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“THERMAL PERFORMANCE ENHANCEMENT OF FINNED ENGINE CYLINDER BLOCKS: A REVIEW OF FIN GEOMETRY, ALTERNATIVE MATERIALS, AND NUMERICAL DESIGN OPTIMIZATION”

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ABSTRACT

Effective thermal management of the engine cylinder block is essential for maintaining engine performance, fuel efficiency, lubricant stability, and component durability, particularly in air-cooled engines where heat is rejected directly to the surrounding air through extended surfaces known as fins. The thermal performance of a finned cylinder block depends on fin geometry, thickness, spacing, perforation or slot arrangement, material properties, airflow conditions, and the operating temperature of the engine. This review paper presents an assessment of recent research on finned engine cylinders and cylinder blocks, with particular emphasis on fin geometry modification, alternative fin and block materials, and numerical design optimization using finite element analysis (FEA) and computational fluid dynamics (CFD). Studies on rectangular, circular, triangular, tapered, slotted, and perforated fins are examined together with comparisons of aluminium alloys, grey cast iron, and other candidate materials. The review also considers thermal-structural analysis for the evaluation of thermal stresses, the use of multi-objective and heuristic optimization techniques, and the importance of mesh independence and experimental validation in establishing the reliability of numerical predictions. The reviewed literature indicates that high-conductivity materials and carefully modified fin geometries can improve heat dissipation and temperature uniformity, but that gains in heat flux are often accompanied by higher thermal gradients, thermal stresses, weight, or manufacturing complexity. Key research gaps are identified, including limited transient analysis, simplified boundary conditions, scarce experimental validation, and few studies of alternative materials under realistic engine duty cycles. The findings are intended to support the design of efficient, lightweight, and durable finned engine cylinder blocks.

Key Words: Engine cylinder block; cooling fins; thermal analysis; finite element analysis; aluminium alloy; grey cast iron; heat transfer enhancement; thermal stress; design optimization.

I. INTRODUCTION

The internal combustion (IC) engine converts the chemical energy of fuel into thermal energy and subsequently into mechanical work. Only a portion of the energy released during combustion is converted into useful work; the remainder is carried away by the exhaust gases, transferred to engine components, or removed by the cooling system. Components such as the cylinder block, cylinder head, and piston are therefore exposed simultaneously to high temperatures and high mechanical loads. If this heat is not removed effectively, it may cause thermal deformation, material degradation, lubricant breakdown, thermal stresses, cracking, and premature failure, and it can reduce engine efficiency and service life. Engine cooling is generally accomplished by liquid cooling or air cooling. Liquid-cooled systems circulate a coolant through passages in the engine and reject heat at a radiator, and they are widely used in passenger cars, heavy-duty vehicles, and high-power engines because they provide effective temperature control under varying loads. Air-

cooled systems transfer heat directly from the external engine surfaces to the surrounding air and are commonly used in motorcycles and other small engines because of their simple construction and lower maintenance requirements. In air-cooled engines, fins are provided on the external surface of the cylinder block to increase the effective area available for convective heat transfer.

The cylinder block is the main structural component of the engine. It houses the cylinders or cylinder liners, supports the cylinder head, crankcase, and crankshaft assembly, provides passages for lubrication and, depending on the design, for coolant, and maintains the alignment of moving components. During operation, heat generated by combustion flows through the cylinder walls into the block and must be dissipated to maintain the engine within its recommended temperature range. Cast iron and aluminium alloys are the two materials most commonly used for cylinder blocks. Cast iron offers good strength, wear resistance, and dimensional stability, but it has a relatively high density and a lower thermal conductivity. Aluminium alloys have a lower density and a considerably higher thermal conductivity, which favours weight reduction and heat dissipation, but they may have lower stiffness and wear resistance and may require liners or surface treatments. Alternative materials, such as magnesium alloys, may offer further benefits, although their strength, thermal expansion, durability, and manufacturing feasibility must be evaluated carefully. The thermal performance of the fins themselves depends on fin height, thickness, spacing, number, length, shape, and material. Increasing the number of fins increases the heat transfer area, but excessive fin density can restrict airflow and increase weight, cost, and manufacturing complexity. Very narrow spacing impedes air movement, whereas very wide spacing reduces the total available area. The selection of fin geometry and material must therefore be treated as an optimization problem rather than as a simple matter of increasing surface area.

