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Thermos Structural Analysis of Two-Wheeler Engine Casing for Better Performance

S. Manikandan[1,*], C. Christina Angelin[2], S. Silvia Priscila[3], Saly Jaber[4]

[1]Department of Robotics and Automation, Dhaanish Ahmed College of Engineering, Chennai, Tamil Nadu, India.
[2]Department of Mathematics, Dhaanish Ahmed College of Engineering, Chennai, Tamil Nadu, India.
[3]Department of Computer Science, Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu, India.
[4]Department of Analytical Chemistry, Saint Joseph University, Beirut, Lebanon.
manikandan@dhaanishcollege.in[1], christeenaangelin@gmail.com[2], silviaprisila.cbcs.cs@bharathuniv.ac.in[3], Saly.jaber@usj.edu.lb[4]

*Corresponding author

Abstract: An engine cylinder is a major automobile component that results in considerable temperature fluctuations and thermal stresses. To enhance the rate of heat dissipation, fins are mounted on its surface. The output of the thermal analysis of these fins provides information regarding the process of heat dissipation inside the cylinder. As the increase in surface area leads to an increase in the rate of heat dissipation, the design of such systems becomes complex. The primary focus of this paper will be on the thermal properties of cylinder fins, which vary in geometry, material, and thickness, using Ansys Workbench. Transient thermal analysis encompasses temperature variations and other thermal properties that change over time, making it crucial for cooling systems. Important parameters can be identified through this, which can determine temperature distribution dynamics, such as design parameters, that could lead to significant enhancements in efficiency and durability. The current study evaluates cylinder fins based on materials such as Aluminium Alloy 6061, which has a higher thermal conductivity coefficient. An appropriate simulation enhances design for better performance and prolongs the lifetime of parts. Issues related to the complexity of engine designs, increased cooling requirements, and reliability concerns are addressed with the assistance of advanced thermal simulation.

Keywords: Engine Cylinder; Thermal Conductivity; Fossil Fuel; Mechanical Energy; Pressure Gases; Ansys Workbench; Thermal Simulation; Cylinder Material; Combustion Engines.

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1. Introduction

Internal combustion engines are based on the combustion of a fuel, usually a fossil fuel, with an oxidizer, which in most cases is air, in a combustion chamber. High-pressure and high-temperature products of combustion directly move parts of an engine, such as pistons, turbine blades, or nozzles, converting the force into mechanical energy [1]. In operation, a significant quantity of heat is transferred to the walls of the cylinder. If this is not dissipated appropriately, it could lead to the pre-ignition of the fuel-air mixture, burning away of lubricants, piston seizure, and damage to the cylinder material, as previously noted in [2].

This makes temperature control in the cylinder wall essential for sustaining optimal engine performance and longevity. However, overcooling is dangerous because it reduces thermal efficiency, leading to increased heat loss, decreased fuel vaporization, and increased lubrication viscosity, which in turn increases piston friction and reduces mechanical efficiency, as noted in research [3]. Thus, cooling must neither be too little nor too much, but rather suitable for effective performance [4].

Internal combustion engines are primarily cooled using a combination of air and water. Numerous studies have been conducted based on this [5]. Air cooling has been used on automobiles and trucks, utilizing airflow over an engine surface to achieve cooling, often with the aid of fins. This improves the effective area for dissipating heat from the surface, but obstructs airflow, establishing a compromise between the enhanced cooling of heat transfer and aerodynamics; experimental analysis explains this [6]. Liquid cooling is commonly used in most maritime and automotive applications, where it transfers heat from the engine using water or chemical coolants. In marine applications, the coolant medium is most often seawater, which can be used directly or as a component of a chemical coolant in closed systems, as described in earlier research [7].

The liquid-cooled systems have water circulated within passages known as water jackets, which absorb heat from the engine. Since the circulating water might arise through the principle of natural circulation based on thermal differences, or by pump-forced circulation, the forced flow enhances the cooling efficiency [8]. The heat is consequently effectively removed due to the use of a centrifugal pump in the crankshaft of the engine, which enhances the flow rates of coolants in forced circulation systems [9]. Water with heated radiators cools off in fins, as established by computational studies [10]. The coolant temperature is controlled by a thermostat valve, which bypasses the radiator at temperatures below 75°C to prevent overcooling and associated problems, such as corrosion and acid formation [11].

In an internal combustion engine, not all of the heat generated in the combustion process is converted to useful work. Of the energy input, about 30% is converted to mechanical work at the crankshaft. The remaining 30% escapes as exhaust heat [12]. Minor losses attributed to friction, compression, and direct heat rejection by the engine are other minor losses that have been accounted for in studies on energy balances [13]. This 30% must be removed from the cooling system to maintain the stability of the engine's operation and to prevent overheating [14]. It is the balance between energy conversion and heat dissipation that highlights the crucial role of cooling systems in an internal combustion engine, a conclusion supported by previous thermal studies [15].

From the thermal engineering perspective, design factors related to the fin and combustion chamber in the construction of components are critical. Fins are commonly used in air- and liquid-cooled engines because their increased surface area provides better heat transfer capabilities. The geometries, shapes, and thicknesses of fins can influence both cooling rates and the overall efficiency of cooling. This has been studied in detail in thermal analysis [1]. Numerical thermal analyses have revealed that optimisation of these parameters improves fin effectiveness and efficiency [5]. For example, permeable fins have been found to provide a higher rate of heat transfer compared to conventional solid fins for similar configurations, as demonstrated in comparative studies [7]. Such developments suggest that innovative design solutions could be found to improve engine cooling performance. Combustion chamber design in SI engines is also a crucial parameter that affects engine performance. Chamber shape, spark plug placement, and valve configuration influence the combustion process, thermal efficiency, and knocking tendency, as discussed in research on engine performance [10].

The primary objectives of the combustion chamber design are to achieve smooth engine operation, maximize power output, and optimize thermal efficiency. These conditions are met by various configurations, such as T-head, L-head, I-head, and F-head types, with factors including octane requirements and operational smoothness [13]. This paper discusses the thermal-structural assessment of engine casings and cylinder fins, aiming to enhance engine performance. It has been recognized that for any engine casing and fins, there is considerable dissipation of heat produced from the combustion processes; therefore, an optimum efficiency rate is a critical factor affecting engine safety temperatures. The effects of varying geometries, shapes, and thicknesses of the fins in numerical analysis-based assessments of heat dissipation rates will be addressed to optimize fin configurations, achieving higher thermal performance. Fins with increased surface area significantly enhance the heat transfer rate, and parameters related to the fin design, such as height, spacing, and material, become critical for developing an effective cooling mechanism, as shown in previous work [9].

