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“COMPARATIVE THERMAL ANALYSIS AND DESIGN OPTIMIZATION OF FINNED ENGINE CYLINDER BLOCKS USING ALUMINIUM ALLOY AND GREY CAST IRON”

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ABSTRACT

This study investigates the combined influence of fin geometry and material on the thermal performance of an air-cooled engine cylinder block. Six finned cylinder-block models, namely plain plate fins of 2, 3, and 4 mm thickness, fins with circular holes, fins with V-notch (tapered) cuts, and fins with rectangular cuts, were modelled in CAD and analysed in ANSYS for two materials, aluminium alloy and grey cast iron. A bore temperature of 600 °C and convective boundary conditions at the outer and fin surfaces were applied, and the temperature drop, total heat flux, directional heat flux, and equivalent thermal stress were evaluated for every model. The aluminium alloy models showed temperature drops of 21.37–37.92 °C compared with 65.78–110.02 °C for grey cast iron, which indicates a markedly more uniform temperature field, and their total heat flux was 8.9–16.5% higher than that of cast iron for every geometry. The peak thermal stress was 56.02 MPa for aluminium alloy and 123.77 MPa for grey cast iron, both occurring in the fins with circular holes. Fins with circular holes gave the highest heat flux (0.325 W/mm² for aluminium alloy), whereas fins with rectangular cuts gave the lowest thermal stress (18.47 MPa). Increasing the plain-fin thickness from 2 mm to 4 mm reduced the temperature drop and thermal stress by about 27–30% with only a small reduction in heat flux. The results show that aluminium alloy combined with perforated or cut fins offers the best balance between heat dissipation, temperature uniformity, and thermal stress, and they provide guidance for material and fin selection in air-cooled engine cylinder blocks.

Key Words: Finned engine cylinder block; thermal analysis; ANSYS; aluminium alloy; grey cast iron; fin geometry; heat flux; 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, but only a fraction of the energy released during combustion becomes useful work. The remainder is transferred to the engine components, carried away by the exhaust gases, or removed by the cooling system. The cylinder block, cylinder head, and piston are therefore subjected to high temperatures and mechanical loads, and inadequate heat removal can cause overheating, thermal deformation, lubricant degradation, increased wear, and thermal stresses that shorten engine life. In air-cooled engines, which are widely used in motorcycles and other small-engine applications, heat is transferred from the external surface of the cylinder block directly to the surrounding air, and fins are provided to increase the effective area available for convection. Liquid cooling is preferred in passenger cars, heavy-duty vehicles, and high-power engines, but finned air-cooled cylinders remain attractive where simple construction and low maintenance are priorities.

The cylinder block is the main structural component of the engine. It houses the cylinders, supports the cylinder head and crankshaft assembly, provides passages for lubrication, and must retain its shape and alignment under combined

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thermal and mechanical loading. Cast iron and aluminium alloys are the materials most commonly used. Cast iron offers good strength, wear resistance, and dimensional stability, but its density is high and its thermal conductivity is low. Aluminium alloys have a lower density and a considerably higher thermal conductivity, which favours both weight reduction and heat dissipation. The thermal performance of the fins also depends on their height, thickness, spacing, number, and shape. More fins or taller fins increase the heat transfer area but also increase weight, cost, and resistance to airflow, so these parameters must be optimized rather than simply increased.

A considerable body of work has examined the effect of fin geometry and material on cylinder cooling. Kumar and Talugeri [1] and Bakchi et al. [2] compared fin geometries and materials numerically, and a simulation study of aluminium 6061 alloy and grey cast iron fins reported that cast iron showed enhanced thermal retention while aluminium offered advantages in weight and manufacturability [3]. The influence of fin thickness and slot placement has been investigated [4], a slotted cylindrical fin was reported to achieve the highest heat transfer rate among the designs compared [5], and direct optimization of fin dimensions was found to improve the total heat flux of an engine cylinder by about 26% over a generic design [6]. Three-dimensional computational studies of fin geometry [7], block-level comparisons of materials [8], and combined geometry–material simulations [9] have also been reported, and perforated and grooved fins have been examined for motorcycle cylinders [10]. Reviews of the field identify geometry and material as the principal means of improving the performance of air-cooled engine fins [11]. However, most studies vary either geometry or material, report only temperature or heat flux, and seldom evaluate the thermal stress produced by the resulting temperature gradients. The present study therefore compares six fin configurations in two materials under identical conditions and reports temperature drop, total and directional heat flux, and thermal stress together, so that the trade-off between heat dissipation and thermal stress can be assessed.