Numerical methods have become the principal tool for evaluating the thermal behaviour of finned cylinder blocks. Three-dimensional models are developed in computer-aided design software such as SolidWorks, CATIA, or Creo and are analysed in finite element packages such as ANSYS to obtain temperature distribution, heat flux, thermal deformation, and thermal stress under steady-state or transient conditions. Where required, CFD is used to model the airflow around the fins and to obtain the convective heat transfer coefficient, which may then be applied as a boundary condition in the solid model or solved directly as a conjugate heat transfer problem. Compared with experimental investigation, numerical analysis allows many geometry and material combinations to be screened quickly and at low cost before prototypes are manufactured. However, the reliability of such predictions depends on the quality of the mesh, the realism of the boundary conditions, the accuracy of the material data, and validation against experimental measurements. Design optimization techniques, including parametric studies, design of experiments, orthogonal testing, direct optimization, and heuristic or data-driven methods, are increasingly combined with numerical simulation to identify fin configurations that balance heat dissipation, weight, strength, and cost. This paper reviews the research published between 2020 and 2026 on these topics and identifies the gaps that remain in the thermal design of finned engine cylinder blocks.

II. PROBLEM IDENTIFICATION

During engine operation the cylinder block is continuously exposed to high temperatures generated by fuel combustion. If the heat is not dissipated effectively, the mechanical properties, dimensional stability, performance, and service life of the block may be adversely affected. Fins increase the surface area available for heat transfer in air-cooled engines, but excessive increases in fin dimensions raise the weight, material consumption, manufacturing cost, and space requirement of the engine. Optimization of fin geometry is therefore necessary to achieve effective cooling with minimum material usage and cost. In addition, localized hot spots and steep temperature gradients within the block can produce thermal stresses and distortion, so the temperature uniformity of the block is as important as the total amount of heat removed.

The selection of fin and block material is a second major challenge. A material with high thermal conductivity may improve heat transfer, but its density, strength, wear resistance, durability, and cost must also be considered. Cast iron and aluminium alloys differ markedly in these respects, and their relative performance depends on fin geometry, operating temperature, and boundary conditions. Existing investigations employ different engines, alloys, fin shapes, fin thicknesses, temperatures, and performance indicators, which makes direct comparison between studies difficult and limits the transferability of their conclusions. Some investigations report only temperature distribution or total heat flux, while others also report directional heat flux, thermal stress, or deformation. A consistent evaluation that considers

heat dissipation, temperature uniformity, and thermal stress together is therefore required.

A further limitation of the existing literature is the reliance on simplified analysis. Many studies assume steady-state conditions, a constant bore or wall temperature, and a constant convective coefficient, and relatively few consider transient start-up and shutdown behaviour, the coupling between airflow and conduction, or the combined effect of thermal and mechanical loading. Mesh-independence studies and experimental validation are not always reported. Accordingly, a systematic review is needed to synthesize the available evidence on fin geometry, alternative materials, and numerical optimization, and to identify the research gaps that should guide future work on finned engine cylinder blocks.

III. RESEARCH OBJECTIVE

The main objective of this review paper is to critically examine recent research on the thermal performance of finned engine cylinder blocks, with emphasis on fin geometry, material selection, numerical analysis, and design optimization. The specific research objectives are as follows:

- To review fin geometries: Examine the influence of fin shape, thickness, spacing, perforations, slots, and tapering on heat dissipation and temperature distribution in finned engine cylinders.
- To evaluate material selection: Compare the thermal and mechanical characteristics of cast iron, aluminium alloys, and other candidate materials for cylinder blocks and cooling fins.
- To analyze heat transfer characteristics: Assess the effect of geometry, material, and operating conditions on temperature drop, total heat flux, directional heat flux, and fin effectiveness.
- To examine thermal stress and deformation: Review the use of thermal-structural analysis to evaluate thermal stresses and distortion caused by temperature gradients in the cylinder block.
- To compare numerical approaches: Evaluate the capabilities and limitations of FEA, CFD, and conjugate heat transfer modelling, together with analytical fin theory, for engine cooling applications.
- To review optimization strategies: Examine parametric, design-of-experiments, direct, multi-objective, heuristic, and data-driven methods used to improve fin design.
- To assess reliability and validation: Investigate the role of mesh-independence studies, boundary-condition realism, and experimental validation in establishing confidence in simulation results.
- To identify research gaps: Identify limitations in existing studies concerning transient behaviour, alternative materials, realistic operating conditions, and combined thermal-structural performance.

IV. LITERATURE REVIEW

Research on the cooling of engine cylinders has expanded considerably because of the demand for lightweight, efficient, and durable engines. The studies reviewed below were published between 2020 and 2026 and are presented in reverse chronological order. For each study the scope, method, and principal findings are summarized as reported by the authors, and its significance for the thermal design of finned cylinder blocks is highlighted. Where a study is described only in terms of its stated scope, no quantitative results are attributed to it.