Additionally, the analysis considers the effectiveness of both natural and forced circulation systems for the water-cooled system. In natural circulation systems, the water flow is induced by temperature-driven density differences. In contrast, in forced circulation systems, coolant is actively circulated through the engine with the help of a centrifugal pump. These ratings assess how well they regulate the engine's temperature, as discussed earlier [14]. Forced circulation, in particular, has the advantage of faster cooling rates, which is necessary for high-performance engines, as already seen in the previous studies [12]. It introduces radiator fins, along with a temperature controller, such as a thermostat valve, to precisely control the coolant temperature. As a result, overheating or overcooling conditions are avoided altogether, as recent simulations have also revealed [11].

This study's results have the potential to optimize system designs and engine parts, enabling further improvement in heat dissipation efficiency. Such a system can keep the engine temperatures safely within predetermined limits, thereby avoiding problems such as pre-ignition, degradation of lubricant levels, or material failure, as observed in numerical models [8]. Moreover, efficient thermal management directly affects the overall efficiency of the engine, as it minimizes heat loss, ensures effective fuel combustion, and reduces friction-related energy losses, as demonstrated in advanced thermal studies [15]. The study also highlights the importance of balancing thermal and mechanical performance, as overcooling leads to a loss of engine efficiency due to increased lubrication viscosity and reduced combustion efficiency, as demonstrated by experimental studies [10].

This holistic approach of thermos-structural analysis has been very valuable in understanding how thermal management relates to engine design. Optimising fin configuration and cooling mechanism, engine design can be done efficiently in ways that provide maximum reliability and performance. It plays a key role in advancements made in both automotive and engineering technologies. These research works not only permit the realization of better current designs but also enable the development of innovative cooling methods that satisfy all the demands modern high-performance engines require, as identified in numerical studies [13]. This work concludes by highlighting the importance of integrating thermal and mechanical considerations into engine design to ensure long-term durability, efficiency, and to mitigate the challenges associated with heat dissipation in internal combustion engines.

Objectives: To attain the above aim, the following objectives are formulated

- Study the cylinder head (Model) without actual manufacturing.
- Select the proper material for the cylinder head.
- The Model of the cylinder head and different fin shapes are also included.
- Analyse the heat transfer rate along the cylinder head and on different-shaped fins.
- Finally, the results of heat transfer by fins are compared.

2. Literature survey

In most cases, the two-wheeler engine casings and fins concerning performance are thermos-structurally analysed. This field focuses on optimizing heat transfer mechanisms and design configurations. Fins on an engine are responsible for dissipating combustion-generated heat. They are sensitive to geometrical parameters, material properties, pitch, number, and environmental conditions while being optimised in thermal performance. Such parameters have been varied in studies showing that the rate of heat dissipation can be dramatically increased. For example, experiments conducted in a wind tunnel demonstrated that modifying the fin geometry and spacing, along with selecting the proper material, enhanced the coefficient of surface heat transfer, as indicated by studies performed in controlled environments [1]. It is also known that fins work most efficiently based on air velocity and the distance between the fins. Hence, optimised geometries of the cylinder body, along with the cylinder head equipped with fins, provide excellent thermal performance.

This can be inferred from prior experimental studies [2]. Combustion models began as zero-dimensional studies, gradually evolving in complexity through the incorporation of additional analysis, as the fin geometry was recognized as pivotal to their performance [6]. Extended fins attached to cylinders and experiments carried out also compared the fin size to the heat transfer. It was established that maximum efficiency is achieved with an optimum thickness of fins, and thinner fins in larger numbers are more suitable for high-speed applications. This is because the thinner fins produce a reduced overall weight for the engine and increase the passage of air through them, thereby enhancing cooling, as seen from tests performed on different fin arrangements [3]. The outer region of the fin was found to have a fair amount of heat transfer, which is still within further scope for enhancement. Researchers suggest that this limitation can be overcome by introducing slits and holes in the fin design, allowing for effective heat dissipation from the external surfaces of the fins, as confirmed by numerical simulation [4].

Optimization of fin dimensions was also carried out using advanced numerical techniques, such as LMM, by which the maximum width and minimum height of fins can be predicted with good precision. In the case of impingement cooling heat sinks, important parameters were found to be those associated with the non-uniform dimensions of the fins. The thermal resistances in systems can be substantially reduced by optimised dimensions in heat sinks, leading to improvements in heat sink design as discovered through comprehensive parametric analyses [5]. The numerical experiments have also demonstrated that the optimum configuration of a heat sink can reduce thermal resistance by over 3% while also increasing Nusselt number and coefficient of efficiency (COE) within the same order of magnitude [15]. Subsequent works discuss the effects of fin parameters and indicate that variables such as cross-section, pitch, material, air velocity, and exposed angle are variables that influence heat transfer rates.

Experiments done over a spectrum of Reynolds numbers have indicated that permeable fins, which are permeable so that air passes through the porous structure of a fin, possess substantially higher Nusselt numbers as compared to a solid fin, as observed in the experimental work performed concerning variations of the Reynolds number [7]. This suggests that permeable fins may provide a more effective cooling solution, especially in applications that require critical consideration of air velocity and flow dynamics [9]. Substantial work has also been done concerning the relationship between the number of fins and dissipation. It is shown that the increase does not necessarily continue as more fins are added, particularly when the surface temperature of the cylinder stabilizes. This has been demonstrated in recent experimental analyses [10].

However, comparative studies on different heat sink configurations have recently garnered the most interest regarding the understanding of fin designs and the effects these impose on natural convection. Significant differences in thermal performance exist among various fin assemblages, including rectangular, trapezoidal, and inverted trapezoidal patterns. For inverted trapezoidal fins, the coefficient of heat transfer was 25% higher than that of a trapezoidal fin and 10% larger than that of rectangular fins, as found through comparison studies performed under controlled conditions [11]. This is due to the good airflow provided by the shape geometry of the inverted trapezoidal fins, which are capable of producing high heat dissipation, as indicated by a parametric evaluation [12].

Apart from the experimental and numerical investigations, simulation through CFD becomes a tool for optimising the geometry of a fin. The performance can be identified in terms of design parameters by simulating various configurations and operating conditions, as carried out in recent advanced studies based on CFD [8]. CFD studies have shown that certain fin configurations, such as varying cross-sectional profiles or perforations, can enhance heat transfer by improving airflow patterns around the fins [13]. These simulations also open up avenues for exploring new materials and coatings that can further enhance thermal conductivity and resistance to environmental degradation. Hybrid approaches to thermal management may be derived from recent studies into the integration of fins with other cooling mechanisms, including liquid cooling systems.

