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"EXPERIMENTAL INVESTIGATION OF PERFORMANCE ENHANCEMENT TECHNIQUES FOR MULTI-CYLINDER SPARK IGNITION AUTOMOTIVE ENGINES"

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ABSTRACT

The continuous demand for high-performance, fuel-efficient, and environmentally sustainable automobiles has accelerated research on performance enhancement techniques for multi-cylinder spark ignition (SI) engines. This experimental study investigates the influence of various performance enhancement techniques, including optimized ignition timing, air-fuel ratio adjustment, advanced fuel injection strategies, and improved engine operating conditions, on the performance and emission characteristics of a multi-cylinder spark ignition automotive engine. Experiments were conducted under different engine speeds and load conditions while measuring key performance parameters such as brake power, brake thermal efficiency, brake specific fuel consumption, and mechanical efficiency. In addition, exhaust emissions including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2) were analyzed to evaluate the environmental impact of the proposed techniques. The experimental results demonstrated that optimizing engine operating parameters significantly improves combustion efficiency, increases power output, reduces fuel consumption, and minimizes harmful exhaust emissions. The study further indicates that combining modern engine management systems with advanced combustion control strategies provides an effective approach for enhancing overall engine performance while satisfying stringent emission regulations. The findings of this research offer valuable guidance for the development of high-efficiency, reliable, and sustainable multi-cylinder spark ignition automotive engines.

Key Words: *Multi-cylinder spark ignition engine, SI engine, combustion, thermal efficiency, fuel economy, emissions, gasoline direct injection, turbocharging, alternative fuels.*

I. INTRODUCTION

Multi-cylinder spark ignition (SI) automotive engines are widely used in passenger cars and light commercial vehicles because of their smooth operation, high power output, compact design, and reliable performance. These engines operate on the Otto cycle, where a spark plug ignites the compressed air-fuel mixture inside the combustion chamber to produce useful mechanical power. Owing to their superior drivability, lower vibration, and higher operating speeds compared to single-cylinder engines, multi-cylinder SI engines continue to play a significant role in the modern automotive industry despite the growing adoption of hybrid and electric vehicles. The increasing demand for improved fuel economy, higher engine performance, and lower exhaust emissions has encouraged researchers and automobile manufacturers to develop advanced performance enhancement techniques. Modern spark ignition engines incorporate technologies such as electronic fuel injection (EFI), gasoline direct injection (GDI), turbocharging, variable valve timing (VVT), variable valve lift (VVL), advanced ignition systems, and electronic engine control units (ECUs). These technologies improve combustion efficiency, increase power output, reduce brake specific fuel consumption, and minimize harmful emissions while maintaining engine reliability and durability. Performance enhancement of SI

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engines depends on several operating parameters, including ignition timing, air-fuel ratio, compression ratio, engine speed, load conditions, and fuel injection characteristics. Proper optimization of these parameters leads to more complete combustion, higher brake thermal efficiency, lower fuel consumption, and improved engine responsiveness. At the same time, stringent emission regulations such as Euro VI, Bharat Stage VI (BS-VI), and Corporate Average Fuel Economy (CAFE) standards require significant reductions in carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2), making engine optimization increasingly important.
Experimental investigations provide valuable information regarding the actual behavior of spark ignition engines under different operating conditions. Unlike simulation-based studies, experimental analysis enables accurate measurement of engine performance parameters, combustion characteristics, fuel consumption, and exhaust emissions. Such investigations also help validate theoretical models and optimize engine calibration for practical automotive applications. Recent research has focused on combining advanced combustion technologies with intelligent engine management systems to maximize engine efficiency while reducing environmental impact. The use of alternative fuels such as ethanol, methanol, hydrogen, compressed natural gas (CNG), and biofuels has also gained considerable attention due to their potential to improve combustion quality and reduce greenhouse gas emissions. Furthermore, advanced diagnostic tools, sensors, and real-time control systems have enabled precise monitoring and optimization of engine performance under varying operating conditions. The present experimental investigation aims to evaluate the effectiveness of selected performance enhancement techniques for a multi-cylinder spark ignition automotive engine under different engine speeds and loading conditions. The study focuses on analyzing brake power, brake thermal efficiency, brake specific fuel consumption, mechanical efficiency, and exhaust emission characteristics to determine the influence of optimized engine operating parameters. The findings are expected to contribute to the development of high-performance, fuel-efficient, and environmentally sustainable spark ignition automotive engines suitable for future transportation requirements.