II. PROBLEM IDENTIFICATION

During engine operation the cylinder block is continuously exposed to the heat of combustion, and effective dissipation of this heat is necessary to protect the mechanical properties, dimensional stability, and service life of the block. Fins increase the heat transfer area, but excessive fin dimensions increase material consumption, weight, manufacturing cost, and space requirement. Geometric modifications such as holes, notches, and cuts can enlarge the effective surface area and disturb the thermal boundary layer, but they also introduce geometric discontinuities that may concentrate heat flux and thermal stress. An increase in heat transfer is therefore not automatically an improvement in overall thermal performance.

The choice of material adds a second dimension to the problem. A high-conductivity material such as aluminium alloy can spread heat quickly and reduce temperature gradients, while grey cast iron offers strength and wear resistance but conducts heat poorly. The relative merit of the two materials depends on the fin geometry and operating conditions. The problem addressed in this study is to determine how fin geometry and material jointly affect the temperature distribution, heat flux, and thermal stress of a finned engine cylinder block, and to identify the combination that dissipates heat effectively while keeping temperature gradients and thermal stresses within acceptable limits.

III. RESEARCH OBJECTIVE

The main objectives of the present study are as follows:

- To develop three-dimensional models of a finned engine cylinder block with plain, perforated, V-notch, and rectangular-cut fins, and with plain fins of different thicknesses.
- To evaluate the temperature distribution and temperature drop of each model for aluminium alloy and grey cast iron under identical boundary conditions using ANSYS.
- To determine the total heat flux and directional heat flux for each geometry and material combination.
- To evaluate the equivalent thermal stress developed in each model as a result of the temperature gradients.
- To examine the effect of fin thickness on temperature uniformity, heat flux, and thermal stress.

- To compare aluminium alloy and grey cast iron and to identify a suitable material and fin configuration for improved cooling of the engine cylinder block.

IV. MODELING AND SIMULATION

4.1 Finite element approach

Because closed-form solutions are not available for the complex geometry of a finned cylinder block, the finite element method (FEM) was used. In this method the solid domain is divided into small elements connected at nodes, the field variable (here temperature) is approximated within each element by interpolation functions, and the element equations are assembled into a global matrix equation that is solved for the nodal values. The analysis was carried out in the ANSYS Workbench environment in two stages. First, a steady-state thermal analysis was performed to obtain the temperature distribution and heat flux. Second, the resulting temperature field was used as the thermal load in a structural analysis to obtain the equivalent (von Mises) thermal stress. For steady-state conduction in the solid with constant properties, the governing equation and the convective boundary condition on the outer and fin surfaces are:

$$\nabla \cdot (k \nabla T) = 0 \quad (1)$$

$$-k (\partial T / \partial n) = h (T_s - T_\infty) \quad (2)$$

where k is the thermal conductivity, T the temperature, h the convective heat transfer coefficient, T_s the surface temperature, and T_∞ the ambient air temperature. The heat dissipated by a surface of area A is $Q = h A (T_s - T_\infty)$. The temperature drop reported in this paper is defined as the difference between the imposed bore temperature (600 °C) and the minimum temperature in the model, so that a smaller temperature drop indicates a more uniform temperature field.

4.2 Boundary conditions

The same boundary conditions were applied to every model and to both materials so that differences in the results can be attributed to geometry and material alone. A temperature of 600 °C was imposed on the inner cylinder (bore) surface to represent the combustion-side thermal load. Convection to the ambient air at 22 °C, with a film coefficient of 1.24×10^{-6} W/mm²·°C, was applied to the outer surface and to all fin surfaces. The analysis was steady-state. Figure 5.2 shows the boundary conditions applied to the plain-fin model.

