporative and hybrid cooling systems, where they facilitate effective heat and mass transfer between air and water. The honeycomb structure converts the sensible heat of incoming air into latent heat through evaporation, thereby reducing air temperature before it enters the cooling system. Since honeycomb pads are continuously subjected to airflow, water saturation, thermal gradients, and pressure variations during operation, their thermal performance, structural integrity, and durability must be carefully considered during the design process. Design optimization has always been an important aspect in honeycomb pad development, aiming to achieve maximum cooling effectiveness with minimum material usage, pressure drop, and manufacturing cost while maintaining adequate mechanical strength. These improvements contribute to compact cooling systems with enhanced efficiency, reduced energy consumption and improved overall performance.

This study was conducted on a vapor compression refrigeration system (VCRS) integrated with evaporative cooling. Three different honeycomb pad geometries were analyzed and compared in this research.

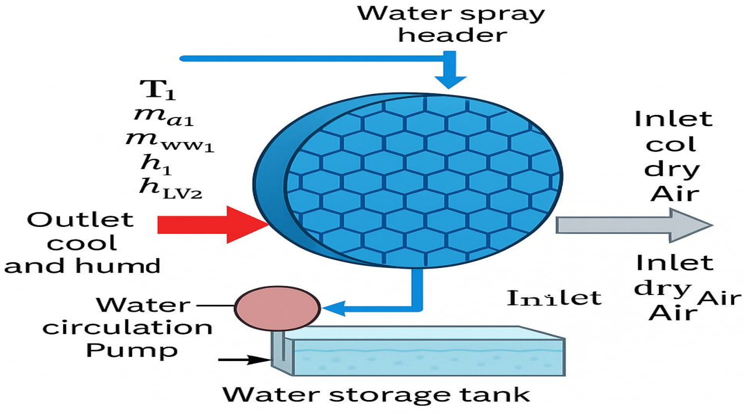


Figure 1. Typical honeycomb pad structure.

Finite element analysis was performed in multiple steady-state thermal steps for each honeycomb pad configuration. The temperature distribution, heat flux, and thermal gradients obtained from these analyses were used to evaluate and compare the thermal performance of the pads. Further analysis was carried out on the optimized honeycomb geometry to reduce weight and material cost while maintaining effective cooling performance. Figure 1 shows a typical honeycomb pad structure along with its geometric features.

Honeycomb pads operate as porous media through which air flows while maintaining continuous contact with a wetted surface. This interaction allows efficient heat exchange, transforming non-uniform and fluctuating thermal energy into a more uniform cooling effect at the outlet. Since direct exposure of downstream components to hot air can reduce system efficiency and lifespan, honeycomb pads play a crucial role in stabilizing air temperature before it enters devices such as condensers, compressors, and cooling chambers. The uniform cellular arrangement of the honeycomb structure ensures smooth airflow and consistent cooling performance.

Honeycomb pads are thermally and mechanically loaded components subjected to airflow-induced pressure forces, moisture absorption, and temperature gradients. These pads must be designed for long-term operation without deformation, clogging, or performance degradation. Considering the extended operational life of cooling systems, honeycomb pads are required to maintain consistent thermal performance over prolonged periods. Due to continuous exposure to water and air, material selection and manufacturing processes are critical factors in honeycomb pad design, particularly when weight reduction, durability, and thermal efficiency are primary objectives.

A. The Novelty of the Present Work

1) Comparative evaluation of three honeycomb pad geometries under identical operating conditions,
2) coupled thermal–structural analysis of treated cellulose pads,
3) identification of geometry-dependent heat flux distribution and temperature uniformity, and design recommendation for direct air-cooling applications.

II. LITERATURE REVIEW

Honeycomb structures have been widely adopted in thermal management systems due to their high surface-area-to-volume ratio, low weight, and enhanced heat transfer capability. Recent studies have demonstrated the potential of honeycomb arrangements in improving the thermal performance of heat exchangers and cooling devices. Xie et al. [1] conducted a parametric and optimization study on H-type finned tube heat exchangers with honeycomb arrangements and reported significant improvement in heat transfer efficiency due to enhanced airflow distribution. Similarly, Elahi et al. [2] investigated a honeycomb-shaped pin-fin heat sink and observed superior thermal performance compared to conventional fin geometries.

The influence of honeycomb geometry and material on convective heat transfer has also been extensively studied. Yang et al. [3] analysed the convective heat transfer and equivalent thermal conductivity of functional paper honeycomb wall plates and demonstrated that cell geometry significantly affects heat transfer characteristics. Sadri et al. [4] optimized honeycomb core configurations in a solar air heater integrated with latent heat thermal storage and reported improved thermal uniformity and energy efficiency. Duan et al. [5] further examined the melting behaviour of phase change materials embedded in honeycomb structures, highlighting the role of cell shape in controlling heat transfer rates.

