engineering proceedings

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Proceeding Paper

Advanced Design and Analysis of Engine Fins to Improve Heat Transfer Rate †

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† Presented at the International Conference on Mechanical Engineering Design (ICMechD 2024), Chennai, India, 21–22 March 2024.

Abstract

Fin analysis is crucial to improve the rate of heat transfer. The main objective of this research is to investigate various fin designs in order to enhance the heat transfer efficiency of cooling fins through modifications in the geometry of the cylinder fins. The investigation of thermal analysis of the cylinder through variation in material, geometry, number, and size of the fins is carried out. Different materials are considered to design the fins, including cast iron, aluminum alloy 6061, and copper. The design of the engine, featuring various fins, is modeled with CATIA, and analysis is performed with ANSYS 2023 R2. The findings indicate that for the modified design-2, the total heat flux is more for aluminum alloy 6061 compared to the other two materials. Additionally, the use of aluminum alloy 6061 results in lower weight, making it a better choice compared to cast iron and copper.

Keywords: thermal analysis; CATIA; ANSYS; fins; materials

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Academic Editors: M. S. Alphin, Divya Zindani, M. Nalla Mohammed and Ramkumar P.

Published: 7 August 2025

Citation: Das, P.K.; Zubbairuddin, M.; Patra, J.; Dash, S.K. Advanced Design and Analysis of Engine Fins to Improve Heat Transfer Rate. *Eng. Proc.* **2025**, *93*, 23. https://doi.org/10.3390/engproc2025093023

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1. Introduction

The engine is the primary part of automobiles and other machinery that is exposed to high temperatures and different types of stress. Engine parts and components, including the camshaft, connecting rod, crankshaft, etc., are constructed from various materials to endure the hot and exposed working conditions. So, to operate properly, an IC engine requires efficient heat transfer. When heat is produced in an engine, the extra heat is also generated due to friction between moving parts. From the literature survey, it was identified that 30% of the energy relieved is transformed into productive work, and 70% of the energy should be extracted from the engine to keep the parts safe. Fins are elongated surfaces employed to dissipate heat from various structures through convection. The efficiency of heat transfer via fins is primarily constrained by the system's design. However, enhancements can be achieved by adjusting specific design parameters of the fins. The cooling system constitutes a critical subsystem of the engine. The effectiveness of the engine's air-cooling mechanism largely relies on the fin design of the cylinder block and head. Fins are intentionally integrated at locations where heat is extracted into the surrounding environment. Rate of heat transfer—whether through conduction, convection, or radiation—of an object is determined by its thermal properties. Mayakannan et al. [1]

investigated different material optimization techniques for heat removal in engine fins, specifically those positioned straight within a reactor core. Initially, the baseline analysis was performed to validate the finite element analysis (FEA) model and to assess the calculated boundary conditions. Subsequently, conductive cooling devices were examined by maintaining certain surfaces at a constant temperature. From the analysis they observed that AL200 exhibited superior thermal performance compared to AL6061, outperforming the existing material. Furthermore, the optimal shape was determined to be concave at the most effective cross-section. Sorathiya et al. [2] calculated thermal behavior by changing the material, design, and thickness of cylinder fins by CFD. Aluminum alloy 204 is used for manufacturing the cylinder fin body. They have also analyzed different materials like aluminum 6061 and grey cast iron and concluded that grey cast iron is better, decreasing thickness to 2.5 mm is better, and using a rectangular fin shape for weight is better. Kumar et al. [3] conducted a simulation with different engine cylinder models while taking into account different parameters such as materials, geometry, height, and number of fins at particular velocities. They have found that in all materials, heat transfer through fins of different thicknesses was greater than that of their equivalent rectangular fin models. The performance of the 16 mm fins was superior to that of the 13 mm fins. The number of fins significantly influenced the results, as the models with seven fins exhibited greater efficiency than those with five fins. An increase in velocity from 35 km/h to 85 km/h resulted in enhanced heat transfer. Gupta et al. [4] analyzed the heat transfer of engine fins with different geometry. The structure of the two-wheelers was designed using parametric 3D modeling software, SolidWorks, and thermal analysis was conducted utilizing ANSYS. Different geometries were used, including convex, tapered, triangular, and rectangular. The fin body was constructed from Al6063 material. They discovered that convex fins have the highest heat flux, followed by tapered, triangular, and rectangular fins. Additionally, the greatest temperature reduction was observed in the tapered fin, with the convex, triangular, and rectangular fins following in that order. They came to the conclusion that variations in geometry can cause temperature drops and increases in heat flux. Das et al. [5] found that the increase in fin thickness from 2 mm to 3 mm resulted in a corresponding rise in the heat transfer rate. They also observed that multiple slots into the fin profile significantly improved the overall heat transfer rate while also leading to substantial reductions in the mass of the material utilized. Srinivas et al. [6] investigated the circular fins' temperature distribution and compared it with rectangular chamfered fins. They found that the cooling rate was higher in rectangular chamfered fins. Additionally, the incorporation of chamfers in rectangular fins resulted in a reduction in the weight of the component while simultaneously improving the cooling rate. They have observed that the fin thickness was inversely proportional to the cooling rate. As pitch increased, cooling rate also increased. Patil and Shetty [7] investigated the thermal analysis of fins to identify the heat transfer rate. They found that as the area of the fins increased, the heat dissipation rate also increased.