V. DESIGN OF FINNED ENGINE CYLINDER MODELS

The cylinder block with fins was modelled in SolidWorks and imported into ANSYS. The fin stack has a plan size of 165 mm × 120 mm with rounded corners. Six models were analysed, as listed in Table 5.1: plain plate fins of 2, 3, and 4 mm thickness, and three modified-fin models with circular holes, V-shaped (tapered) notches, and rectangular notches, which were compared against the plain 2 mm model as the baseline. Figure 5.1 shows the plan and isometric views of the plain, circular-hole, V-notch, and rectangular-cut fin models.

Table 5.1: Finned engine cylinder block models analysed

Model	Fin configuration	Purpose
M1	Plain plate fins, 2 mm	Baseline model
M2	Plain plate fins, 3 mm	Effect of fin thickness
M3	Plain plate fins, 4 mm	Effect of fin thickness
M4	Fins with circular holes	Increased surface area and flow disturbance

M5	Fins with V-notch (tapered) cuts	Increased perimeter and exposed edge area
M6	Fins with rectangular cuts	Increased perimeter with square-edged cuts

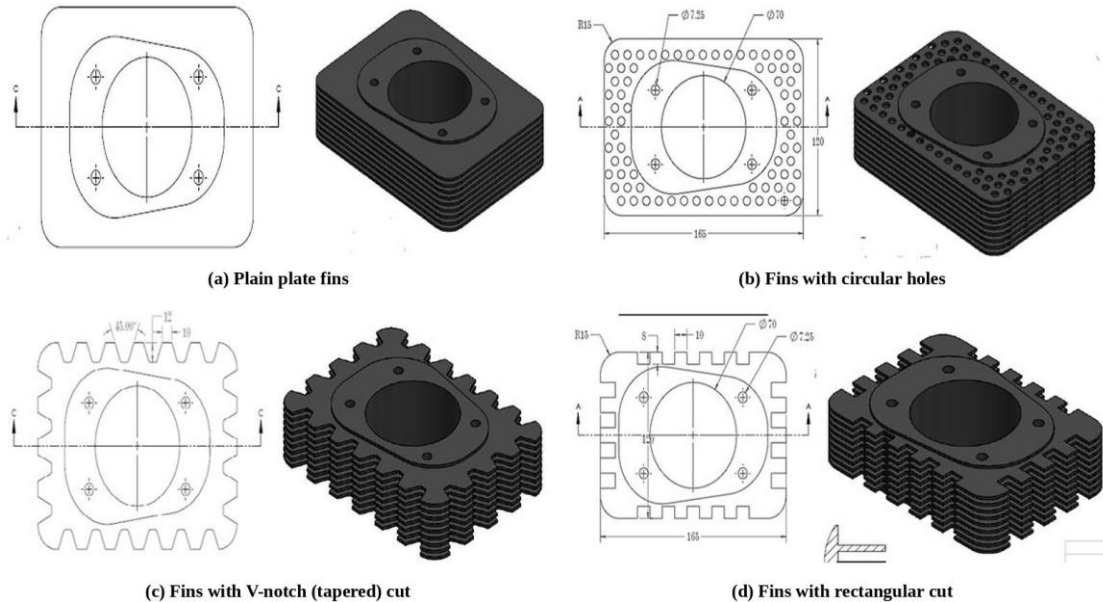


Figure 5.1 Plan and isometric views of the fin models: (a) plain, (b) circular holes, (c) V-notch cut, (d) rectangular cut

Both materials were assigned in turn to each geometry. The properties used in the analysis are given in Table 5.2. Aluminium alloy has about 2.7 times the thermal conductivity of grey cast iron (140 versus 52 W/m·°C) and less than 40% of its density, whereas grey cast iron has a higher elastic modulus and a lower coefficient of thermal expansion.