The unique approach, combining fin-based air cooling with forced liquid cooling, could result in excellent heat dissipation for high-performance applications, such as in engines where water or other coolants are circulated through passages close to the casing, absorb the heat, and transfer it to the fins for dissipation. In these systems, centrifugal pumps and radiator fins are utilized to further enhance cooling efficiency, allowing the engine to operate safely at a limited temperature, as supported by analyses of hybrid cooling systems [6]. The other major area is the design and management of the combustion chamber, including heat transfer and the ideal performance of the engine. The shape and size of the chamber, along with the spark plugs and valves, will determine the combustion process and, consequently, the amount of heat produced. Optimized designs for the combustion chamber reduce the thermal load on the engine casing, thereby improving the efficiency of the cooling system, as has also been found in studies specifically focused on the configuration of the combustion chambers [14]. These findings suggest the need for an integrated approach to engine design, where thermal management is considered in conjunction with mechanical and combustion efficiency [7].

3. Methodology

The material selection, structural change, design principles, thermal simulation, and advanced computer-aided tools design all comprise the methodology for optimising the two-wheeler engine casing performance by thermos-structural analysis. Aluminium alloy, with its high thermal conductivity and ease of weldability, has been extensively used in fins and tubes. Similar components are brass. These materials have been selected due to their excellent corrosion resistance, strength, and flexibility. These materials have been selected for this application to make the engine casing, offering thermal performance improvements in extreme conditions due to their endurance. Aluminium alloy has been selected due to its standard-setting machinability, which enables the provision of accurate dimensions without requiring minimum machining.

The existing design of the engine, which consisted of flat-structured fins, was redesigned to improve heat dissipation rates. The changes involved alterations to fin geometry, along with an increase in its thickness, whereas the spacing between fins is another modification made here. With optimisation for increased cooling performance in the new design, its performance regarding heat gain is expected to improve with this new model. All the modifications were drafted using PTC Creo, and an ANSYS Workbench tool was then applied to create a thermal analysis simulation, advancing the research to a new level. Simulations comparing the two structures showed that the new design outperformed conventional flat fins in terms of higher heat transfer rates.

The fin dimensions were balanced in consideration of environmental conditions, the blower's potential, and the structure applied in the used air conditioning system of the engine. The optimised dimensions of the tube included an outer diameter of 54 mm, an inner diameter of 52 mm, and a length of 96 mm. The fins were designed to have a thickness of 3 mm and a spacing of 5 mm between them. This design optimised the orientation to achieve the maximum heat transfer coefficient for the system under a range of operating conditions and efficiencies. Other adverse effects considered to be caused by engine overheating included the evaporation of lubricating oil, which creates a metal-to-metal contact condition, leading to the seizure of the piston and cylinder wall. It can produce thermal stresses in the cylinder, piston, and cylinder head that can cause cracking or deformation. The sticking of piston rings, poor sealing of the cylinder, and increased blow-by of gases were other problems involved. All these decrease the thermal efficiency. All of these improvements enhance the redesigned cooling system, thereby improving the reliability and durability of the engine.

The scope of the paper involved designing and analysing a cylinder fin configuration for a 125cc engine. The analysis included variation in geometry, thickness, and spacing of fins to optimise the thermal properties. The assumptions incorporated uniform ambient air temperature everywhere around the engine, constant heat convection coefficient everywhere in the boundary layer, and ideally linear relations among loads and the corresponding responses of the system under these loads and boundary conditions. All the loads/boundary conditions during the simulation had to be consistent for the corresponding results. Advanced CAD/CAM systems were applied for modeling and analysis to optimize design stages in terms of efficiency and accuracy. This helped develop complex geometric models through CAD and ensured a smooth transition to manufacturing stages through CAM. These ensured better productivity, uniformity, and quality in designs with a lesser probability of errors due to manual drafting. Die moulds, fixtures, and EDM electrodes were designed using CAD/CAM to achieve accuracy in manufacturing.

The applications also included NC and CNC machining programming, as well as tool design and quality control measures. AutoCAD further enabled flexible yet accurate design visualization through 2D drafting and 3D wireframe modeling. Furthermore, dimensioning, annotation, and font usage would help to present the design effectively. With an integrated CAD/CAM approach and enhanced responses to design challenges, the time to develop a prototype was significantly reduced. This would lead to material optimisation, innovative fin designs, advanced simulations, and CAD/CAM technologies that come under the thermos-structural analysis methodology for two-wheeler engine casings. Such a practice helps improve reliability, efficiency, and performance by effectively handling overheating and thermal stress in two-wheeler engines. The solid groundwork for this study is based on the complete implementation of computational tools coupled with materials engineering for designing thermal management systems for efficient two-wheeler engines.

The methodology employed by ANSYS for conducting thermos-structural analysis of a two-wheeler engine casing utilizes advanced modeling, meshing techniques, and simulation approaches to achieve accurate and reliable results. ANSYS Design Modeler is a powerful 3D modeling tool with a parametric, feature-based approach for model creation and optimization. Contrast ANSYS Design Modeler with other typical 3D tools due to its ability to represent positions within a 3D space using planes, which also enables the precise definition of lengths, diameters, and angles; thus, all these can be quickly captured at the design intent. Using the following features for any addition or removal of extrusion, cut, or slot in creating detailed geometry, as applied for complicated parts such as the casings of an engine.

The underlying methodology is Finite Element Analysis, which offers a solving technique for problems in continuum mechanics. FEA is a discretization method that divides a continuous domain into finite elements, coupled by nodes that can, on their own, accurately model both stress, heat transfer, and dynamic responses. Of the three, structural is the most applied, and is not only used with structures and engineering works, but also in mechanical parts ranging from pistons to casings and tools, among others. It includes seven categories of structural analysis, including stationary, modal, harmonic, transient dynamic, buckling analysis, and frequency response analysis. Using this application can solve most operational conditions in a computer. Transient thermal analysis is the assessment of change in time, but its importance derives from the consideration that thermal stresses, which may provoke material failure, must not be neglected.