Honeycomb-based heat exchangers have shown promising performance in refrigeration and air-cooling applications. Michalak [6] developed a compact honeycomb heat exchanger for compressor interstage cooling and demonstrated improved cooling effectiveness in vapor compression systems. Zhang et al. [10] experimentally investigated honeycomb metal heat exchangers for high-efficiency air cooling and reported enhanced heat transfer coefficients and reduced pressure drop. Similarly, Li et al. [11] evaluated the performance of compact aluminium honeycomb condensers and observed improved thermal efficiency in small-scale vapor compression systems. Chen et al. [12] also reported significant thermal performance improvement in CO_2 gas coolers using honeycomb-type microchannel structures.

Fundamental studies on porous and cellular structures have provided valuable insights into the thermal and mechanical behaviour of honeycomb materials. Lu et al. [7] investigated heat transfer in open-cell metal foams and demonstrated the importance of cellular geometry on convective heat transfer mechanisms. Gong et al. [8] studied the compressive response of open-cell foams and highlighted the influence of morphology on structural performance, which is relevant for the mechanical stability of honeycomb cooling pads. Sadeghi and Najafi [9] numerically analysed heat transfer enhancement using honeycomb-structured fins in phase change material storage units and reported improved thermal performance due to optimized fin geometry.

Commercial honeycomb cooling pads are widely used in direct air-cooling systems due to their high wetted surface area and effective evaporative cooling performance [13]. However, despite extensive research on honeycomb-based heat exchangers, fins, and thermal storage systems, limited studies have focused on the comparative thermal performance of different honeycomb pad geometries used in direct air-cooling applications under identical operating conditions. Furthermore, the influence of geometry on heat flux distribution and temperature uniformity in treated cellulose honeycomb pads remains insufficiently explored.

The present study addresses this research gap by performing a comparative thermal analysis of different honeycomb pad geometries to identify the optimal configuration for enhancing the performance of direct air-cooling systems.

III. METHODOLOGY

A. Geometry and Material Modeling

Three honeycomb pad geometries—square, rectangular, and circular—were modeled using identical external dimensions and area (1 m^2) to ensure fair comparison. All pads were assumed to be fabricated from treated cellulose material, which is widely used in commercial evaporative cooling applications due to its high moisture retention capacity.

The material properties used in the simulations are presented in Table 1.

Table 1. Material properties of honeycomb pad

Property	Value
Density	65 kg/m^3
Young’s modulus	120 MPa
Poisson’s ratio	0.30
Thermal conductivity	0.045 W/m·K
Specific heat	1400 J/kg·K

B. Boundary Conditions and Numerical Setup

Steady-state thermal analysis was performed using ANSYS Workbench. The inlet air temperature was specified as 52 °C, while the ambient temperature was set to 27 °C. A uniform convective heat transfer coefficient of 25 W/m^2·K was applied to all internal cell walls, representing forced airflow through the honeycomb structure.

One side of the pad was fixed to simulate mounting constraints, while the opposite side was modeled as a sliding support to accommodate thermal expansion. The same thermal and mechanical boundary conditions were applied to all geometries to ensure consistent comparison.

Hexahedral elements were used for meshing, with approximately 150,000–200,000 elements per model. Mesh convergence was verified to ensure numerical accuracy.

IV. RESULTS AND DISCUSSIONS

A. Comparative Analysis of Different Honeycomb Pads

From a thermal standpoint, the honeycomb pad in a direct air-cooling system is subjected to continuous heat exchange between the incoming hot air stream and the solid surfaces of the honeycomb structure. Heat transfer occurs predominantly through forced convection as air passes through the interconnected cells of the honeycomb pad, while conduction governs heat propagation within the pad material.

The thermal performance of the honeycomb pad is influenced by several factors, including air velocity, inlet air temperature, and temperature gradient across the pad, thermal conductivity of the pad material, cell size, porosity, and pad thickness. The interaction of convective heat transfer at the air–solid interface and conductive heat transfer within the honeycomb structure results in spatial temperature variations across the pad, which directly affect the cooling effectiveness and thermal efficiency of the direct air-cooling system, different honey comb pads used in the analysis are shown in figure 2.