Table 5.2: Material properties used in the analysis

Property	Aluminium alloy	Grey cast iron
Density (kg/m ³)	2770	7200
Young's modulus (GPa)	71	110
Coefficient of thermal expansion (1/K)	2.3×10^{-5}	1.1×10^{-5}
Poisson's ratio	0.33	0.28
Ultimate tensile strength (MPa)	310	240
Thermal conductivity (W/m·°C)	140	52

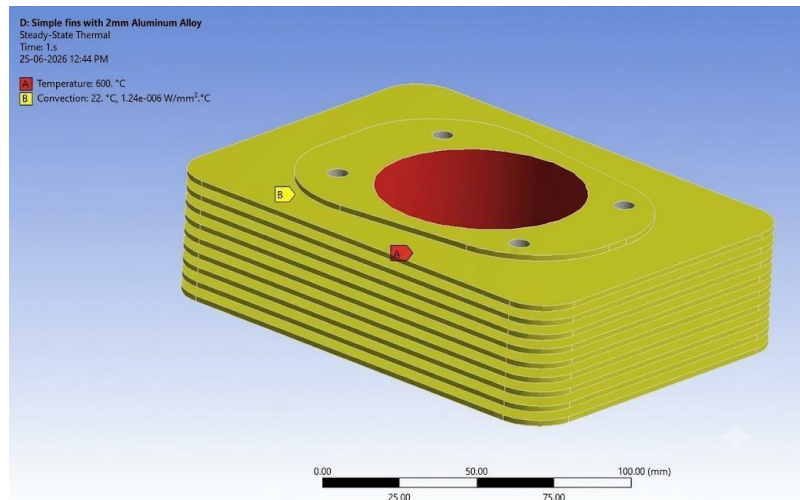


Figure 5.2 Boundary conditions applied to the plain-fin model (bore temperature 600 °C; convection to ambient air at 22 °C)

VI. RESULT AND DISCUSSION

6.1 Temperature distribution

Figures 6.1 and 6.2 show the temperature contours of the models for aluminium alloy and grey cast iron. In all cases the highest temperature (600 °C) occurs at the bore, and the temperature falls toward the outer edges of the fins. In the aluminium alloy models the minimum temperature remained between 562.08 °C and 578.63 °C, whereas in the grey cast iron models it fell to between 489.98 °C and 534.22 °C. The much steeper gradient in cast iron is a direct consequence of its lower thermal conductivity, which prevents heat from being conducted efficiently from the bore to the outer fin surfaces.

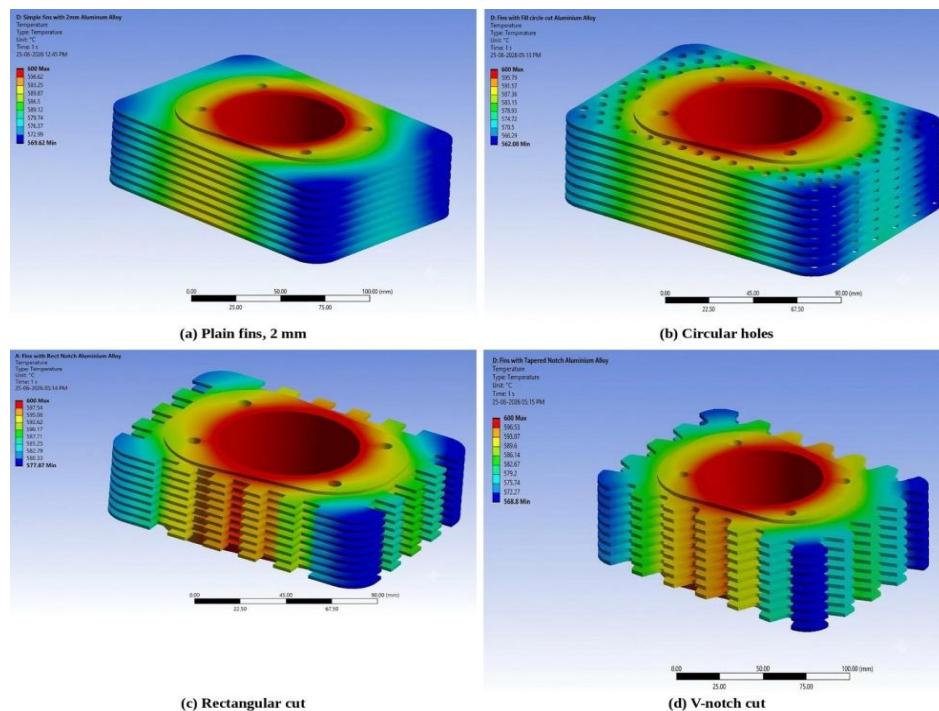


Figure 6.1 Temperature distribution of the aluminium alloy models: (a) plain fins, 2 mm, (b) circular holes, (c) rectangular cut, (d) V-notch cut

