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"STEADY-STATE THERMAL ANALYSIS OF AIR-COOLED ENGINE CYLINDER FINS OF CIRCULAR, RECTANGULAR, AND ROUNDED-SQUARE GEOMETRY IN ALUMINIUM ALLOY 6061 USING ANSYS"

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ABSTRACT

The cylinder of an air-cooled engine rejects heat to the surrounding air through fins, and the shape of the fins influences how the heat spreads through the cylinder and how much is dissipated. This study compares the steady-state thermal behaviour of three engine cylinder fin geometries, namely circular fins, rectangular fins, and fins of rounded-square plan, all made of aluminium alloy 6061. The three models were prepared in CATIA V5 and analysed in ANSYS Workbench with a temperature of 300 °C on the inner wall of the cylinder, an ambient temperature of 22 °C, and convection on the outer and fin surfaces with a temperature-dependent film coefficient of 1.24 × 10⁻⁶ to 1.24 × 10⁻⁵ W/mm²·°C. The temperature drop between the bore and the coolest point was 3.25 °C for the circular fins and 3.37 °C for the rectangular fins, but 23.24 °C for the rounded-square fins, and the maximum total heat flux was 0.0351, 0.0331, and 0.1322 W/mm², respectively. The rounded-square model therefore showed a temperature drop about 7.2 times and a peak heat flux about 3.8 times those of the circular model, whereas the circular and rectangular models differed by less than 6% in both quantities. A fin-efficiency estimate based on the Biot number showed that the fins of 3 mm thickness are almost isothermal at the convection coefficients used, so that the heat dissipation is limited by the convection and by the exposed area rather than by the conductivity of the alloy. The results are consistent with published studies in which circular aluminium-6061 fins performed well, and they provide a basis for comparing fin plan shapes, with total heat dissipation, validation, and cast-iron comparison identified as further work.

Key Words:. *Engine cylinder fins; thermal analysis; ANSYS; aluminium alloy 6061; circular fins; rectangular fins; heat flux; steady-state; convection coefficient.*

I. INTRODUCTION

A substantial part of the energy released by the fuel in an internal combustion engine is rejected as heat, and the cooling system must hold the cylinder, piston, and lubricant within safe temperatures [1]. In air-cooled engines, which are widely used in motorcycles and small engines, the heat is conducted through the cylinder wall and rejected by convection to the surrounding air from fins on the outer surface. Since the convection coefficient of air is small, a larger surface area is the practical way of raising the heat dissipation, and the shape, pitch, thickness, and material of the fins determine how effective this area is. Experiments in wind tunnels have shown that the air velocity and the fin spacing have the greatest influence on the surface heat transfer coefficient [2].

Numerical analysis is now widely used to compare fin designs before prototypes are made. Rao and Vardhan [3] analysed the fins of a 150 cc engine cylinder for rectangular, circular, and curved geometries, several thicknesses, and aluminium alloy A204, aluminium alloy 6061, and a magnesium alloy, and Babu and Lavakumar [4] concluded that a circular fin of aluminium alloy 6061 with a thickness of 2.5 mm was the best of the combinations they compared.

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Kumar et al. [5] reported a static thermal analysis of fin models in ANSYS using aluminium alloy 1060. Recent studies have compared aluminium 6061 with grey cast iron [6], examined slotted fins [7], and applied direct optimisation to the fin dimensions [8]. These studies usually vary the thickness, material, or shape of the fin on a common cylindrical base, whereas comparisons of fins of different plan shape under identical thermal boundary conditions are less common.
The present study analyses three fin geometries of aluminium alloy 6061, the circular, the rectangular, and a rounded-square geometry, under the same boundary conditions in ANSYS Workbench, and reports the temperature distribution, total heat flux, and directional heat flux for each. A fin-efficiency estimate is added to explain the magnitude of the temperature drop observed.

II. Problem Identification

The cylinder of an air-cooled engine is exposed to combustion temperatures that are far above the permissible temperature of the cylinder material. The heat must be removed quickly enough to prevent overheating, although over-cooling reduces the thermal efficiency of the engine. The fins increase the area available for convection, but their plan shape affects the path of the heat from the bore to the outer edges and the area that is exposed to the air. If the shape is poorly chosen, hot spots and steep temperature gradients may occur, whereas a good shape spreads the heat more evenly.

The problem addressed in this study is to determine how the plan shape of the fins (circular, rectangular, or rounded-square) affects the temperature distribution and the heat flux in an aluminium alloy 6061 cylinder under identical thermal conditions, and to understand from a simple fin analysis which physical mechanism controls the results.