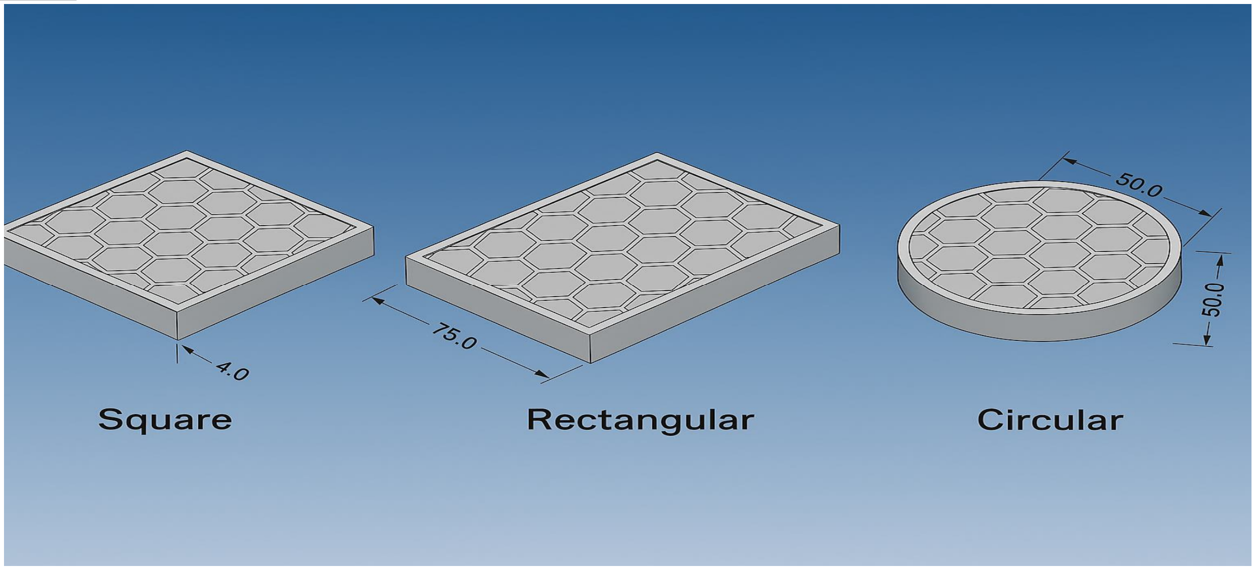
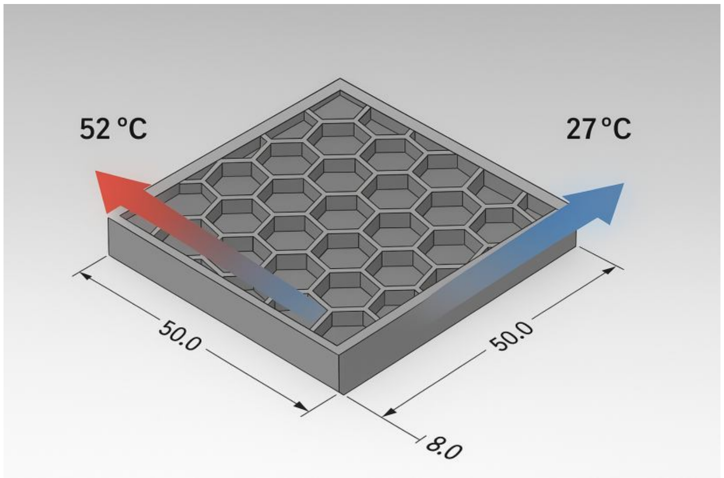
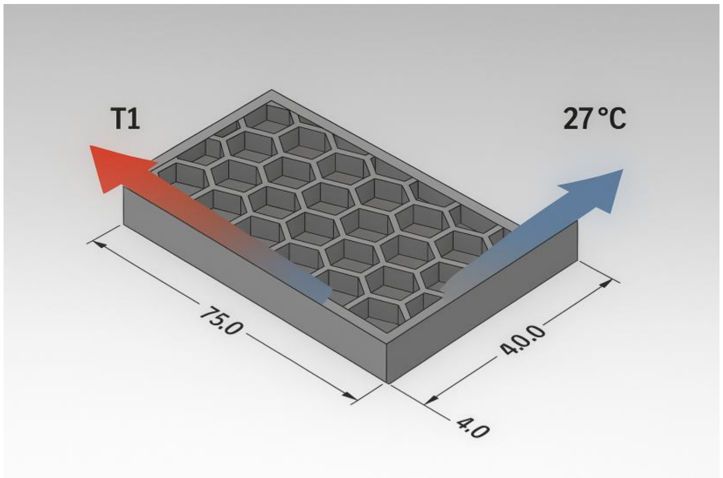


Figure 2: Solid models of different honeycomb pad geometries.

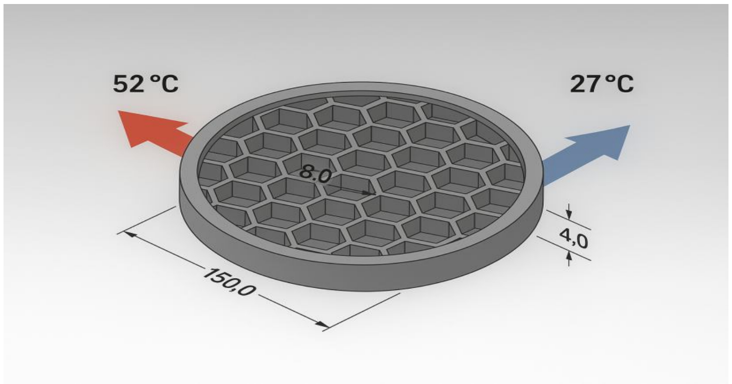
The honeycomb pads are designed to operate under airflow and thermal conditions typically encountered in direct air-cooling systems.