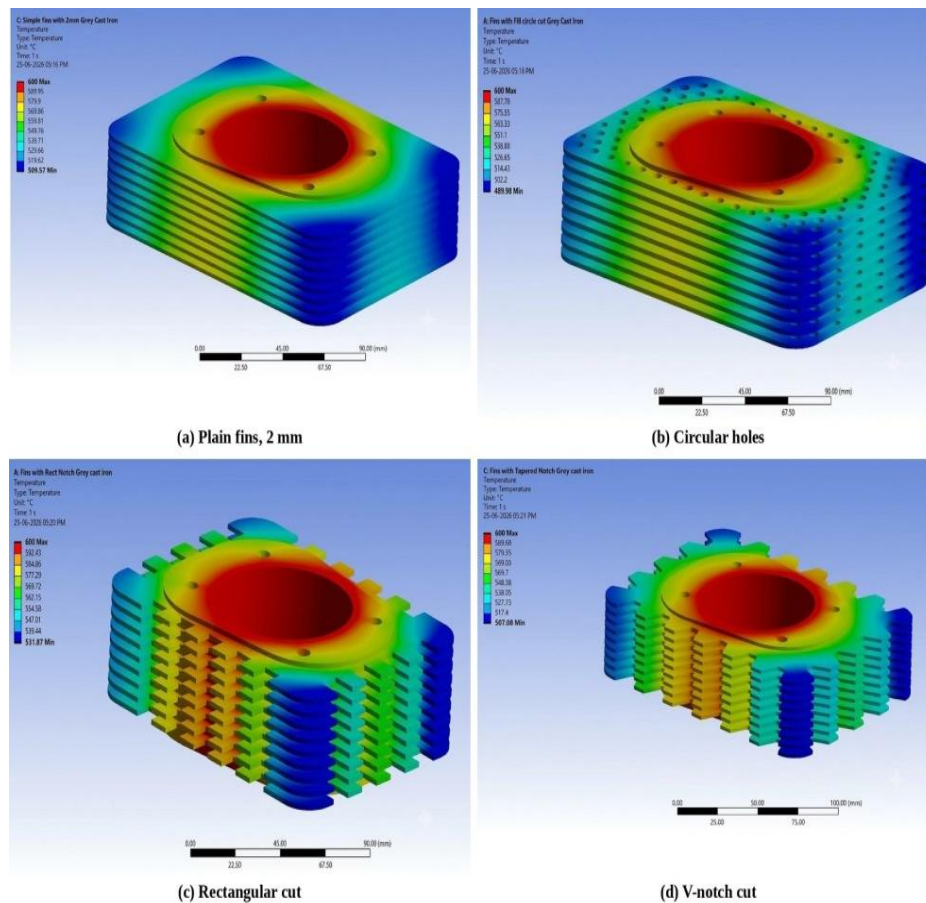


Figure 6.2 Temperature distribution of the grey cast iron models: (a) plain fins, 2 mm, (b) circular holes, (c) rectangular cut, (d) V-notch cut

6.2 Temperature drop, heat flux, and thermal stress

The results for aluminium alloy and grey cast iron are summarized in Tables 6.1 and 6.2. For aluminium alloy, the largest temperature drop (37.92 °C), total heat flux (0.325 W/mm²), directional heat flux (0.284 W/mm²), and thermal stress (56.02 MPa) all occurred in the fins with circular holes. The smallest temperature drop (21.37 °C) occurred in the 4 mm plain fins, the lowest total heat flux (0.159 W/mm²) in the fins with rectangular cuts, and the lowest thermal stress (18.47 MPa) also in the fins with rectangular cuts. Grey cast iron showed the same ranking of geometries but with much larger temperature drops and stresses.