III. Research Objective

The main objectives of the present study are as follows:

- To prepare three-dimensional models of engine cylinder fins of circular, rectangular, and rounded-square geometry in CATIA V5.
- To carry out a steady-state thermal analysis of each model in ANSYS Workbench for aluminium alloy 6061 with a temperature-dependent convection coefficient.
- To obtain the temperature distribution, the total heat flux, and the directional heat flux for each geometry.
- To compare the geometries and to explain the results by estimating the Biot number and the fin efficiency.

IV. Modeling and Simulation

4.1 Governing relations

In the steady state, the temperature field in the solid satisfies the heat conduction equation $\nabla\cdot(k\,\nabla T) = 0$, where k is the thermal conductivity. On the outer surface and the fin surfaces the heat leaves by convection, according to Newton's law of cooling,

$$-k\,\partial T/\partial n = h\,(T_s - T_\infty) \qquad Q = h\,A\,(T_s - T_\infty) \qquad (1)$$

in which h is the convection coefficient, T_s is the surface temperature, T_∞ is the ambient temperature, and A is the area. The finite element method divides the solid into small elements joined at nodes and solves the assembled system for the nodal temperatures, from which the heat flux is obtained as the product of the conductivity and the temperature gradient. The analysis was carried out in ANSYS Workbench 2021 R2 using the steady-state thermal system.

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4.2 Boundary conditions

The inner wall of the cylinder was given a temperature of 300 °C, ramped from the initial temperature of 22 °C, and the ambient air was taken to be at 22 °C. Convection was applied to the outer surface of the cylinder and the fin surfaces with a film coefficient that depends on temperature, as given in Table 4.1 and Figure 4.1, with the average film temperature used as the independent variable. The coefficient increases from 1.24×10^{-6} W/mm²·°C at 1 °C to 1.24×10^{-5} W/mm²·°C at 1000 °C, that is, from 1.24 to 12.4 W/m²·K, and it is about 8.3 W/m²·K at 300 °C. The same conditions were applied to all three models.

Table 4.1: Temperature-dependent film coefficient used in the analysis

Temperature (°C)	Film coefficient (W/mm²·°C)
1	1.24×10^{-6}
10	2.67×10^{-6}
100	5.76×10^{-6}
200	7.25×10^{-6}
300	8.30×10^{-6}
500	9.84×10^{-6}
700	1.101×10^{-5}
1000	1.24×10^{-5}

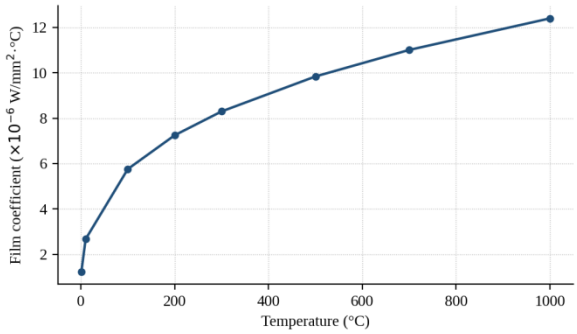


Figure 4.1 Variation of the film coefficient with temperature

4.3 Meshing

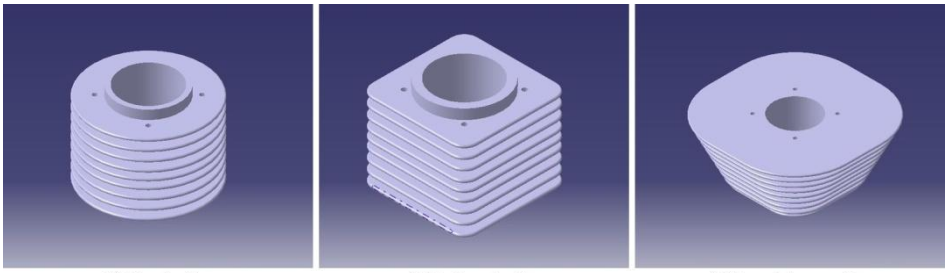
Each model was meshed with the tetrahedral mesh generator of ANSYS, with program-controlled element order, default element size, adaptive sizing enabled, and medium smoothing. The mesh of the rectangular model had 40 016 nodes and 19 693 elements, and that of the rounded-square model had 50 389 nodes and 25 150 elements. A mesh-independence study was not reported.

V. Design Of The Fin Models

The three models were created in CATIA V5 as a cylinder block with a central bore and a stack of horizontal plate fins, as shown in Figure 5.1. The circular model has circular fins of 3.0 mm thickness at a spacing of 8 mm, the rectangular model has rectangular (square-plan) fins of 3.0 mm thickness, and the third model has fins of rounded-square plan whose size decreases toward the bottom of the stack. The aluminium alloy 6061 used for the fins is a heat-treatable alloy with good machinability, forming, and weldability, a lower density than cast iron, and a high thermal conductivity; its conductivity is of the order of 167 W/m·K in the T6 condition, which is a typical handbook value

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assumed in this paper and not a value taken from the simulation files.