Involving these processes, gradually introducing nonlinear phenomena that can arise from material properties, temperature dependence, or radiation, enables the acquisition of a solution in a highly realistic and precise manner. Another very major step is mesh generation in FEA. The physical model or original part of interest would subsequently be analyzed numerically, utilizing elements and nodes in the design. Any meshing type, by its very nature and quality, yields accuracy in the obtained results. Generally, the type of meshing is defined by the complex piece of geometry, boundary conditions, types of analyses to be performed on it, or even the desired precision. Automatic mesh generation is easier but less effective in areas with stress gradients. In contrast, parametric or manual mesh generation offers more control and enhanced convergence with structured elements, such as brick elements. Meshing involves defining element attributes and material properties, applying mesh control, and generating a mesh, all optimised for a balance between computational efficiency and result accuracy.

This central platform enables ANSYS Workbench to interface with multiphysics simulations through a single, intuitive interface. Users can build a parametric model, perform sensitivity analysis, and optimise designs between coupled physics domains. It produces a much bigger value in simulating realistic conditions that are often infeasible or too expensive to test physically. ANSYS enables innovation in products through virtual prototyping, offering a range of tools that cater to organisations' needs, from the most commonly used to those requiring high levels of expertise. Ease in scalability, in terms of performance from desktop level to supercomputer level, and flexibility in one user level, enterprise-wide deployments, ease of use with present and future challenges.

Material properties and assumptions are also integral to the methodology employed in simulations. Aluminium alloy, with high thermal conductivity and machinability, has been selected for the engine casing and fins. Here, element attributes have been used to define the thermal and mechanical properties of materials, allowing their behavior to be accurately represented. As much as possible, due to the limited complexity, all assumptions were considered with a constant ambient air temperature, along with other linear load response relationships of any other relevant element in the analysis. Merging powerful modelling capabilities with the analytical power of FEA and advanced meshing techniques, along with a multiphysics simulation environment provided in ANSYS Workbench, has been very effective. Again, through these integrating tools and approaches, more holistic knowledge regarding thermos-structural behavior than could ever be achieved through efficient, reliable, and innovative designs of the two-wheeler engine casings has emerged (Figure 1).

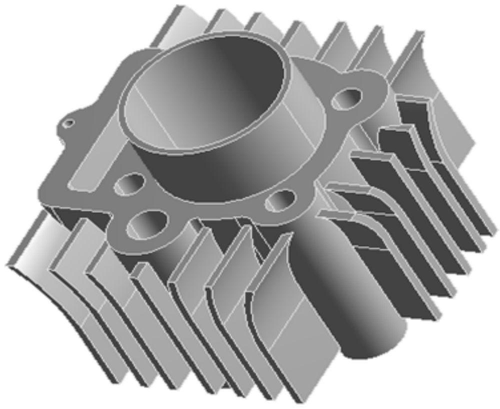

Figure 1: 3D model of engine casing with fins for enhanced heat dissipation in two-wheeler engines

3.1. Procedures to Perform FEA by ANSYS

Finite element analysis in ANSYS can be accurately followed only through a five-step process. It is the only process that ensures the accuracy and reliability of the results. Information gathering involves collecting details about the problem to be addressed, specifically geometric and material details, as well as the applied load. Steps in the process of creating a finite element model encompass an important sequence of steps, including the following: setting the system of units to be used, choosing the applicable types of elements, specifying the material properties of concern, and describing the finite element geometry. ANSYS assumes no system of units for any analysis it assumes. The user needs to prepare and maintain consistency at every step.

This requires much attention to maintaining uniformity in dimensions, loads, and material properties. Very important is the proper selection of elements. The choice of elements depends on their ability to represent the physical and geometrical characteristics of the problem analyzed correctly. Included in these considerations are the type of loading, geometry of the structure, and the expected response. All these decisions directly affect the accuracy of the analysis and the computational efficiency. The building of the model requires setting material properties, such as elasticity, density, and thermal conductivity, in a manner that allows materials to behave realistically under all conditions. All these activities assure that a properly prepared finite element model is supplied and can, therefore, pass all the subsequent analysis steps with fairly good accuracy, especially in representing reality. Such a structured approach would enable ANSYS users to develop models that provide meaningful insights into the behavior of complex systems under specific conditions.

Figure 2 represents the thermos-structural analysis of the process using ANSYS. To start with, the first step is to create or input a 3D model, which serves as the basic model for the system or component being analysed. It further develops and defines that model in ANSYS Workbench with materials and boundary conditions, meaning the thermal or structural constraints that are applied to actualize simulation parameters. Then, a Loading Case defines the kinds and amplitudes of external forces, pressures, or thermal inputs that represent operational conditions. Once setup is complete, data is imported into the FEM Input, where it is discretized into a finite number of elements, allowing for analysis to be computed with very good accuracy.

This FEM data is used for the computation of results under the specified conditions of stress, deformation, or temperature distribution. Finally, after the completion of the simulation process, an Analysis of the results evaluates the output data to gain insights into performance, identify critical areas, and enhance the design. The flowchart is presented as a methodical process that involves conceptual design progressing toward detailed analysis, integrating various computational tools and techniques.

Through this methodological approach, the model will be prepared correctly, simulated properly, and evaluated thoroughly to enhance its performance.

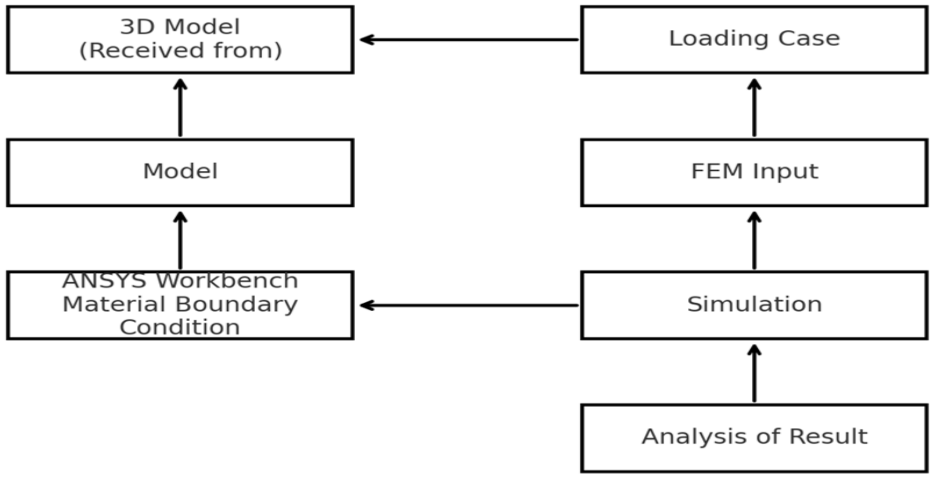

Figure 2: Flowchart of the thermos-structural analysis process in ANSYS

4. Results

This study has established significant thermal and mechanical performances for a two-wheeler engine casing. A detailed thermo-structural analysis, based on temperature distributions, stress distributions, and deformation behaviors in critical areas, has been conducted and discussed here to enhance the durability and efficiency of the casing design. The analysis reveals that combustion heat increases the temperature concentration in the region near the cylinder wall and in the surrounding area up to 4230 K. The areas on the exposed outer surfaces are cooler as they are subjected to natural convection. The boundary conditions of convection effectively simulated the air-cooling system by illustrating how heat is dissipated from the casing into the surrounding environment.