Previously, many similar types of research work have been done based on both experimental and numerical studies [8–10]. But still the literature lacks a comprehensive study on different materials selection and fin design; the results so far reported are even contradictory. In this present study, a numerical investigation has been carried out to simulate different geometry and heat transfer of engine fins. Different materials are used for fins, such as aluminum alloy 6061, cast iron, and copper. The model of the engine, featuring various fins, was designed by CATIA, and numerical simulation of the model was solved by using ANSYS 23.0 R2 software. It is observed that for the modified design-2, the total heat flux is more for aluminum alloy 6061 compared to the other materials. Additionally, the use of aluminum alloy 6061 results in lower weight, making it a better choice compared to cast iron and copper.

2. Materials and Methods

In this study, we have considered different designs and materials for identifying rate of heat transfer in engine fins. Three separate geometry models are designed for the simulation. Tables 1 and 2 indicate the engine specification and parameters of the design. Materials and dimensions of the models are described below:

Table 1. Engine specifications.

S No.	Details	Specification
1.	Name of the model	Splendor
2.	Cubic capacity	100
3.	Stroke (mm)	49.5
4.	Bore (mm)	50
5.	Fin count	11-8-11
6.	Pitch of the fin (mm)	9
7.	Fin position w.r.t axis of the cylinder	Parallel
8.	Vehicle cylinder position	Horizontal

Table 2. Parameters of the design.

Parameters	Value	Units
Surface area of fins	0.003511	m^2
Thickness	2	mm
Width of fin	50	mm
Length of fin	70	mm
Number of fins	11-8-11	-
Inside temperature	150	°C
Ambient temperature	35	°C
Thermal diffusivity (α)	0.000023585	m^2/s
Momentum diffusivity (υ)	0.00001648	m^2/s

For the existing design—thickness of fins, 2 mm, and distance between the fins, 9 mm.

For the modified design-1—thickness of fins, 2 mm, and distance between the fins, 9 mm (shape is different).

For the modified design-2—thickness of fins, 2 mm, and distance between the fins, 10 mm.

Materials—cast iron, copper, and aluminum alloy 6061.

3. Mathematical Models

The Splendor 100 cc cylinder block is taken for the study, and the model of the geometry is prepared with the help of CATIA software V5 R21. The engine is modeled with various geometrical fin configurations. Figure 1 shows the geometry model of the (a) existing design, (b) modified design-1, and (c) modified design-2, respectively.

3.1. Meshed Profile of the Geometry

Figure 2 shows the meshed profile of the model for the (a) existing design, (b) modified design-1, and (c) modified design-2, respectively. The mesh elements are suitably sized to produce dependable simulation results effectively.