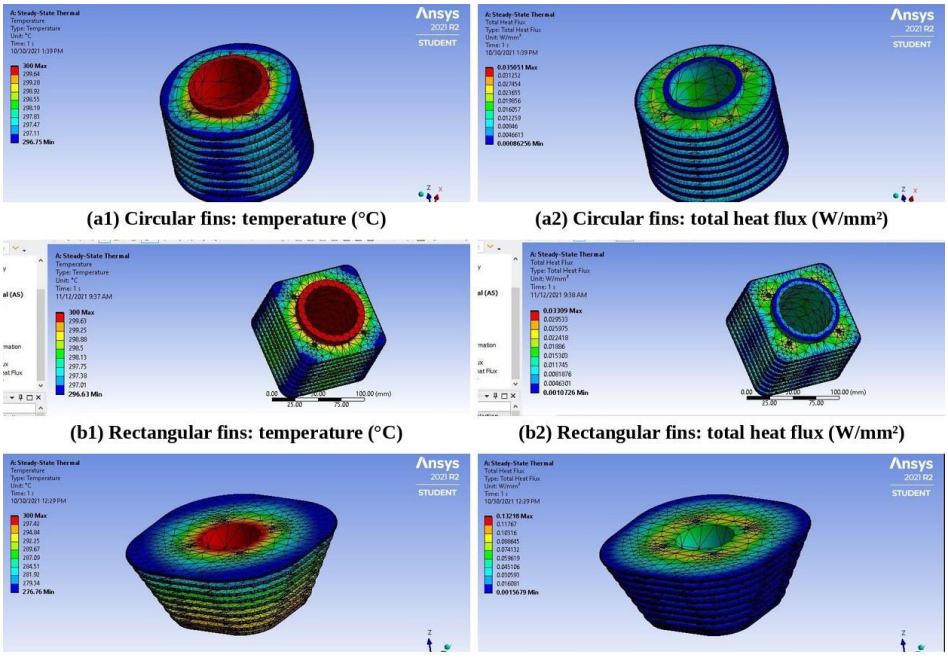
(a) Circular fins (b) Rectangular fins (c) Rounded-square fins

Figure 5.1 CATIA models of the cylinder fins: (a) circular, (b) rectangular, (c) rounded-square

VI. Result and Discussion

6.1 Temperature and heat flux

Figure 6.1 shows the temperature and total heat flux contours of the three models. In all cases the highest temperature (300 °C) is at the inner wall, and the temperature falls toward the outer edges of the fins. The total heat flux varies over the body between the maximum and minimum values listed in Table 6.1.



(a1) Circular fins: temperature (°C) (a2) Circular fins: total heat flux (W/mm²)

(b1) Rectangular fins: temperature (°C) (b2) Rectangular fins: total heat flux (W/mm²)

(c1) Rounded-square fins: temperature (°C) (c2) Rounded-square fins: total heat flux (W/mm²)

Figure 6.1 Temperature and total heat flux for (a) circular, (b) rectangular, and (c) rounded-square fins

Table 6.1: Results of the steady-state thermal analysis for aluminium alloy 6061

Model	T max (°C)	T min (°C)	Total heat flux max (W/mm²)	Total heat flux min (W/mm²)	Directional flux max (W/mm²)	Directional flux min (W/mm²)
Circular fins	300.00	296.75	0.03505	0.00086	0.02830	-0.02722
Rectangular fins	300.00	296.63	0.03309	0.00107	0.02562	-0.02552
Rounded-square fins	300.00	276.76	0.13218	0.00157	0.10682	-0.10146

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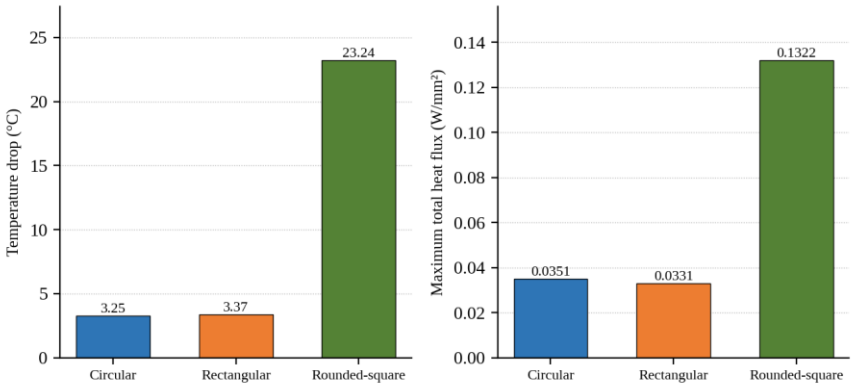