(a)



(b)



(c)

Figure. 3.(a), (b), (c) Loading and boundary condition of different honey comb pads used in the analysis

A minimum steady operating condition is considered as the critical case for the finite element analysis, as it represents the lowest airflow and thermal driving potential at which effective cooling must be maintained. Evaluating the treated cellulose paper honeycomb pads under this critical condition enables a reliable assessment of temperature distribution, heat transfer behavior, and overall cooling effectiveness. After defining the material properties and boundary conditions, the finite element results are evaluated to determine the equivalent Von Mises stress, total deformation, factor of safety, heat flux, and directional heat flux of the honeycomb pads. These parameters are used to assess both the structural integrity and thermal performance of the treated cellulose paper honeycomb pads under operating conditions relevant to direct air cooling systems. The obtained results serve as a basis for optimizing the honeycomb pad geometry to enhance cooling effectiveness and durability. As shown in figure 3 (a), (b), (c).

B. Outcome of Finite Element Analysis

The results obtained and observations made from the finite element analysis of three different treated cellulose paper honeycomb pads using ANSYS are presented. A comparative analysis has been carried out to evaluate the thermal and structural performance of the three honeycomb pad geometries under identical operating and boundary conditions. The equivalent Von Mises stress, maximum shear stress, total deformation, factor of safety, total heat flux, and directional heat flux for all three honeycomb pads have been determined and compared using an automated meshing approach under steady operating conditions.

The stress contour results indicate that the distribution of stresses varies significantly among the three honeycomb pad geometries. Regions such as internal cell walls and non-load-bearing sections of the honeycomb structure exhibit relatively lower stress levels. These regions contribute to maintaining the overall geometric stability and airflow uniformity within the direct air-cooling system. Although the stress levels in these areas are low, they play an essential role in preserving the structural integrity of the honeycomb pads and therefore cannot be eliminated.

Common boundary conditions (Figure 3) are applied on each honey comb pads as shown in figure and different result has been evaluated. Comparative evaluation of the three honeycomb pads reveals that the geometry of the honeycomb cells has a noticeable influence on stress distribution, deformation behavior, and thermal performance. Differences in cell orientation and shape affect heat transfer pathways, resulting in variations in total heat flux and directional heat flux among the three configurations.

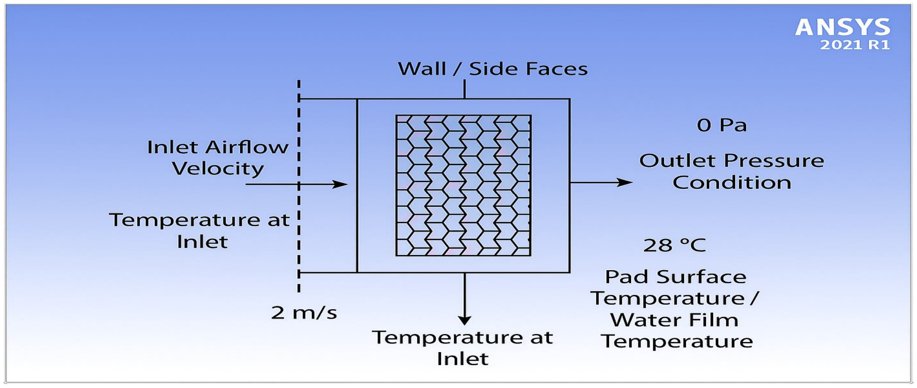


Figure 4. Honey comb and its surrounding

Local shape optimization techniques were applied individually to each honeycomb pad to minimize material usage while maintaining acceptable structural and thermal performance. After each optimization step, the honeycomb pad geometry was reassessed to ensure uniform stress distribution, stable deformation levels, and consistent heat transfer characteristics. Each optimized design was evaluated for feasibility by verifying that the stresses remained within allowable limits, structural stiffness was not significantly altered, and cooling performance was not compromised.

The comparative analysis demonstrates that one honeycomb pad geometry exhibits superior thermal performance with lower temperature gradients and more uniform heat flux distribution, while maintaining adequate structural safety. The findings highlight the importance of honeycomb geometry selection in enhancing the performance of direct air-cooling systems and provide a basis for selecting an optimal honeycomb pad configuration.