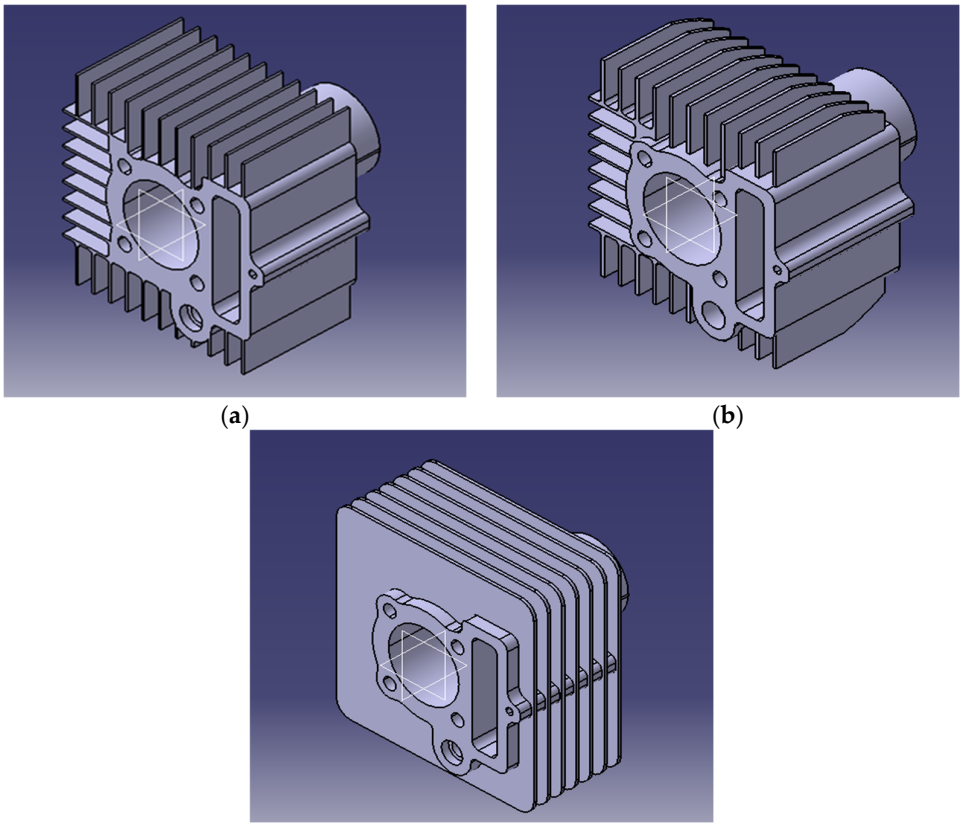


Figure 1. Geometry model of the (**a**) existing design, (**b**) modified design-1, and (**c**) modified design-2.