Figure 6.2 Temperature drop and maximum total heat flux of the three models

The temperature drop between the bore and the coolest point is 3.25 °C for the circular fins, 3.37 °C for the rectangular fins, and 23.24 °C for the rounded-square fins. The circular and rectangular models are very similar: the rectangular model has a temperature drop that is 3.7% larger and a maximum total heat flux that is 5.6% smaller than the circular model. The rounded-square model, in contrast, shows a temperature drop of 7.2 times and a maximum total heat flux of 3.8 times those of the circular model, and its directional heat flux in the X direction is about 3.8 times as large. Its temperature field is therefore much less uniform, with the coolest point about 23 °C below the wall temperature. A possible reason is the longer conduction path from the bore to the outer parts of the larger plan, together with the taper of the stack, but the present results do not separate the effect of the plan shape from that of the taper and of the overall dimensions of the model, which are not given in the source files.

6.2 Why the temperature drop is small: Biot number and fin efficiency

The very small temperature drops of the circular and rectangular models, about 3 °C on a bore temperature of 300 °C, can be understood from a simple fin analysis [9]. For a plate fin of thickness t = 3 mm and conductivity k = 167 W/m·K, the Biot number at the film coefficient of 8.3 W/m²·K (300 °C in Table 4.1) is Bi = h (t/2) / k = 7.5 × 10^{-5}, which is far smaller than unity, so the temperature is nearly uniform across the thickness of the fin. For a fin of uniform thickness the fin parameter is $m = (2h / kt)^{1/2}$ = 5.76 m^{-1}, and the fin efficiency $\eta = \tanh(mL) / (mL)$ is 0.999 for a fin length of 10 mm and 0.973 for 50 mm. The fins are therefore almost isothermal and the heat they can dissipate is limited by the convection coefficient and the exposed area, not by the conductivity of the aluminium alloy. This explains the small temperature differences and indicates that, for aluminium 6061 fins at these convection coefficients, increasing the exposed area, for example by closer or additional fins within the limit of boundary-layer overlap, is more effective than changing the alloy. The estimate is approximate: it uses a typical conductivity, treats the fins as flat plates, and ignores the curvature and the interaction between the fins.

6.3 Comparison with the literature

The results are consistent with studies that found aluminium alloy 6061 and circular fins to be favourable in comparisons with other shapes and materials [3], [4]. A recent simulation study that compared aluminium 6061 with grey cast iron found that the aluminium alloy had advantages in weight and manufacturability, whereas the cast iron retained heat longer [6], and a study of slotted fins [7] and a direct-optimisation study [8] showed that the dimensions and the shape of the fin can change the total heat flux appreciably. The present results add a comparison of three plan shapes under identical conditions, and they show that the circular and the rectangular fins behave almost identically at the dimensions analysed, whereas the rounded-square, tapered model has a markedly larger temperature drop and heat flux.

6.4 Limitations

The following limitations apply. Only aluminium alloy 6061 results are reported here; a comparison with grey cast iron and other alloys was part of the original study, but the corresponding results were not available in the source files. The

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analysis is steady-state with a uniform wall temperature, no combustion heat-flux variation, and a film coefficient that depends only on temperature, so that the effect of vehicle speed and of the air flow between the fins is not included. The contour values are local maxima and minima in the solid, and the total heat transferred to the air was not computed. The dimensions of the models other than the thickness and spacing of the circular and rectangular fins are not stated, the mesh-independence of the results was not reported, and no experimental validation was performed. The results should therefore be regarded as a comparison between geometries, not as absolute predictions of the cooling performance.

VII. CONCLUSION

Three engine cylinder fin geometries of aluminium alloy 6061 were analysed in ANSYS under identical steady-state thermal boundary conditions: a bore temperature of 300 °C, an ambient temperature of 22 °C, and a temperature-dependent film coefficient. The temperature drop between the bore and the coolest point was 3.25 °C for circular fins, 3.37 °C for rectangular fins, and 23.24 °C for rounded-square fins, and the maximum total heat flux was 0.0351, 0.0331, and 0.1322 W/mm². The circular and rectangular models behaved almost identically, with differences of less than 6%, whereas the rounded-square, tapered model showed a much less uniform temperature field and a heat flux about 3.8 times larger. A Biot-number and fin-efficiency estimate showed that the 3 mm aluminium fins are almost isothermal, so the heat dissipation is limited by the convection and by the exposed area, not by the conductivity of the alloy. Future work should report the total heat dissipated, include the comparison of aluminium 6061 with grey cast iron and other alloys, take account of vehicle speed through CFD, include transient and thermal-stress analyses, perform a mesh-independence study, and validate the results by wind-tunnel experiments.

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