Table 6.1: Results for the aluminium alloy models

Model	Temperature drop (°C)	Total heat flux (W/mm ²)	Directional heat flux (W/mm ²)	Thermal stress (MPa)
Fins with circular holes	37.92	0.325	0.284	56.02
Fins with V-notch (tapered) cut	31.20	0.23	0.189	48.93
Fins with rectangular cut	22.13	0.159	0.133	18.47
Plain fins, 2 mm thick	30.38	0.18	0.177	32.37
Plain fins, 3 mm thick	24.45	0.18	0.162	25.43
Plain fins, 4 mm thick	21.37	0.168	0.16	23.02

Table 6.2: Results for the grey cast iron models

Model	Temperature drop (°C)	Total heat flux (W/mm ²)	Directional heat flux (W/mm ²)	Thermal stress (MPa)
Fins with circular holes	110.02	0.279	0.247	123.77
Fins with V-notch (tapered) cut	92.92	0.203	0.167	111.79
Fins with rectangular cut	68.13	0.146	0.12	43.08
Plain fins, 2 mm thick	90.43	0.161	0.158	72.97
Plain fins, 3 mm thick	74.41	0.16	0.145	58.03
Plain fins, 4 mm thick	65.78	0.154	0.147	52.72

6.3 Comparison of aluminium alloy and grey cast iron

Figures 6.3 to 6.5 compare the two materials for each geometry, and Table 6.3 gives the relative differences. The temperature drop in the aluminium alloy models was 65.5–67.5% lower than in the corresponding cast iron models, which means that the temperature field in aluminium is roughly one-third as steep. At the same time the total heat flux of the aluminium alloy models was 8.9–16.5% higher for every geometry, showing that aluminium both removes more heat and keeps the block more uniformly heated. The thermal stress was 54.7–57.1% lower in aluminium alloy. The maximum stress of 123.77 MPa in the cast iron model with circular holes is about 52% of the ultimate tensile strength of grey cast iron (240 MPa), whereas the maximum stress of 56.02 MPa in the corresponding aluminium alloy model is about 18% of the strength of the alloy (310 MPa). Although the stresses reported here result from the thermal load alone and do not include gas pressure or mechanical loading, the margin is clearly much larger for aluminium.

The stress results are consistent with simple thermo-elastic reasoning. For a fully constrained body the thermal stress is approximately $E \alpha \Delta T / (1 - \nu)$, which is about 2.44 MPa per °C for the aluminium alloy and 1.68 MPa per °C for grey cast iron using the properties in Table 5.2. Per degree of temperature difference, aluminium is therefore the more stress-prone material, but the temperature differences within the cast iron models are about three times larger, and this dominates the result. The low conductivity of cast iron, not its mechanical properties, is thus the main cause of its higher thermal stress.