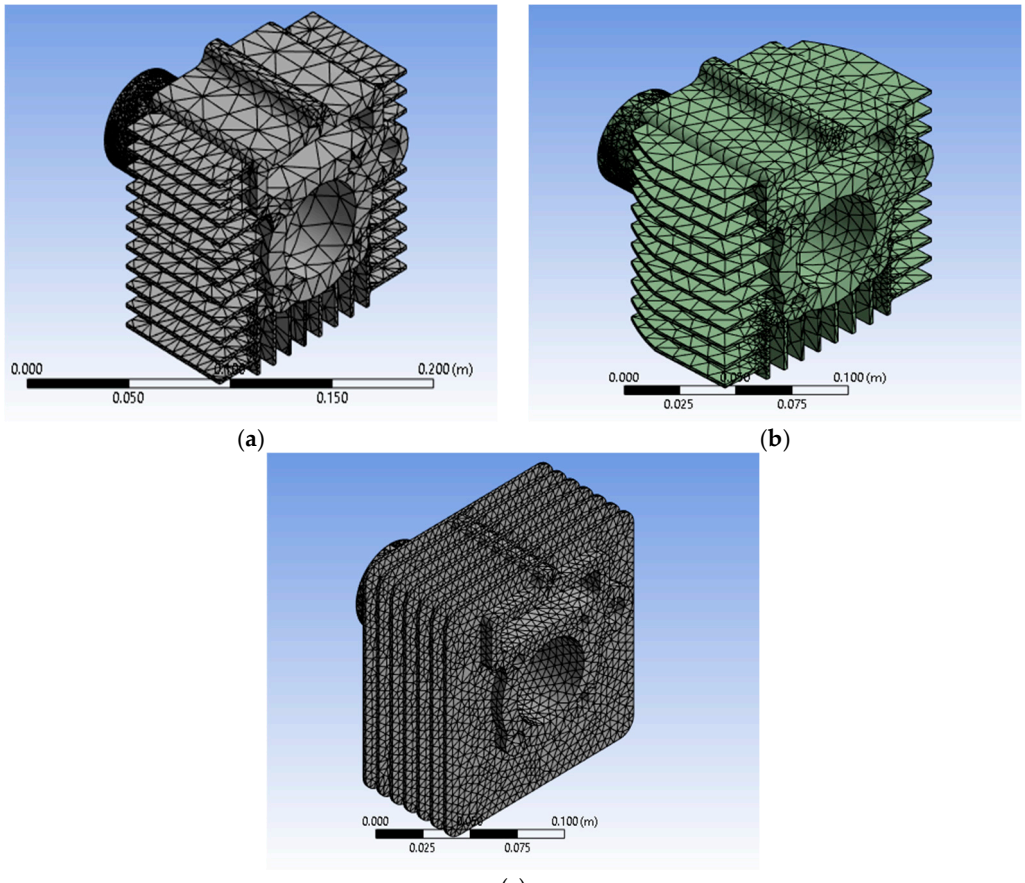


Figure 2. The meshed profile of the (**a**) existing design, (**b**) modified design-1, and (**c**) modified design-2.

3.2. Model Calculations

The following formulas and properties were taken from Cengel and Ghajar [11];

Final temperature (T_f) = $\frac{tb+t\infty}{2}$, T_f = $\frac{150+35}{2}$ = 92.5 °C = 365.5 K

Biot number, β = $\frac{1}{Tf}$ = $\frac{1}{92.5}$ = 2.73 × 10^{-3}

Prandtl number, P_r = $\frac{v}{\alpha}$ = $\frac{16.48\times10^{-6}}{23.585\times10^{-6}}$ = 0.698

Grashof number, G_r = $\frac{g\beta\Delta TL^3}{V^2}$ = $\frac{9.81\times2.73\times10^{-3}\times(150-35)\times(70)^3}{(16.48\times10^{-6})^2}$, ($G_r$ = 38.89 × 10^5)

Rayleigh number, R_a = G_r × P_r = (38.89 × 10^5) × (0.698) = 27.14 × 10^5

where R_a < 10^9; therefore,

Nusselt number, Nu = $[0.825 + \frac{0.387\times(Gr\times Pr)^{0.167}}{\{1+[\frac{0.492}{Pr}]^{0.5625}\}^{0.296}}]^2$ = 21.83

Heat transfer coefficient, h = $\frac{Nu.K}{L}$ = $\frac{21.83\times50}{0.070}$ = 15592.85

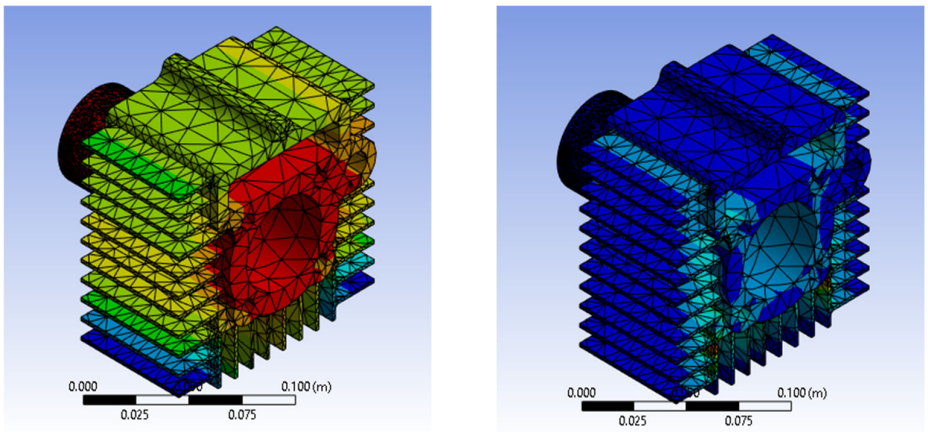
Convective heat transfer, Q_{conv} = h × $As(Tb - T\infty)$ = 15592.85 × 0.003511 (150 – 35)

Q_{conv} = 6295.84 w

Heat flux, q = $\frac{Qconv}{As\times30}$ = $\frac{6295.84}{0.003511\times30}$ = 59772.52 w/m^2