The analysis of thermal stresses has shown that the steepest temperature gradients near the combustion chamber produce the highest levels of thermal stress. In the mounting region, it reaches its maximum due to the combined effects of operational load and thermal expansion. The deformation analysis yielded a generally satisfactory overall value of deformation; however, localized peaks in deformation exist, which can create zones of probable fatigue or fracture during extensive operations. Material properties played a significant role in the analysis, where materials with high thermal conductivity and strength performed better by minimizing stress concentrations and improving heat dissipation. Heat Conduction Equation (3D steady-state) is:

$$\nabla(k\nabla T) + Q = 0 \quad (1)$$

Here, k: Thermal conductivity, T: Temperature distribution, Q: Internal heat generation per unit volume.

Table 1: Calculation of static analysis

S. No.	Model name	Total deformation(mm)	Thermal strain (No Unit)	Equivalent stress (MPa)
1	Model: 1	0.25	0.003	684.69
2	Model: 2	0.30	0.012	831.46
3	Model: 3	0.25	0.004	1185.6
4	Model: 4	0.24	0.003	1174.6
5	Model: 5	0.32	0.010	572.51

Table 1 presents the static analysis of the five models selected for the engine casing. The total deformation, thermal strain, and equivalent stress are represented under operating conditions. Models 1 and 3 exhibit the same total deformation, which is 0.25mm. However, the values of the other two, namely, the thermal strain and the equivalent stress, differ slightly. Model 3 provided a higher thermal strain of 0.004 and equivalent stress of 1185.6 MPa as compared to model 1, which recorded a thermal strain of 0.003 and an equivalent stress of 684.69 MPa. Model 2 exhibited the highest thermal strain of 0.012 and an equivalent stress of 831.46 MPa, as well as the highest total deformation of 0.30 mm, indicating that it might be more susceptible to greater thermal and mechanical stresses.

Model 4 had a lower deformation of 0.24 mm and an equivalent stress of 1174.6 MPa, compared to Model 3. However, the thermal strain of model 4 was comparable to that of model 1, which is 0.003. The model 5 was considered to have equal performance. Model 5's total deformation of 0.32 mm had a moderate thermal strain of 0.010. It also revealed the minimum value of equivalent stress among the models as 572.51 MPa. The reduced equivalent stress in Model 5, therefore, reflects better resistance to thermal stresses and generally improved performance under similar conditions. From the results, Model 5 is thus recommended as the optimum design for the engine casing, as its equivalent stress is found to be significantly lower than that of the others, thereby greatly enhancing durability and reliability, which leads to superior performance and a reduced probability of failure or thermal fatigue during long-duration operation. The thermal stress relation is:

$$\sigma_{ij} = \lambda \delta_{ij} \nabla \vec{u} + 2G\varepsilon_{ij} - \beta(3\lambda + 2G)\delta_{ij}(T - T_0) \qquad (2)$$

σ_{ij}: Stress tensor, λ: $Lame^1s$ first parameter, δ_{ij}: Kronecker delta, $\vec{u}$: Displacement vector, G: Shear modulus, ε_{ij}: Strain tensor, β: Thermal expansion coefficient, T: Current temperature, *To*: Reference temperature.

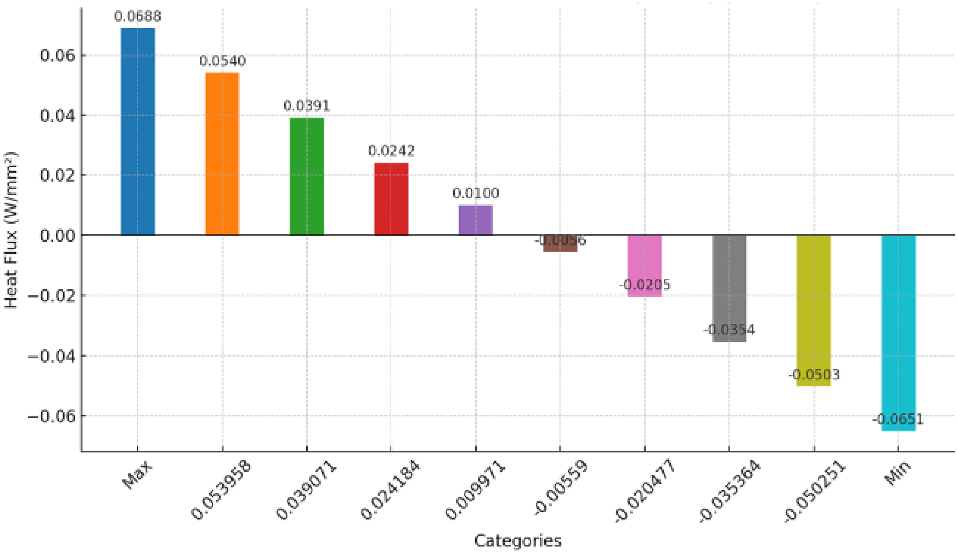

Figure 3: Total heat flux along the X-axis represented as directional heat flux for various categories

Figure 3 illustrates the total heat flux in terms of direction, with values of directional heat flux plotted along the X-axis, categorized from greatest to least. In this chart, each bar represents the intensity of the heat flux in the direction it is directed. For example, a positive value depicted flow in one direction, while a negative value described the flow in the opposite direction. The maximum heat flux in the first category will be 0.068845 W/mm², representing the largest intensity of heat transfer along the X-axis. They have been succeeding in falling, one after another, through all the categories in which these values are lower.