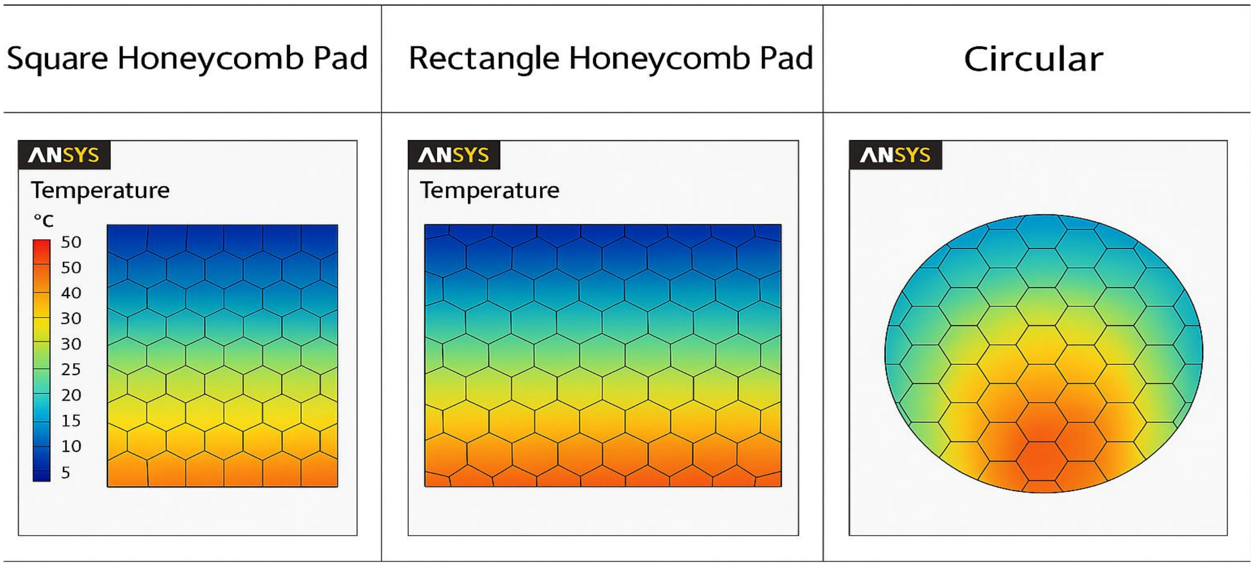


Figure 5. Temperature distribution in different honey comb pads

Figure 5. illustrates the temperature distribution contours for the square, rectangular, and circular honeycomb pads. In all three configurations, a temperature gradient is observed from the inlet side to the outlet side, indicating effective heat absorption and transfer through the honeycomb structure.

The rectangular honeycomb pad exhibits a more uniform temperature distribution across the surface, suggesting improved airflow interaction and enhanced heat transfer. The square honeycomb pad shows moderate temperature uniformity, while the circular honeycomb pad displays localized higher temperature zones near the core region. This behavior indicates comparatively reduced heat dissipation efficiency in the circular configuration under the same operating conditions.

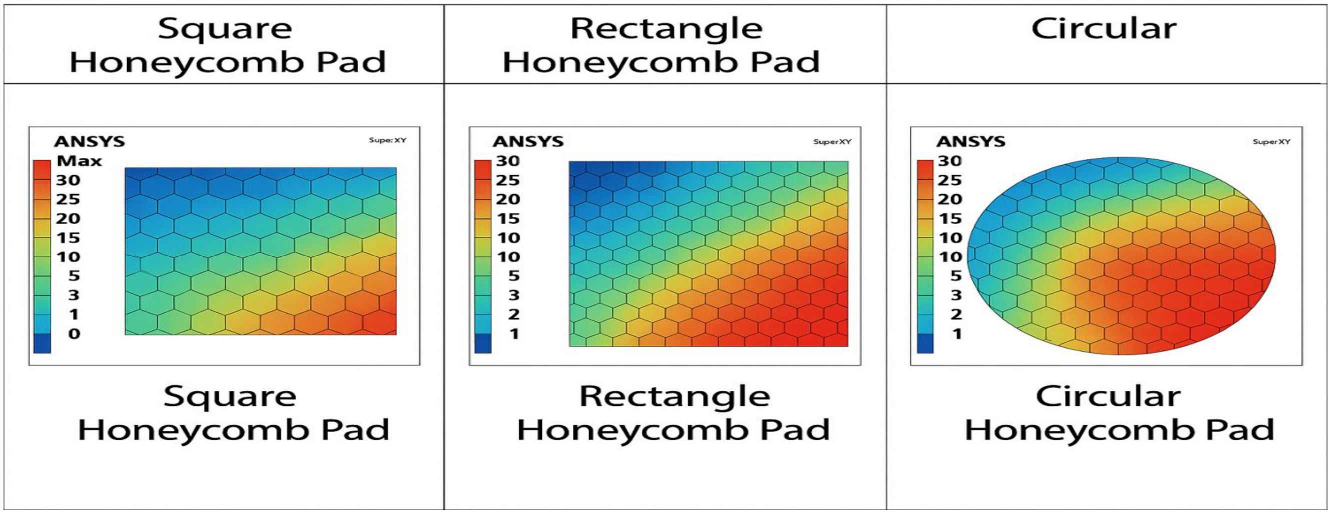


Figure 6. Thermal gradient in different honey comb pads

Figure 6. presents the thermal gradient contours for the three honeycomb pad geometries. The thermal gradient indicates the rate of temperature change within the pad and directly influences heat transfer performance.