4. Results and Discussion

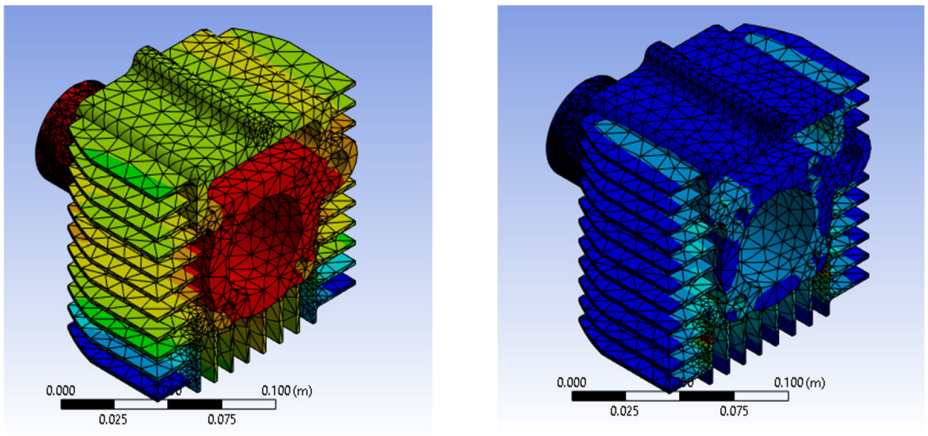
Figure 3 shows the (a) temperature distribution and (b) heat flux of the existing design for cast iron material. The maximum and minimum temperatures obtained for this material are 150 °C and 135.41 °C, respectively. The maximum and minimum heat flux are 53,110 W/m^2 and 3.11 × 10^{-8} W/m^2, respectively. Figure 4 indicates the (a) temperature distribution and (b) heat flux of the modified design-1 for cast iron material. The maximum and minimum temperatures obtained for this material are 150 °C and 138.65 °C, respectively. The maximum and minimum heat flux are 40,473 W/m^2 and 4.3795 × 10^{-7} W/m^2, respectively.



(**a**) (**b**)

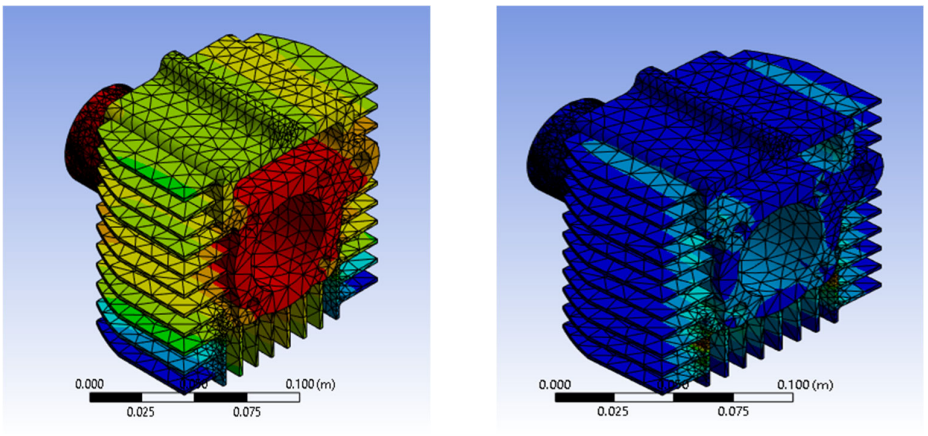
Figure 3. Shows the (**a**) temperature distribution and (**b**) heat flux of the existing design for cast iron material.

Figure 5 shows the (a) temperature distribution and (b) heat flux of the modified design-1 for aluminum alloy 6061 material. The maximum and minimum temperatures obtained for this material are 150 °C and 144.88 °C, respectively. The maximum and minimum heat flux are 34,167 W/m^2 and 2.452 × 10^{-7} W/m^2, respectively. Figure 6 indicates the (a) temperature distribution and (b) heat flux of the modified design-1 for copper material. The maximum and minimum temperatures obtained for this material are 150 °C and 147.97 °C, respectively. The maximum and minimum heat flux are 34,907 W/m^2 and 4.2155 × 10^{-7} W/m^2, respectively.



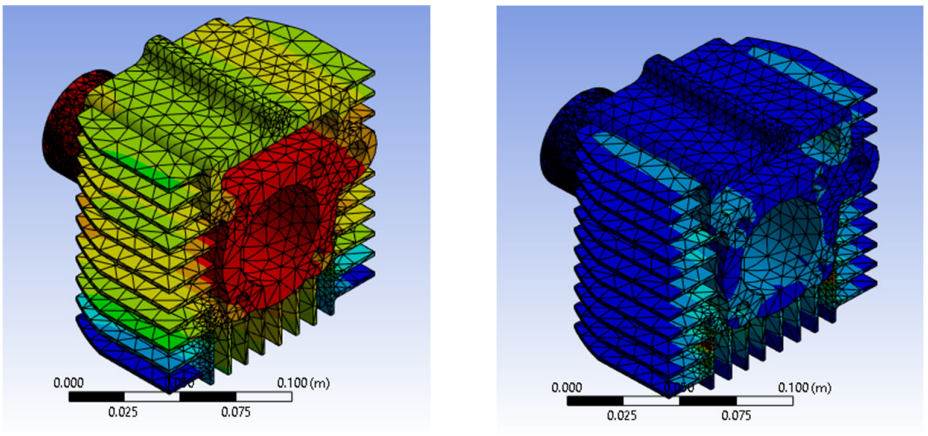
(**a**) (**b**)