Kumar and Talugeri (2026) [1] examined the thermal behaviour of engine cylinder fins by varying fin geometry and material. The study reflects the common approach of comparing candidate fin shapes and materials through numerical thermal analysis, and it reinforces the point that geometry and material must be considered together rather than independently when the objective is to improve heat dissipation.

Bakchi et al. (2025) [2] carried out a numerical investigation aimed at optimizing engine cooling by using different fin geometries and materials on an engine cylinder. The work illustrates the ability of numerical models to screen several geometry–material combinations before any physical prototype is manufactured, which is the central motivation for simulation-based cylinder design.

A study reported in Engineering Proceedings (2025) [3] addressed the design and analysis of engine fins with the aim of improving the heat transfer rate. It is representative of continuing efforts to modify conventional fin profiles so that heat dissipation can be increased without enlarging the overall dimensions of the cylinder.

A 2025 simulation study presented at AIMACE-2025 [4] compared aluminium 6061 alloy and grey cast iron for fins with fillet corners and drafted edges at thicknesses of 2.5 mm and 4 mm, using SolidWorks simulation under natural convection. The authors reported that grey cast iron showed enhanced thermal retention, whereas aluminium 6061 offered advantages in weight and manufacturability, and that drafted edges produced a more uniform heat distribution than fillet corners. The design was optimized by considering performance together with material cost. This study is directly relevant to the present review because it addresses the same two materials and highlights that the preferred material depends on the balance between thermal performance, weight, and cost.

Mehta and Sinha (2024) [5] investigated the thermal performance of IC engine cylinder fins with emphasis on the role of fin thickness and slot placement. Both parameters are inexpensive to modify in manufacturing, and the study therefore supports the use of parametric thickness and slot studies as a practical route to improved cooling.

Prakash and Sagar (2024) [6] presented the design and thermal analysis of modified engine cylinder fins using ANSYS. Their work is typical of the many studies in which a conventional fin is modified geometrically and the modified design is evaluated through steady-state thermal analysis of temperature and heat flux.

Korwar et al. (2024) [7] performed a thermal analysis of an engine cylinder with fins, and Kummarikuntla et al. (2024) [8] reported a computer-aided engineering (CAE) based thermal analysis of cylinder fins using various geometric profiles and materials. Together these studies confirm that CAD modelling combined with finite element thermal analysis has become a standard workflow for comparing fin profiles and materials.

Mishra et al. (2024) [9] presented a review of thermal analysis of engine cylinder fins for enhancing heat dissipation, and Borthakur and Borthakur (2024) [10] discussed the role of thermal analysis in engine fin design, offering insights and perspectives on its application. These overviews underline the importance of thermal analysis at the design stage, and they also indicate that the field is still dominated by steady-state studies of individual parameters.

Muthuram et al. (2024) [11] studied rectangular and cylindrical fins made of aluminium 1100 alloy. The models were created in PTC Creo Parametric, and steady-state thermal and modal analyses were carried out in ANSYS 2023 R1. The results showed that the slotted cylindrical fin design achieved the highest heat transfer rate compared with the conventional fin design. The study demonstrates that introducing slots to expand the effective surface area can enhance cooling, and that thermal analysis may be complemented by modal analysis to examine the structural consequences of modifying fins.

A 2024 study published in Processes [12] applied ANSYS finite element analysis together with a direct optimization (DO) approach to identify an optimal fin design for an engine cylinder. The analysis showed that fin length and width play critical roles in cooling efficiency, with the maximum cylinder temperature reduced to 549.46 K and the total heat flux increased to 7225.31 W/m², an improvement of 25.87% over the generic design. The authors noted that heat dissipation at the fin tips could still be improved, recommended a balanced fin dimension to limit material cost, and suggested that alternative materials, transient heating analysis, and experimental verification should be examined in the future. The study demonstrates the potential of formal optimization and clearly identifies the gaps that remain.

A 2024 study on aero-piston air-cooled engine cylinders [13] used an orthogonal test design for the multi-objective optimisation of heat transfer and structural strength. Because both thermal and structural objectives were considered

simultaneously, the work is relevant to cylinder block design, where improvements in cooling must not compromise the strength of the component.

Studies on pin-fin optimization and finned-tube heat exchangers (2024) [14], [15] further illustrate the methods available for optimizing extended surfaces. Optimization of pin fins using CFD and machine learning has been reported [14], and Farajollahi et al. (2024) [15] analysed tube arrangements of a finned-tube heat exchanger using an artificial neural network and response surface methodology. Although these studies do not concern engine cylinders directly, they show that response-surface and data-driven surrogate models can be transferred to the optimization of finned engine components.