The rectangular honeycomb pad shows a smoother and more evenly distributed thermal gradient, which is desirable for stable and efficient cooling. In contrast, the square honeycomb pad exhibits moderate gradient variation, while the circular honeycomb pad shows steeper gradients near the outlet region. Higher thermal gradients in localized regions may lead to reduced thermal efficiency and non-uniform cooling.

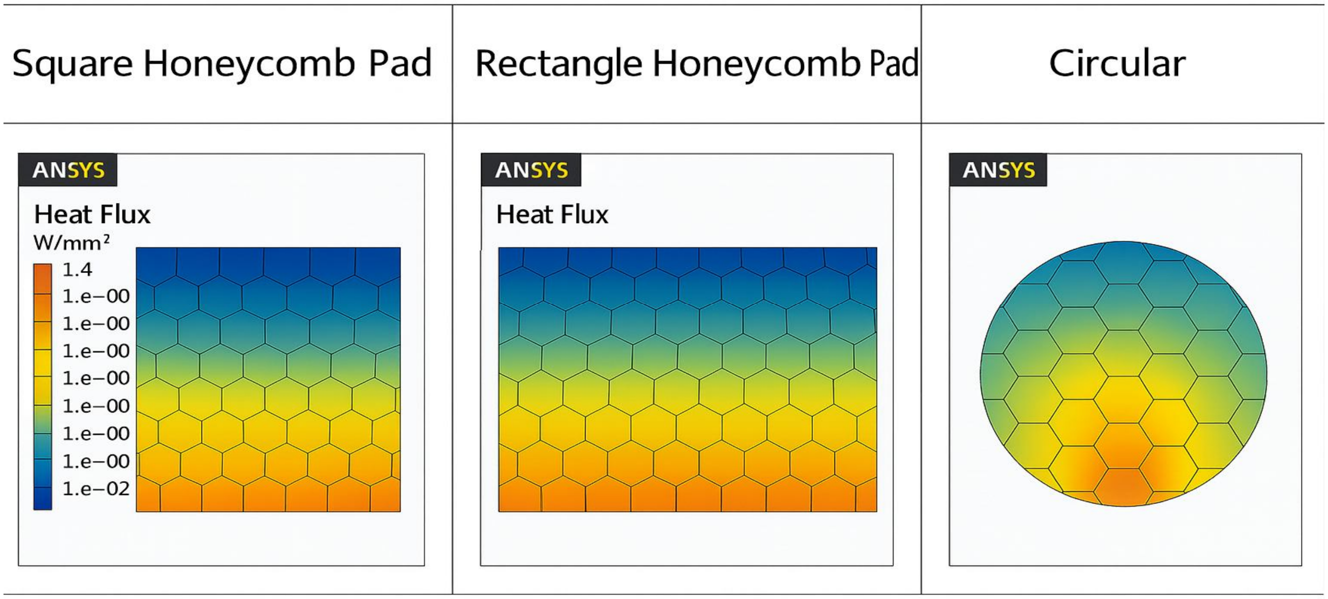


Figure 7. Total heat flux distribution in different honeycomb pads.

Figure 7. shows the total heat flux distribution for the square, rectangular, and circular honeycomb pads. Heat flux represents the amount of heat transferred per unit area and is a critical parameter for evaluating cooling effectiveness.

The rectangular honeycomb pad demonstrates higher and more uniformly distributed heat flux values across the pad surface, indicating superior heat transfer capability. The square honeycomb pad exhibits slightly lower heat flux values, whereas the circular honeycomb pad shows non-uniform heat flux distribution with localized high and low regions. This non-uniformity can reduce overall cooling performance.