Figure 4. The (**a**) temperature distribution and (**b**) heat flux of the modified design-1 for cast iron material.



(**a**) (**b**)

Figure 5. The (**a**) temperature distribution and (**b**) heat flux of the modified design-1 for aluminum alloy 6061 material.

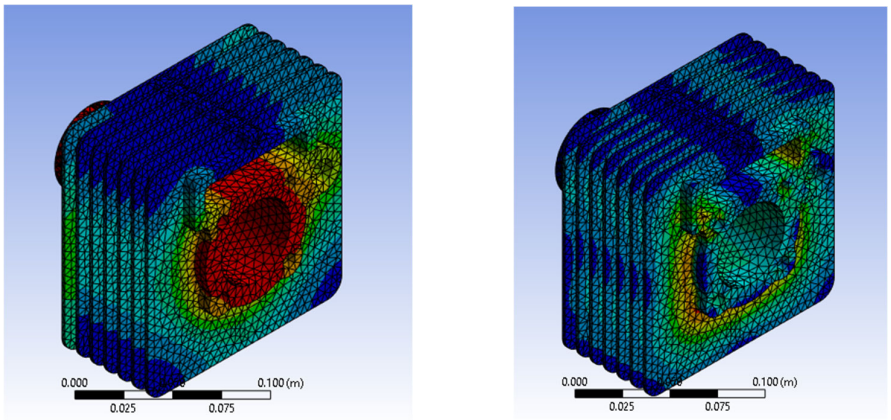


(**a**) (**b**)

Figure 6. The (**a**) temperature distribution and (**b**) heat flux of the modified design-1 for copper material.

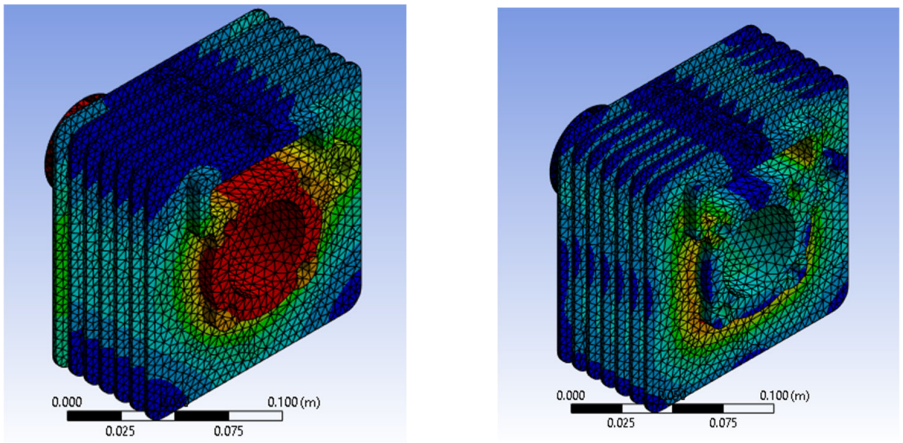
Figure 7 shows the (a) temperature distribution and (b) heat flux of the modified design-2 for cast iron material. The maximum and minimum temperatures obtained for this material are 150 °C and 140.43 °C, respectively. The maximum and minimum heat flux are

27,147 W/m^2 and 1.1719 × 10^{-7} W/m^2, respectively. Figure 8 shows the (a) temperature distribution and (b) heat flux of the modified design-2 for aluminum alloy 6061 material. The maximum and minimum temperatures obtained for this material are 150 °C and 145.74 °C, respectively. The maximum and minimum heat fluxes are 22,594 W/m^2 and 1.568 × 10^{-7} W/m^2, respectively. Figure 9 shows the (a) temperature distribution and (b) heat flux of the modified design-2 for copper material. The maximum and minimum temperatures obtained for this material are 150 °C and 148.32 °C, respectively. The maximum and minimum heat fluxes are 23,024 W/m^2 and 2.9289 × 10^{-7} W/m^2, respectively.