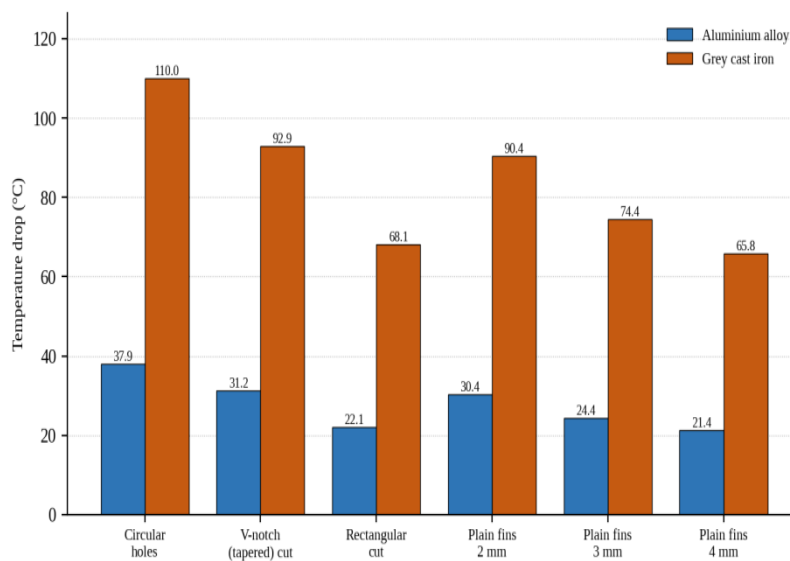


Figure 6.3 Comparison of temperature drop for aluminium alloy and grey cast iron

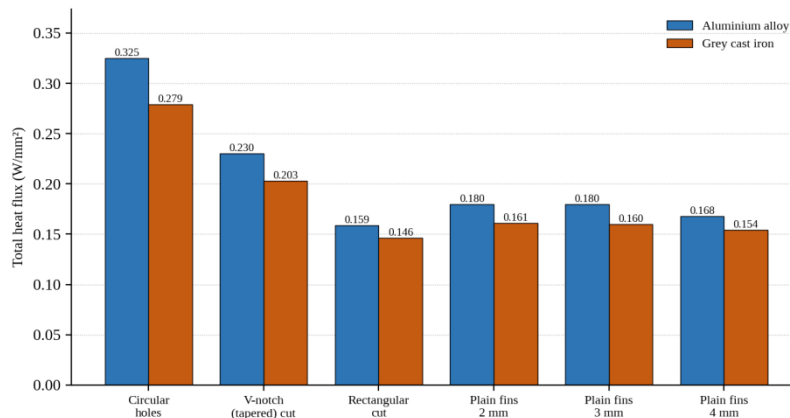


Figure 6.4 Comparison of total heat flux for aluminium alloy and grey cast iron

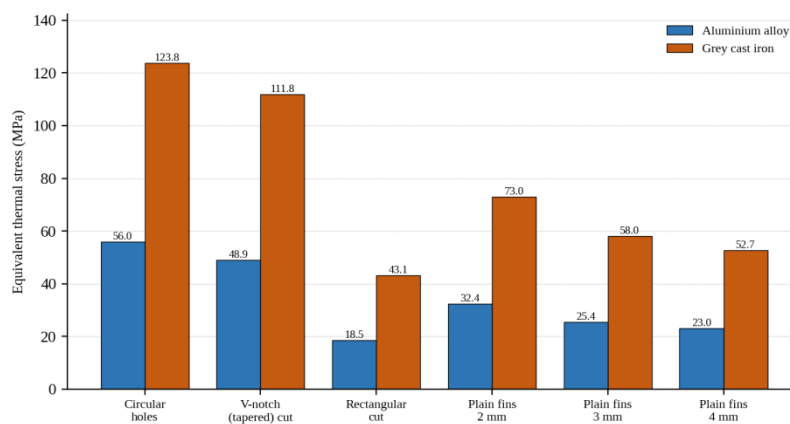


Figure 6.5 Comparison of thermal stress for aluminium alloy and grey cast iron

Table 6.3: Advantage of aluminium alloy over grey cast iron

Model	Temperature drop reduction (%)	Total heat flux increase (%)	Thermal stress reduction (%)
Fins with circular holes	65.5	16.5	54.7
Fins with V-notch (tapered) cut	66.4	13.3	56.2
Fins with rectangular cut	67.5	8.9	57.1
Plain fins, 2 mm thick	66.4	11.8	55.6
Plain fins, 3 mm thick	67.1	12.5	56.2
Plain fins, 4 mm thick	67.5	9.1	56.3

6.4 Effect of fin thickness

Increasing the plain-fin thickness from 2 mm to 4 mm made the temperature field more uniform in both materials (Figure 6.6). For aluminium alloy the temperature drop decreased from 30.38 °C to 21.37 °C (29.7%) and the thermal stress from 32.37 MPa to 23.02 MPa (28.9%); for grey cast iron the temperature drop decreased from 90.43 °C to 65.78 °C (27.3%) and the stress from 72.97 MPa to 52.72 MPa (27.8%). The total heat flux decreased only slightly, from 0.180 to 0.168 W/mm² for aluminium (6.7%) and from 0.161 to 0.154 W/mm² for cast iron (4.3%). Thicker fins provide a larger conduction cross-section, so heat is carried further along the fin with a smaller temperature gradient,

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which lowers the thermal stress. The penalty is the additional weight and material cost of thicker fins, which must be weighed against the gain in uniformity.