These lower magnitudes are 0.024184 W/mm² and 0.009971 W/mm², respectively. Since the values are negative, starting from -0.00559 W/mm² in later categories dominate those values of change in heat transfer directionality, and the minimum magnitude of oppositely moving heat flow is given by a minimum heat flux value of -0.065138 W/mm². Some other colours would make this representation much clearer, as every bar has a uniquely assigned colour within the chart. The illustration effectively conveys the distribution of heat flux and its directional variations, making it more useful for thermal analysis and studies on heat management. The negative and positive values are symmetrically arranged to demonstrate the dynamics of heat transfer in the system. Navier-Cauchy equation for Thermo-Elastic deformation is given below:

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \nabla \sigma_{ij} + f_i \qquad (3)$$

Here, ρ: Density, u_i: Displacement components, t: Time, σ_{ij}: Stress tensor, f_i: Body force per unit volume. Energy conservation (Thermal Loading) can be framed as:

$$\frac{\partial}{\partial t}(\rho e) + \nabla \cdot \vec{q} = \dot{q} + \sigma_{ij}\frac{\partial \varepsilon_{ij}}{\partial t} \qquad (4)$$

Here, ρ:Density, e: Internal energy per unit mass, $\vec{q}$: Heat flux vector, q: Heat generation rate, σ_{ij}: Stress tensor, ε_{ij}: Strain tensor.

Table 2: Categorised deformation ranges with representative values observed in static structural analysis

Range 1 (Min - 0.072509 mm)	**Range 2 (0.072509 - 0.14502 mm)**	**Range 3 (0.14502 - 0.21753 mm)**	**Range 4 (0.21753 - 0.29004 mm)**	**Range 5 (0.29004 - Max)**
0	0.072509	0.14502	0.21753	0.29004
0.036255	0.10876	0.18127	0.25378	0.32629
0.072509	0.14502	0.21753	0.29004	Max

Table 2 shows the deformation ranges for static structural analysis of the system. The deformation ranges are five: Range 1 (Min - 0.072509 mm), Range 2 (0.072509 - 0.14502 mm), Range 3 (0.14502 - 0.21753 mm), Range 4 (0.21753 - 0.29004 mm), and Range 5 (0.29004 - Max). The numbers in the table are the deformation levels within these ranges. Major thresholds for the first row: 0 mm to Maximas for each one of them, 0.072509 mm in Range 1 and 0.29004 in Range 4. The middle row contains the midpoint value for deformation per range, providing a more even view of the variation within that range. For Range 1, the value was 0.036255 mm, and for Range 5, it was 0.32629 mm. The last row is the critical thresholds, which are just a repeated final major with Range 5 featuring "Max, which is the maximum deformation measured in this study. The structured view presented serves as the basis for understanding material deformation between ranges, thereby developing an impression of material performance and stress in the testing material. This is data that must be used for optimising the design parameters with structural integrity under operational conditions. The boundary condition for heat transfer is:

$$-k\frac{\partial T}{\partial n} = h(T - T_\infty) \qquad (5)$$

Here, k: Thermal conductivity, h: Convective heat transfer coefficient, T: Surface temperature, T_∞: Ambient temperature, $\frac{\partial T}{\partial n}$: Temperature gradient normal to the surface. Mesh refinement significantly impacted the accuracy of the results, particularly in regions of high stress and temperature gradients. A mesh size of 5 mm was used to give a fair balance between the computational intensity and result fidelity. There was scope for in-depth information in key areas without incurring excessive computational costs. The integration of thermal analysis with structural analysis provided insights into areas where design optimization was expected to lead to performance enhancements, including wall thickness optimization, the use of composite materials, and redesign to provide efficient cooling from the fins. This made it easy to study parts like the head of the piston or the spark plug, but the focus was maintained by considering the behaviour at the casing to hold a practical and detailed study. Some results from the ground indicate that building and developing even more robust and potent casings within the engines can reduce the risk rates of thermal fatigue and operational age. Such a comprehensive review highlights the use of thermo-structural analysis that can be required to enhance two-wheeler performance.

It enables advancements in modern two-wheeler design, particularly in terms of performance, reliability, and sustainability objectives. The various engine casing models are of great importance for evaluating complex mechanical systems under numerous operating conditions. Several types of structural elements, all designed for specific structural action, are required for accurate and reliable results. The determination of which element to apply depends on the characteristic responses the system should exhibit under study. Among them, truss elements are one of the basic ones and are used the most for modelling two-force members in terms of tension and compression loads. The degree of freedom is given at nodes that have been set as being equal to one for each node of one axial displacement.

In most cases, the properties of the material as well as the dimensions of the cross-section are the same over their entire length. Truss elements are available in two-dimensional and three-dimensional configurations. Therefore, they can be used for a wide variety of structural analyses. The most common use is in the analysis of truss structures, where axial forces predominate and simplicity in modeling and computing is an important consideration. The second important element in the modeling arsenal is the beam element, which is designed to resist lateral loads and bending moments. They can have six degrees of freedom per node, which include translations and rotations. In the case of pure bending, the number of degrees of freedom can be reduced to four while simplifying the model without compromising the accuracy of the bending behavior. Beam elements are crucial in the analysis of structural systems that undergo significant bending forces. These include bridges and frames. They are essential in finite element analyses, as they can accurately mimic complex bending and rotational behaviors.

Figure 4 shows the result of the transient thermal analysis in terms of absolute temperatures and percentage increase across certain criteria. The recorded temperature varied between 141.4°C and as high as 200°C. The critical inclinations within this paper were those mentioned above: 147.91, 154.43, and 186.98°C. Here, every bar represents a point in space, and each bar represents a discrete level of temperature at a specific point. The orange line is an accumulation curve that reflects the progressive buildup of temperatures, indicating the accumulation of thermal load over the system. This double representation accounts for a comprehensive presentation of thermal behavior, allowing for an easier pathway to observing localized variations in temperature and their contribution to overall system thermal dynamics. Sharp increases in the curve at the high end of the temperature range show that the effects of higher intensity are becoming significant on the system.

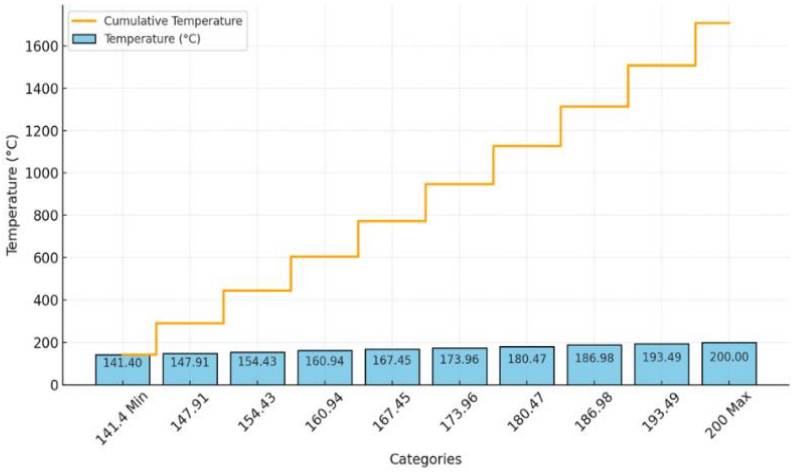

Figure 4: Depiction of temperature distribution and cumulative thermal load

The waterfall chart can best portray this; steep spikes may denote well-optimised or even improved spots of thermal management. As such, it serves as an influential visualizing tool to analyze performance, given that it may exhibit some degree of fluctuations with varying thermal loads. It could therefore prove very effective for heat dissipation, material choice, and overall efficiency optimization in systems. Frame elements possess properties of truss and beam elements. Frame elements can resist lateral loads, axial forces, and moments. The frame elements are referred to as beam-column elements. They are very useful in three-dimensional structural modelling where biaxial bending, torsion, axial deformation, and biaxial shear deformations occur simultaneously. Frame elements are assumed to be two-joint connections with straight-line connectivity.