(**a**) (**b**)

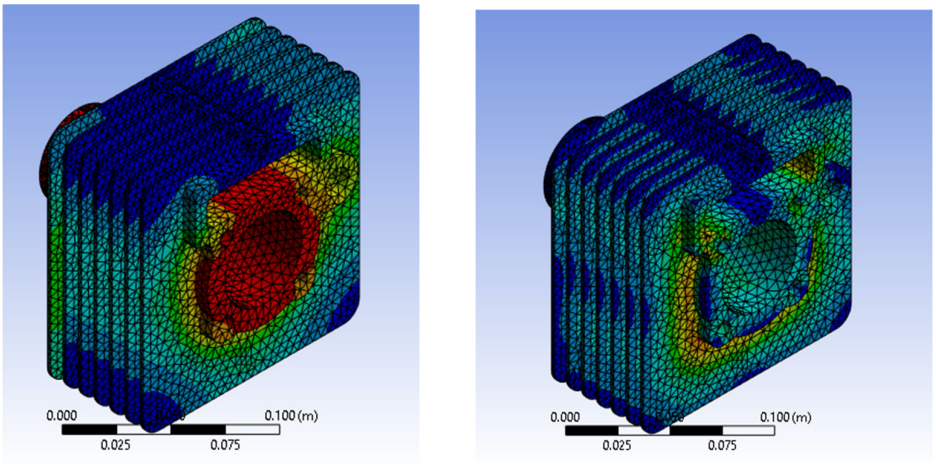
Figure 7. The (**a**) temperature distribution and (**b**) heat flux of the modified design-2 for cast iron material.



(**a**) (**b**)

Figure 8. The (**a**) temperature distribution and (**b**) heat flux of the modified design-2 for aluminum alloy 6061 material.

In the analysis of all different models, the temperature distribution and total heat flux over the fins' results are simulated by ANSYS software. By comparing the above results, we can identify that the modified design-2 shows more cooling as compared to the existing and modified design-1 model. The results of all the models obtained from the software are mentioned in the following table. Table 3 indicates the results for the existing model of temperature range and theoretical and analytical heat flux. Table 4 indicates the results for the modified designs 1 and 2 of temperature range heat flux for different materials.



(**a**) (**b**)

Figure 9. The (**a**) temperature distribution and (**b**) heat flux of the modified design-2 for copper material.

Table 3. The results of existing models.

S No.	Geometry	Temperature (°C)		Total Heat Flux (w/mm²)	
1.	Existing model	Max 150	Min 135	Theoretical 0.059	Analytical 0.053

Table 4. The results of modified designs.

S No.	Geometry	Temperature (°C)					
		CI		Al (6061)		Copper	
		Temperature (Min)	Total Heat Flux (Max)	Temperature (Min)	Total Heat Flux (Max)	Temperature (Min)	Total Heat Flux (Max)
1.	Modified design-1	138.65	0.040	144.88	0.034	147.97	0.0349
2	Modified design-2	140.43	0.027	145.74	0.022	148.32	0.023

5. Conclusions

- The present analysis is investigated based on a two-wheeler engine cylinder consisting of fins. Different fin designs are considered to increase the rate of heat transfer. The investigation of the engine cylinders is conducted with regard to thermal properties, utilizing various fin materials and designs.
- Three different models are simulated, i.e., the existing model, modified design-1, and modified design-2. Different materials are used for fins, such as aluminum alloy 6061, cast iron, and copper.
- The model of the engine, featuring various fins, is designed by CATIA, and thermal analysis is done with ANSYS. By observing the thermal analysis results, for modified design-2, the total heat flux is more for aluminum alloy 6061 than other two materials. The use of aluminum alloy 6061 results in lower weight, making it a better choice compared to cast iron and copper.

Author Contributions: Conceptualization, the design process of fin and its simulation process, methodology, P.K.D.; software, validation, P.K.D.; formal analysis, P.K.D. and M.Z.; investigation, J.P. and S.K.D.; data curation, P.K.D.; writing—original draft preparation, P.K.D., M.Z., J.P. and S.K.D.; writing—review and editing, P.K.D., M.Z., J.P. and S.K.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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