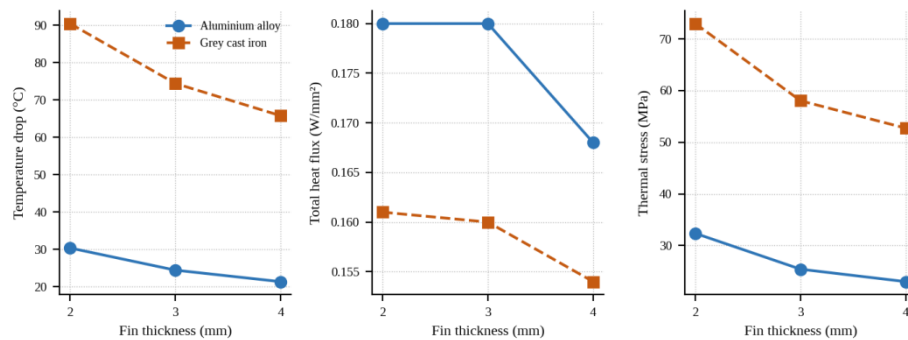


Figure 6.6 Effect of plain-fin thickness on temperature drop, total heat flux, and thermal stress

6.5 Effect of fin geometry

Relative to the plain 2 mm baseline, the fins with circular holes increased the total heat flux by 80.6% for aluminium and 73.3% for cast iron, but they also increased the thermal stress by 73.1% and 69.6%, respectively, and gave the largest temperature drops. The holes enlarge the exposed surface and disturb the thermal boundary layer, but they also interrupt the conduction paths in the fin and create local stress concentrations. The V-notch cuts increased the total heat flux by 27.8% (aluminium) and 26.1% (cast iron) with a similar temperature drop to the baseline, but the thermal stress rose by about 51.2% and 53.2%. In contrast, the rectangular cuts reduced the temperature drop by 27.2% (aluminium) and 24.7% (cast iron) and the thermal stress by 42.9% and 41.0%, at the cost of a 11.7% and 9.3% lower total heat flux. Geometry therefore provides a trade-off: perforated and notched fins favour maximum heat dissipation, while rectangular cuts and thicker plain fins favour temperature uniformity and low stress.

6.6 Design selection and limitations

For applications in which maximum heat dissipation is the priority, the aluminium alloy block with circular-hole fins is the strongest candidate, since its peak stress remains well below the strength of the alloy. Where thermal uniformity and durability are more important, the aluminium alloy block with rectangular-cut fins, or with thicker plain fins, provides the lowest temperature drop and stress. Grey cast iron remains a reasonable choice where wear resistance, rigidity, and heat retention are required, but its poor conduction produces steep gradients and high stress in finned form, so aluminium alloy is preferable for the finned portion, with wear-resistant liners where the bore requires them. These conclusions apply to the conditions studied. The analysis was steady-state, the bore temperature and the convective coefficient were assumed to be uniform, only thermal loading was considered, and the results have not yet been verified by a mesh-independence study reported here or by experiment. Transient start-up and shutdown behaviour, airflow-coupled CFD analysis, and experimental validation are therefore recommended for future work.

VII. CONCLUSION

A finned engine cylinder block was analysed in ANSYS for six fin configurations and two materials, aluminium alloy and grey cast iron, under identical boundary conditions. The aluminium alloy models showed temperature drops of 21.37–37.92 °C, compared with 65.78–110.02 °C for grey cast iron, a reduction of 65.5–67.5%, together with 8.9–16.5% higher total heat flux and 54.7–57.1% lower thermal stress. Fins with circular holes gave the highest heat flux (0.325 W/mm² for aluminium alloy) but also the highest temperature drop and thermal stress (56.02 MPa), while fins with rectangular cuts gave the lowest thermal stress (18.47 MPa) with a lower heat flux. Increasing the plain-fin thickness from 2 mm to 4 mm reduced the temperature drop and thermal stress by about 27–30% with a small loss of heat flux. Grey cast iron developed stresses up to 123.77 MPa, about 52% of its tensile strength, because of the steep temperature gradients caused by its low thermal conductivity. Aluminium alloy with circular-hole or rectangular-cut fins is therefore recommended for efficient and reliable cooling of air-cooled engine cylinder blocks, depending on

whether heat dissipation or temperature uniformity is the priority. Future work should include transient analysis, coupled CFD airflow modelling, mesh-independence and experimental validation, and the evaluation of other lightweight materials.

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