The local coordinate system defines section properties and directions of loads applied. This feature of frame elements enables them to handle the behavior of both axially loaded members and bending forces simultaneously. So, they find wide applications in structures such as building frameworks and mechanical supports subjected to the combined action of forces acting on individual members. Shell elements constitute a significant portion of the finite element modelling technique. This consists of three-dimensional solid elements, which are identified by the characteristic that one of their dimensions is significantly smaller compared to the other two. It carries both membrane loads and plate bending/shear, and can be both quadrilateral or triangular. The major use occurs where stress levels may be localised in more complex structures such as cellular superstructures, piers, and caissons. Shell elements provide internal forces at the element mid-surface per unit length as well as on the top and bottom surfaces in terms of force per unit area. They are indispensable in structural analyses where local stress concentration needs to be evaluated with very high accuracy.

The plate element is a type of shell element, specifically formulated for two-dimensional plate-bending behavior. Elements of plates possess two rotational degrees of freedom in an out-of-the-plane and one normal displacement degree of freedom. They are more efficient in modelling both normal moments and cross moments in the same plane. The application of plate elements occurs when the structural behavior of flat surfaces under bending loads needs to be analyzed, considering no membrane effects. Plate elements are widely used in the analysis of thin-walled structures, bridges, and slabs. Tetrahedral elements are preferred in three-dimensional finite element modeling; one major reason is that such elements are easy to discretize geometries into a basic form. Another important feature of the tetrahedron element is the shape function, which interpolates the solution between discrete nodes of the mesh. Linear shape functions are mostly used due to the simplicity of computation that such arithmetic demands. Such elements have proven useful in the Galerkin method as they ensure good numerical solutions. The model can efficiently simulate the behaviour of irregular geometries under different loading conditions by dividing a structure into smaller tetrahedral components.

Meshing is perhaps one of the most crucial steps in finite element modeling, providing a balance between computational efficiency and solution accuracy. Mesh discretises the simulation domain into smaller elements, and the size and quality of the mesh have direct implications on the fidelity of the results. In areas with high gradients or stress concentrations, a finer mesh will improve the accuracy of the solution by capturing the details of the structural behaviour. In turn, finer meshes increase computational time with their use, therefore requiring proper consideration when seeking an optimal balance for the study. For this study, the selected mesh size is 5 mm, resulting in a model with 39,324 elements and 11,333 nodes. Mesh refinement: The numerical solution is close to the true one, more so in the regions of stress or gradients of thermal distributions.

Boundary conditions: These conditions provide the boundary constraints and loadings applied during simulation for the model, ensuring that the simulated conditions are accurately representative of reality. In a thermal analysis, the boundary conditions consist of thermal loads and convection boundaries applied to the outer surfaces of the system. For the engine casing model under discussion, surface temperatures of 450 K and 4230 K have been applied for the cylinder wall, as typical for the temperature distributions prevailing in the case of a steady-state run for spark-ignition engines. For this study, such parts as a piston head or spark plug have not been considered. They were deemed negligible in influencing the overall temperature field distribution. Therefore, the mode of heat transfer due to radiation has not been taken into consideration. Instead, the whole dissipation of heat through the body to the ambient has been modelled with the help of convection, depending upon the nature of the flow conditions, and, therefore, must be found out for the case in consideration.

Apart from the thermal boundary conditions, static analysis incorporates the result of the thermal analysis, considering temperature-caused stresses. The displacement restraint was applied to restrain movement in some directions. For instance, the bottom faces of the cylinder block and liner were restrained from vertical motion, whereas the top face was restrained from downward displacement. Such restraints simulate structural behaviour under engine casing operational conditions, accounting for both thermal and mechanical loads. This definition provides a realistic description of the engine casing's performance and safety. Finite element modelling of engine casings in general involves a holistic approach that incorporates a diversity of structural elements, careful meshing, and proper boundary conditions. This model should include all the truss, beam, frame, shell, plate, and tetrahedron elements to accurately represent various structural behaviors. While meshing and boundary conditions are given proper care, a real-world operation is assuredly simulated, and the entire complexity of casings in a real engine is wholly analysed with high accuracy by engineers and researchers. This facilitates critical design decisions in support of advanced modeling techniques, and the mechanical system ultimately proves to be safer and more efficient.

5. Discussion

The discussion section aims to make sense of what happened, utilizing results obtained from thermo-structural and transient thermal analyses of the two-wheeler engine casing. Using insights from data, tables, and graphical representations, it has been demonstrated that there are critical aspects of the casing's performance that lend credibility to design optimization and improved functionality. Table 1 gives the results from static analysis on total deformation, thermal strain, and equivalent stress in five different models. Among these, model 5 is considered the best, exhibiting a moderate total deformation of 0.32 mm and a thermal strain of 0.010, with the lowest equivalent stress of 572.51 MPa. All these characteristics indicate excellent resistance to both thermal and mechanical stresses, suggesting that Model 5 can provide an appropriately balanced structural response, thereby rendering it a favourable candidate for further design applications.

On the other hand, Model 3 suffers from fatigue failure under the same operating conditions with the largest equivalent stress of 1185.6 MPa and considerable thermal strain. These comparisons underscore the importance of limiting stress concentrations to ensure the casing's long-term durability. Table 2 presents the deformation ranges for further qualification purposes to identify potentially differing types of structural response zones. The deformation ranges considered were from a minimum of 0 mm to a maximum of 0.32629 mm, with intermediate steps at 0.072509 mm and 0.14502 mm. This, in turn, provides a better understanding of material behaviour due to operational loads. Such areas of high deformation would also incur probable localised stress concentration that would compromise the structure's integrity shortly. The data is very useful in deciding which materials to select and where reinforcement is needed.