Kumar et al. (2023) [16] conducted a three-dimensional computational investigation of thermal performance on an engine cylinder, examining the effect of different fin geometries. Three-dimensional modelling captures conduction in the cylinder wall and along the fin simultaneously, which is not possible with one-dimensional fin theory, and the study therefore supports the use of full three-dimensional models for geometry comparison.

Sachar et al. (2023) [17] reviewed heat transfer enhancement of air-cooled engine fins through geometrical and material analysis. Their review identifies geometry and material as the two principal levers for improving fin performance, which is consistent with the structure of the present review.

Subbiah et al. (2023) [18] analysed an engine cylinder block with fins by varying the material. This study is particularly relevant because it considers the block as a whole rather than the fin alone, so that material conduction through the block wall as well as along the fin influences the results.

Varghese et al. (2022) [19] proposed a heuristic technique for the multi-objective optimisation of engine cylinder fins, and Risal et al. (2022) [20] presented an integrated approach to the heat transfer analysis of engine fins. These studies indicate a gradual shift from single-parameter comparisons toward integrated and multi-objective treatments of fin design.

Sonawane et al. (2022) [21] performed numerical simulations to evaluate the thermal performance of engine cylinder fins, with the effects of fin geometry and fin material considered together. The study is another example of the combined geometry–material comparison that dominates the literature, and it supports the use of identical boundary conditions across all models so that differences can be attributed to design variables.

Shareef et al. (2021) [22] reported the design and thermal analysis of an engine cylinder fin body using various fin profiles, and Patil and Shetty (2021) [23] performed a thermal analysis of two-wheeler engine fins. Rupesh et al. (2021) [24] carried out a computational investigation of heat transfer on the surface of an engine cylinder with fins of different shapes and materials. Collectively, these studies show that two-wheeler and motorcycle cylinders are a frequently studied application of finned cylinder analysis.

Angamuthu et al. (2021) [25] conducted modelling and simulation studies of a 100 cc motorcycle engine cylinder with groove and perforated fin designs using different materials. Because grooves and perforations modify the effective surface area and the local flow and conduction paths of the fin, this study is relevant to the evaluation of fins with holes and cuts, which also introduce geometric discontinuities that can concentrate thermal stress.

Thiagarajan et al. (2020) [26] analysed heat transfer and optimization of an engine cylinder liner using different materials, showing that the influence of material selection extends beyond the fins to the liner and block interface. Gawande and Mahamandre (2020) [27] reviewed the design and thermal analysis of 250 cc engine cylinder fins made of different materials using ANSYS, again confirming the dominance of ANSYS-based comparisons in the literature.

Summary of the literature. Several consistent themes emerge from the reviewed studies. First, fin geometry and material are the two principal design variables, and most investigations compare shapes such as rectangular, circular, triangular, slotted, perforated, and drafted fins against a plain baseline using ANSYS or SolidWorks. Second,

aluminium alloys are generally favoured for their higher thermal conductivity, lower weight, and manufacturability, whereas grey cast iron retains heat longer and offers greater strength and wear resistance [4]. Third, modifications that increase the effective surface area, such as slots, have been reported to improve heat transfer rates [11], and grooves and perforations have also been examined [25], but such modifications alter the local temperature gradient and stress distribution, so that heat flux, temperature uniformity, and thermal stress should be assessed together. Fourth, formal optimization, whether based on direct optimization, orthogonal testing, heuristic algorithms, or response-surface and machine-learning models, is increasingly applied [12], [13], [19]. Finally, most studies remain limited to steady-state analysis with simplified boundary conditions, and experimental validation is not consistently reported [12].

V. CONCLUSION

This review examined recent research on the thermal performance of finned engine cylinder blocks, focusing on fin geometry, alternative materials, and numerical design optimization. The literature indicates that fin geometry, thickness, and material strongly influence heat dissipation and temperature distribution. Aluminium alloys are generally preferred where weight reduction and effective heat dissipation are required, while grey cast iron remains attractive for strength, wear resistance, and heat retention. Geometric modifications such as slots, perforations, tapering, and drafted edges can improve heat transfer, but they must be evaluated together with thermal stress, weight, and manufacturing feasibility. Finite element analysis and CFD provide detailed temperature, heat flux, and stress information and allow many designs to be screened economically, although reliable predictions require appropriate boundary conditions, mesh-independence verification, and validation against experimental data. Future research should focus on transient start-up and shutdown behaviour, coupled airflow and conduction modelling, thermal-structural evaluation, realistic engine duty cycles, and alternative lightweight materials, together with multi-objective optimization that balances heat dissipation, thermal stress, weight, and cost. Integrating these elements can support the development of efficient, lightweight, and durable finned engine cylinder blocks for automotive applications.

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