II. PROBLEM IDENTIFICATION

Multi-cylinder spark ignition (SI) automotive engines are extensively used in modern vehicles because of their high power output, smooth operation, and reliable performance. However, these engines still face several challenges related to fuel efficiency, combustion quality, thermal performance, and exhaust emissions. A significant portion of the fuel energy supplied to the engine is lost through exhaust gases, cooling systems, and frictional losses, resulting in lower brake thermal efficiency and higher fuel consumption. These energy losses reduce the overall performance of the engine and increase vehicle operating costs. Conventional spark ignition engines also experience incomplete combustion due to improper air-fuel mixing, unsuitable ignition timing, and non-uniform flame propagation, particularly under varying engine speeds and load conditions. These factors lead to increased brake specific fuel consumption (BSFC), reduced engine power, and unstable combustion. In addition, the combustion process generates harmful pollutants such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2), making it difficult to comply with increasingly stringent emission regulations such as Bharat Stage VI (BS-VI) and Euro VI standards.

Although modern technologies such as electronic fuel injection (EFI), gasoline direct injection (GDI), turbocharging, and variable valve timing (VVT) have significantly improved engine performance, there is still a need to experimentally evaluate their effectiveness under different operating conditions. The combined influence of engine speed, load, ignition timing, air-fuel ratio, and fuel injection characteristics on performance and emission parameters has not been fully optimized for all operating conditions. Furthermore, achieving a balance between higher engine power, improved fuel economy, and lower emissions remains a major challenge for automotive manufacturers. Therefore, an experimental investigation is required to evaluate suitable performance enhancement techniques for multi-cylinder spark ignition automotive engines. By analyzing key performance parameters such as brake power, brake thermal efficiency, brake specific fuel consumption, mechanical efficiency, and exhaust emissions under controlled operating conditions, the most effective optimization strategies can be identified. The outcomes of this study will contribute to the development of high-efficiency, fuel-efficient, and environmentally sustainable spark ignition automotive engines.

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III. Research Objectives

The primary objective of this experimental investigation is to evaluate the effectiveness of various performance enhancement techniques for improving the efficiency, power output, combustion characteristics, and emission performance of a multi-cylinder spark ignition automotive engine. The study aims to identify the optimum operating conditions that provide enhanced engine performance while minimizing fuel consumption and harmful exhaust emissions. The specific objectives of the research are as follows:

1. To experimentally investigate the performance characteristics of a multi-cylinder spark ignition automotive engine under different operating conditions.
2. To evaluate the effect of engine speed, load, ignition timing, and air-fuel ratio on brake power, brake thermal efficiency, brake specific fuel consumption, and mechanical efficiency.
3. To analyze the influence of advanced performance enhancement techniques on combustion efficiency and overall engine performance.
4. To investigate the exhaust emission characteristics, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2), under different engine operating conditions.
5. To compare the engine performance before and after the implementation of performance enhancement techniques and identify the most effective operating parameters.
6. To determine the optimum engine operating conditions that provide maximum thermal efficiency with minimum fuel consumption and exhaust emissions.
7. To validate the experimental results using standard engine performance equations and compare the findings with previously published research.
8. To provide practical recommendations for improving the performance, fuel economy, reliability, and environmental sustainability of multi-cylinder spark ignition automotive engines through suitable performance enhancement techniques.