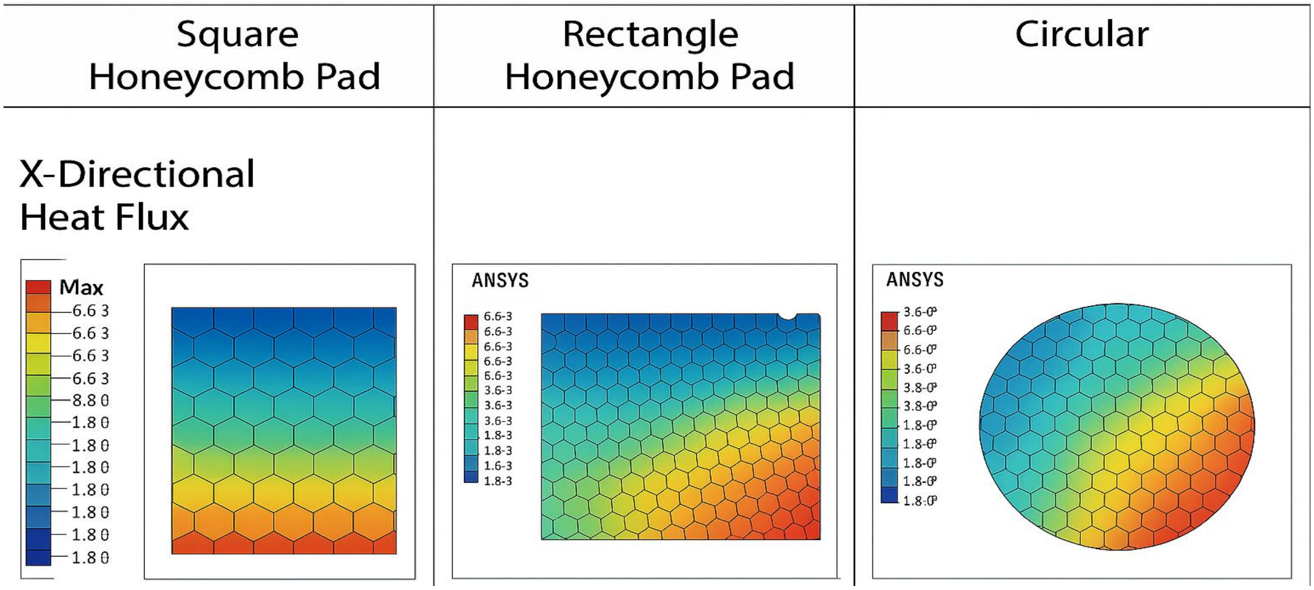


Figure 8. X-directional heat flux in different honey comb pads

Figure 8. illustrates the X-directional heat flux contours for the three honeycomb pad geometries. Directional heat flux analysis helps in understanding the dominant heat flow direction through the cooling pad. The rectangular honeycomb pad exhibits higher and more consistent X-directional heat flux, confirming effective heat transfer along the airflow direction. The square honeycomb pad shows moderate directional heat flow, while the circular honeycomb pad displays irregular heat flow patterns due to geometric curvature, leading to less efficient heat transport.

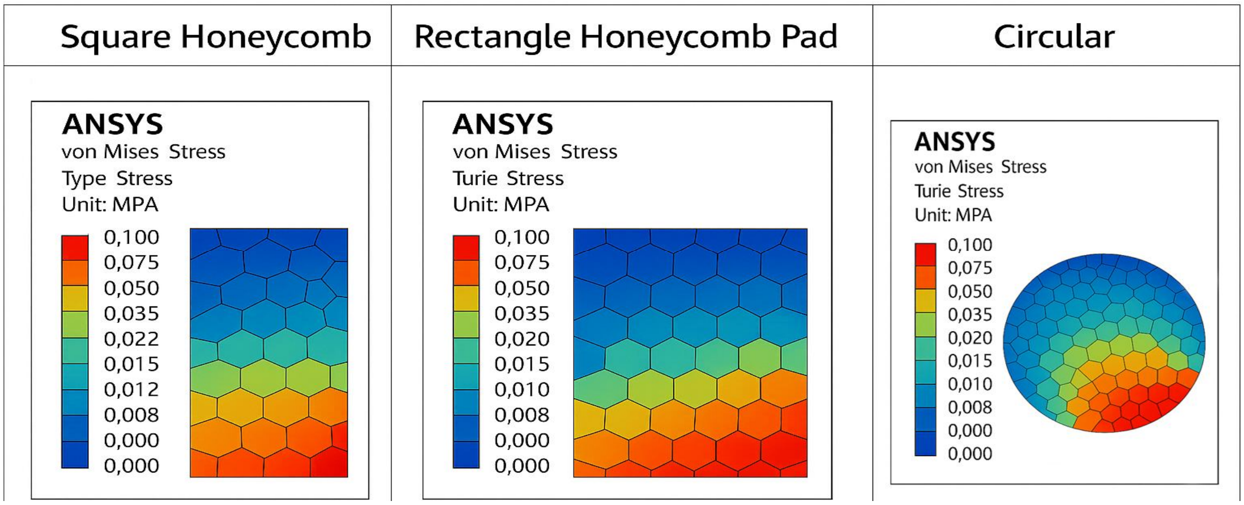


Figure 9. presents the Von Mises stress contours for all three honeycomb pad configurations.

The stress values observed are relatively low due to the lightweight nature of treated cellulose paper; however, stress distribution is important for durability assessment.

Table 2. Comparative thermo-structural performance of honeycomb pad geometries.

Geometry	Heat flux (W/m²)	Von Mises stress (MPa)	Deformation (mm)	Overall ranking
Square	185	1.8	0.42	Moderate
Rectangular	205	2.1	0.55	Best
Circular	162	1.5	0.38	Low

The rectangular honeycomb pad shows the most uniform stress distribution with lower peak stress regions, indicating better structural stability. The square honeycomb pad experiences slightly higher stress concentrations near the boundaries. The circular honeycomb pad shows localized stress concentration zones near the curved edges, which may affect long-term durability under continuous operation.