Graphical representation facilitates further discussion of the assistance provided by directional heat flux and the distribution of temperature accumulation. A colour bar is a graph that illustrates the total heat flux along the X-axis, as demonstrated in Figure 3, which clearly shows the variation in direction of heat transfer. At some locations, the heat flux is positive; that is, the maximum local thermal behavior yields a maximum heat flux of 0.068845 W/mm², while the minimum heat flux is -0.065138 W/mm². Such maxima and minima points indicate the need for better work in regions to optimise the temperature gradient, ensuring thorough heat dissipation and establishing thermal stability. For instance, the best fin for cooling by heat or increased coefficient of thermal conductivities of material may not be associated with overheating effects. The local distribution of heat flux also indicates that cooling solutions must be designed specifically to focus on regions of higher thermal gradients for the overall efficiency of the casing.

Figure 4 presents a comprehensive view of the cumulative temperature distribution, along with the corresponding heat flux analysis. This would fall between 141.4°C and 200°C. The graph illustrates the progressive thermal loads along the engine casing, with sharper rises in the upper ranges. Such a profile thus emphasises the areas where a more aggressive form of thermal control is needed. The aggregate view can help determine the pattern of temperature rise in the casing, indicating a need for more potent cooling methods to handle thermal loading. Materials that can dissipate heat more effectively or improved designs for airflow around the casing can easily enhance the casing's thermal performance. The data correlated in these tables and graphs, along with the intimate interaction of thermodynamic and structural parameters, becomes vital. In this particular model 5, the development of low equivalent stress, along with characteristics of heat-flux distribution and the total accumulated temperature field, confirms the need for full consideration in choosing casing construction. Proper heat-flux management will allow regions of low stress concentrations away from this engine casing to operate for longer periods than its service conditions. For instance, regions with high directional heat flux or high cumulative temperature rises are excellent locations where high-performance cooling or composite materials of high thermal resistance can be utilised.

Some actionable recommendations result from the outcomes based on the design perspective: Optimising the wall thickness at areas of higher stress and thermal gradients would balance weight against the strength of the wall. The geometrical structure of the cooling fins must be optimised, especially in areas where thermal hotspots have already been recognised, to enhance heat transfer. Materials with good thermal conductivity, combined with good mechanical properties, would relieve deformation and stresses under operational conditions. Finally, optimised airflow around the casing—especially in critical high-temperature zones—significantly lowers thermal loads and enhances overall performance. The broader implications of thermo-structural behaviour on engine performance can also be inferred from the findings. Lower thermal and mechanical stresses, with a corresponding reduction in probable fatigue failure, may result in higher reliability and longer lifetimes.

More importantly, stable operating temperatures, achieved through improved heat dissipation, are crucial for achieving an engine's optimal efficiency and reducing emissions. Therefore, this research has placed significant emphasis on the coupling of thermal and structural analyses to verify enhanced designs of the engine casing that satisfy performance, durability, and sustainability goals. The synthesis of the results from static and thermal analyses will be presented, providing a comprehensive characterization of the casing's behavior under various conditions. Model 5 was the one that gave the most balanced performance and could be chosen for practical application. The bar chart and the waterfall graph reveal the visual insights of targeted heat management and structural optimisation. It may reduce thermal hotspots and stress concentrations. The enhanced material usage could enable the creation of a casing that is tougher than a better-performing casing, supporting even more ambitious goals toward sustainability and efficiency in two-wheeler designs.

6. Conclusion

The paper describes a cylinder fin body for a 125cc motorcycle, designed using parametric software PTC Creo to be tested and improved in terms of its thermal and structural performance. This study has changed the traditional flat fin geometry into an advanced fin profile to enhance the rates of heat transfer and overall cooling efficiency. The research study, in the most obvious terms, has brought to notice an extreme increase in the rate of heat dissipation from the cooling system due to geometric alterations within the fin. The complex designs of the fin facilitate faster and more uniform cooling of the cylinder's body, enhancing surface area and improving airflow across the body to minimize thermal stress inside the engine casing. The hot spot concentrations are appropriately controlled, preventing overheating in the concentrated spot areas; hence, there is a lower chance of structural fatigue occurring in the focused area of an engine structure.

Advanced fin profiles are added to stabilize the temperature distribution across the casing with minimal deformation and corresponding equivalent stress, as deduced from the analyses. This research work establishes the importance of fin geometry in the efficient thermal management of motorcycle engines. Optimisation profiles of engine fins enable engines to operate at safety levels for heat parameters, ensuring extended stability under various load types and maintaining performance sustainability. This aligns well with sustainability guidelines. Reason: Such designs reduce the requirements for cooling energies, simultaneously making it proficient and effective to handle cooling. That way, there is an improvement in fuel efficiency, as well as a decrease in emissions. Work tends to provide the basis for accepting more advanced geometries of the fins in designing an engine to achieve durability, along with supremacy in performance and the environment.

6.1. Limitations

Some limitations restrict the study, and therefore, the completeness of the results may be affected. Idealisation of boundary conditions and material properties is one such limitation. This means that the study cannot capture some real complexities associated with the casing of the engine during actual operations. Generally, dynamic and transient factors resulting from loads that develop, rapid temperature variations, and thermal fatigue cannot be adequately addressed in static thermal-structural analysis. Defects in manufacturing, material anisotropy, and residual stresses developed by different fabrication processes cannot be accommodated in a simulation, so the predictions would probably drift further away from reality. The study does not account for wear, corrosion, and creep, which are crucial for the long-term durability of engine parts. Computing powers that may have been utilised for numerical approximations on such simulations, such as mesh quality and convergence criteria, may be of a lesser magnitude, resulting in poor results. It might also consider the conditions that include the operations regarding the practical application of engines, as well as the efficiency concerning the consumption of fuels that vary extensively in most practical uses.

6.2. Future Scope

The further extension of dynamic and transient thermal-structural analyses can be incorporated in the simulation of real-time operating conditions. High-performance alloys or composites with improved thermal and mechanical properties can be used to enhance casing performance. Techniques like topology optimisation may be applied to produce new designs with minimal weight and maximum heat dissipation. The experiments would validate the numerical models through advanced technologies, such as digital image correlation and infrared thermography, to enhance the reliability of the generated models. Other areas being analyzed include the manufacturing process, material fatigue, and long-term wear under realistic engine conditions. This would bring the study into sustainability aspects that encompass recyclability and environmental impacts, aligning with the current industrial trend.

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Ethics and Consent Statement: The consent was obtained from the organization and individual participants during data collection, and ethical approval and participant consent were received.

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