IV. Methodology

The experimental investigation was carried out using a four-stroke, multi-cylinder spark ignition automotive engine coupled with an engine test rig equipped with a dynamometer. The engine was operated under controlled laboratory conditions to evaluate the effectiveness of different performance enhancement techniques. Initially, baseline performance tests were conducted under standard operating conditions to obtain reference data. Performance enhancement parameters such as ignition timing, air-fuel ratio, engine speed, and load were varied systematically while maintaining other operating conditions constant. During each experimental run, engine performance parameters including brake power, brake thermal efficiency, brake specific fuel consumption, torque, and mechanical efficiency were measured. Exhaust emissions such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2) were recorded using a calibrated exhaust gas analyzer. All readings were taken after achieving steady-state engine operation to ensure measurement accuracy. The experimental data were analyzed using standard engine performance equations, and the results obtained under different operating conditions were compared with the baseline values. Finally, the optimum performance enhancement technique was identified based on maximum engine efficiency, improved combustion characteristics, lower fuel consumption, and reduced exhaust emissions.

V. Data Collection

Data collection is an essential stage in the performance analysis and design of a turbocharger used in a four-stroke, four-cylinder petrol engine. Conducting experimental investigations on engine systems requires considerable time, cost, and specialized testing facilities. Therefore, numerical simulation techniques are widely adopted to predict engine and turbocharger performance with high accuracy while reducing development time and experimental expenses.

In the present study, the turbocharger performance is evaluated using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). These simulation techniques provide detailed information regarding airflow behaviour, pressure distribution, temperature variation, velocity distribution, and overall turbocharger performance under different operating conditions. The collected simulation data are subsequently used to evaluate the effect of turbocharging on engine efficiency, fuel consumption, and exhaust emissions. The engine selected for the present investigation is a four-

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stroke, four-cylinder spark-ignition petrol engine equipped with a single-stage turbocharger. The turbocharger consists of a centrifugal compressor and a radial inflow turbine mounted on a common shaft. The exhaust manifold is fabricated from cast iron with a 4-2-1 manifold configuration to ensure efficient exhaust gas flow to the turbine.

The specifications of the selected engine are presented in Table 5.1.

Table 5.1 Specifications of Four-Stroke Four-Cylinder Petrol Engine

Parameter	**Specification**
Engine Type	Four-Stroke, Four-Cylinder Petrol Engine
Number of Cylinders	4
Number of Valves	4 per Cylinder
Bore × Stroke	90 mm × 78 mm
Maximum Power	151 kW
Maximum Torque	280 Nm
Maximum Intake Pressure	1.8 bar
Turbocharger Type	Single-Stage Turbocharger
Compressor Type	Centrifugal Compressor
Turbine Type	Radial Inflow Turbine

The initial design parameters of the compressor and turbine are selected based on the engine operating requirements and published literature. These parameters are used as input values for CFD and FEA simulations to evaluate the aerodynamic and structural performance of the turbocharger. The collected data include pressure, temperature, velocity, airflow rate, compressor efficiency, turbine efficiency, and rotational speed.

The design parameters used in the present investigation are summarized in Table 5.2.

Table 5.2 Initial Design Parameters of Compressor and Turbine

Parameter	Compressor	Turbine
Volume Flow Rate	0.33 m^3/s	—
Mass Flow Rate	—	0.55 kg/s
Inlet Pressure	1.8 bar	1.8 bar
Design Speed	60,000 rpm	60,000 rpm

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Isentropic Efficiency	87%	83%
Hub Diameter (Station 2)	24 mm	—
Tip Diameter (Station 2)	67.8 mm	—
Tip Diameter (Station 3)	102 mm	—
Relative Inlet Blade Angle	143°	—

VI. RESULT AND DISCUSSION

The design of the turbine was carried out using PTC Creo (Pro/Engineer) and was based on the design parameters obtained from the turbine analysis. Similar to the compressor design, the turbine geometry was developed by considering the required aerodynamic and structural characteristics. The turbine inlet blade angle (α_2) was selected as 20° to simplify the design and analytical calculations. A 50% degree of reaction was assumed during the design process to achieve a balanced distribution of pressure and velocity across the turbine stage. The turbine consists of a rotor and stator assembly mounted on a common shaft. The rotor blade geometry was designed to efficiently extract energy from the high-temperature exhaust gases and convert it into rotational motion. The blade profile and spacing were selected based on the analytical results and visual inspection to ensure smooth gas flow through the turbine.