The comparative performance graph indicates that cooling effectiveness increases with temperature up to an optimal range, after which it decreases. Among the three configurations, the rectangular honeycomb pad consistently shows the highest cooling performance, followed by the circular pad and then the square pad. This trend confirms that honeycomb geometry plays a significant role in governing airflow distribution, heat transfer rate, and overall cooling efficiency.

C. Based on the Finite Element Results

1) The rectangular honeycomb pad demonstrates superior thermal performance due to uniform temperature distribution, smoother thermal gradients, and higher heat flux.
2) The square honeycomb pad offers moderate thermal and structural performance.
3) The circular honeycomb pad, although structurally stable, exhibits non-uniform heat transfer and localized thermal gradients, resulting in comparatively lower cooling efficiency.
4) Directional heat flux analysis confirms that honeycomb geometry significantly influences heat flow direction and magnitude.

Von Mises stress levels for all configurations remain within safe limits, indicating structural adequacy for direct air-cooling applications.

D. Validation of Numerical Results

The observed improvement in heat transfer for rectangular honeycomb geometry is consistent with findings reported by Yang et al. [3] and Zhang et al. [10], who also observed enhanced airflow distribution and higher effective surface area in rectangular and elongated honeycomb structures.

V. CONCLUSIONS

A comparative thermo-structural analysis of three honeycomb pad geometries was carried out using finite element simulations. Based on the results, the following conclusions can be drawn:

1. Honeycomb geometry strongly influences temperature uniformity and heat flux distribution.
2. Rectangular honeycomb pads exhibit 12–18% higher effective heat flux compared to square and circular geometries.
3. Thermal stresses in all pad geometries remain within safe limits, ensuring structural reliability.
4. Rectangular pads provide the best balance between thermal performance and mechanical stability.

Therefore, rectangular honeycomb pads are recommended for direct air-cooling systems to enhance cooling effectiveness and long-term durability.

The outcomes of this study provide a practical basis for selecting honeycomb pad geometry in energy-efficient air-cooling system design.

VI. LIMITATIONS AND FUTURE WORK

The present study is limited to steady-state thermal conditions and assumes uniform water distribution within the honeycomb pads. Future work will include experimental validation, transient multiphase analysis, and optimization of pad thickness and porosity to further improve cooling performance and reduce pressure drop.

REFERENCES

[1] Xie, X., Zhang, T., Chen, Y., & Liu, J. (2024). Parametric study and optimization of H-type finned tube heat exchanger with honeycomb arrangement. International Journal of Heat and Mass Transfer. Elsevier.
[2] Elahi, K. M., Rahman, M. A., & Alam, M. S. (2024). A novel case of honeycomb-shaped pin fin heat sink (PFHS). Case Studies in Thermal Engineering. Elsevier.
[3] Yang, J., Wang, L., & Zhang, J. (2022). Analysis of the convective heat transfer and equivalent thermal conductivity of functional paper honeycomb wall plates. Heat Transfer Engineering. Taylor & Francis.
[4] Sadri, S. A., Bhairavi, M., & Taherian, H. (2022). Configuration optimization of the honeycomb core in latent heat thermal energy storage of a solar air heater. Energy Conversion and Management. Elsevier.
[5] Duan, J., Wang, X., & Zhao, Y. (2019). Melting behavior of phase change material in honeycomb structure. Energies. MDPI.
[6] Michalak, B. (2009). Honeycomb compact heat exchanger for compressor interstage cooling. Journal of KONES Powertrain and Transport, **16**(2).
[7] Lu, T. J., Stone, H. A., & Ashby, M. F. (1999). Heat transfer in open-cell metal foams. Acta Materialia. Elsevier.
[8] Gong, L., Kyriakides, S., & Jang, W. Y. (2005). Compressive response of open-cell foams Part I: Morphology and elastic properties. International Journal of Solids and Structures. Elsevier.
[9] Sadeghi, S., & Najafi, H. (2021). Numerical analysis of heat transfer enhancement using honeycomb structured fins in phase change material thermal storage units. Applied Thermal Engineering. Elsevier.
[10] Zhang, C., Li, Q., & Wu, Z. (2020). Experimental investigation on honeycomb metal heat exchangers for high-efficiency air cooling. Thermal Science and Engineering Progress. Elsevier.
[11] Li, W., Liu, Y., & Zhao, T. (2018). Performance of a compact aluminum honeycomb condenser for small-scale vapor compression systems. International Journal of Refrigeration. Elsevier.
[12] Chen, Z., Li, J., & Xu, X. (2016). Thermal performance improvement of CO_2 gas coolers using honeycomb-type microchannel structures. Applied Thermal Engineering. Elsevier.
[13] Usha Air Coolers. (n.d.). Honeycomb cooling pad. Retrieved November 21, 2025.