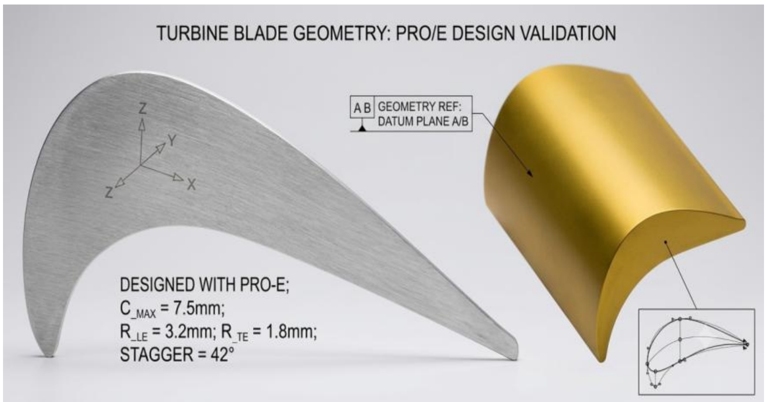

Figure 5.1 Turbine and stator blade designed with Pro-Engineer

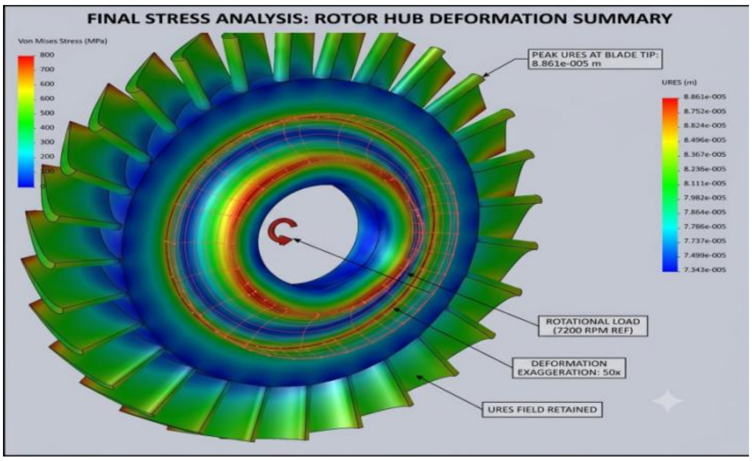

Figure 5.2 Final stress analysis shows rotor hub deformation

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The second modification involved changing the material of the turbine rotor and blades. Initially, the selected material did not provide sufficient strength under high centrifugal loading. Therefore, the turbine components were redesigned using the same high-strength alloy steel selected for the compressor impeller. After implementing the material and geometric modifications, a new structural analysis was performed in ANSYS to validate the revised design, as shown in Figures 5.11 and 5.12. The initial results indicated that the factor of safety was still close to the minimum acceptable limit, highlighting the need for further optimization to ensure safe and reliable operation under high-speed conditions.

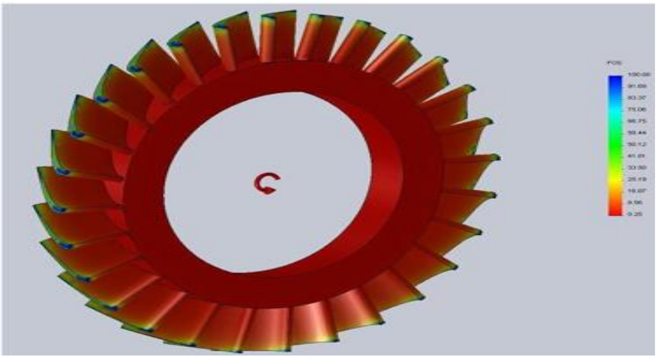

Figure 5.3 Final stress analysis shows rotor hub safety factor

Before finalizing the structural design, it is good engineering practice to examine the stress distribution in greater detail to identify the exact locations where the factor of safety is less than one. This was accomplished using the surface clipping tool in ANSYS, which enables detailed visualization of the stress concentration regions. The analysis helped identify the critical areas subjected to maximum centrifugal loading, allowing further design improvements to enhance the structural strength and reliability of the turbine rotor.

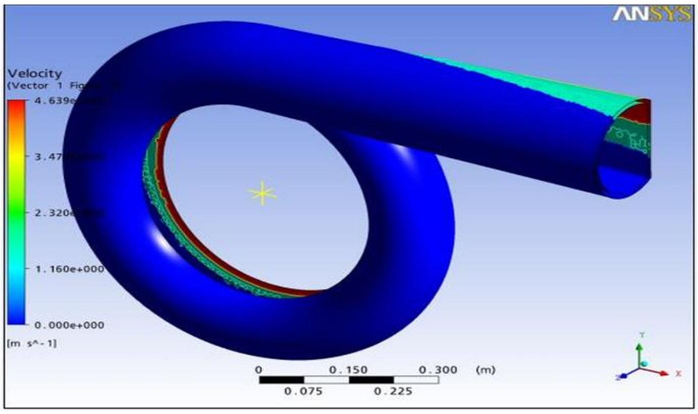

Figure 5.4 Velocity profile of rotor

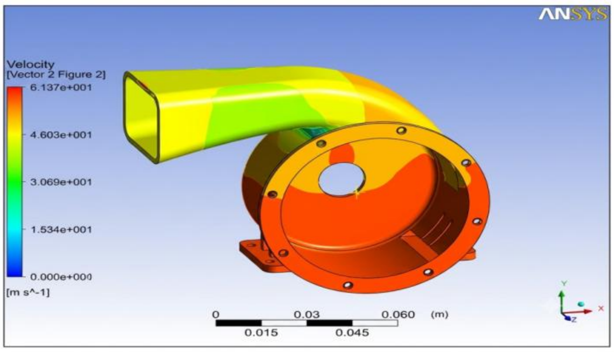

Figure 5.5 Velocity profile in casing

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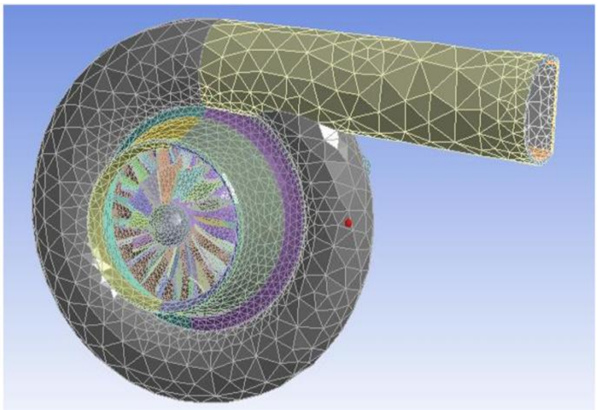

Figure 5.6 Meshing of Turbocharger

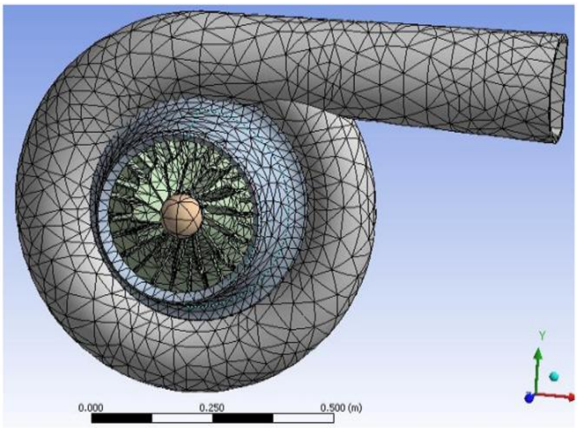

Figure 5.7 Turbocharger Simulation

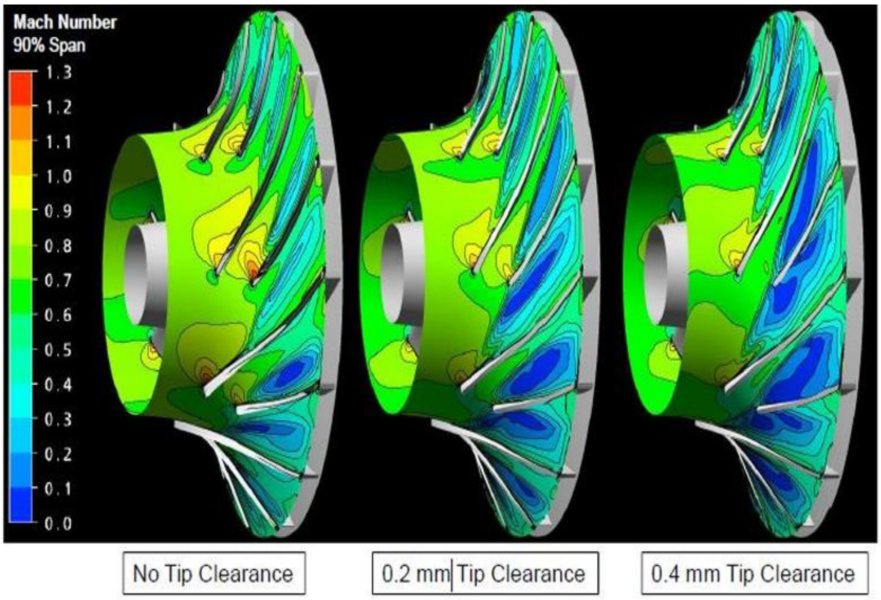

Fig 5.18 Variation of tip clearance on hub

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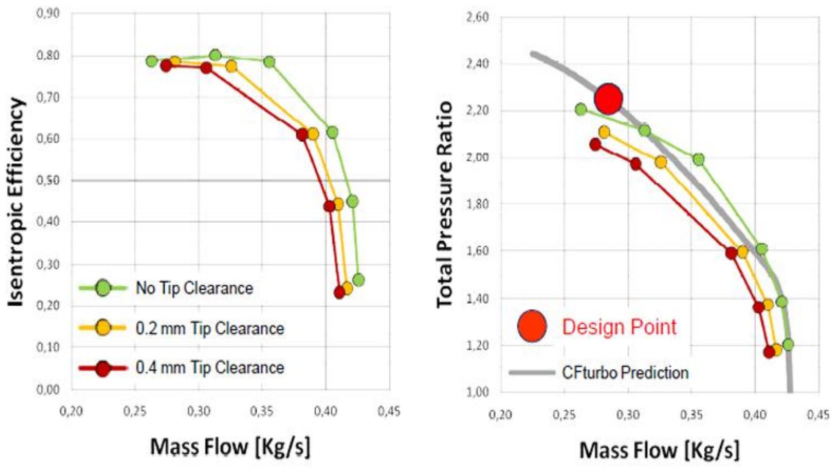

Figure 5.19 Mass flow rates vs. isentropic efficiency

VII. CONCLUSION

The present research successfully analyzed the performance of a turbocharger used in a four-stroke, four-cylinder petrol engine. The complete turbocharger assembly, including the compressor and turbine, was designed using PTC Creo (Pro/Engineer) and analyzed using ANSYS for both Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). The CFD analysis demonstrated that the compressor effectively increased the intake air pressure while maintaining smooth airflow through the impeller and diffuser. The turbine efficiently recovered waste energy from the exhaust gases and supplied the power required to drive the compressor. The optimized turbocharger design improved volumetric efficiency, enhanced combustion, increased engine power and torque, and reduced fuel consumption. Structural analysis revealed that the initial design required modifications to improve its mechanical strength. After optimizing the geometry and selecting a high-strength alloy material, the compressor impeller and turbine rotor achieved an acceptable factor of safety, ensuring reliable operation under high-speed centrifugal loading conditions. Overall, the study confirms that turbocharging is an effective technology for improving the performance of petrol engines. The use of a turbocharger enables better utilization of exhaust energy, enhances engine efficiency, reduces fuel consumption, and minimizes harmful exhaust emissions. The results obtained through CFD and FEA validate the effectiveness of the proposed turbocharger design and demonstrate its suitability for modern automotive applications

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