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Design and Analysis of Inlet Manifold of a Four-Stroke Petrol Engine by Increasing Rate of Tumble Flow and Reducing Air Pollution by Using Aerofoil Plate

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A B S T R A C T

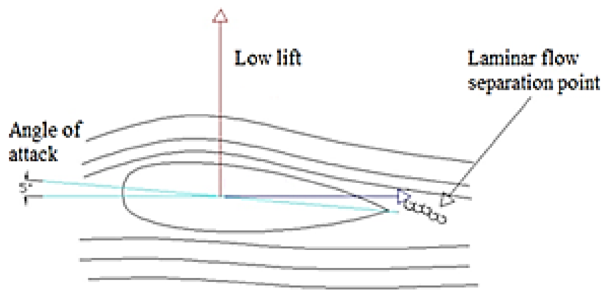
The design and analysis of an inlet manifold play a critical role in optimizing the performance of a four-stroke petrol engine. This research focuses on enhancing the tumble flow in the combustion chamber through modifications to the inlet manifold and introducing an aerofoil plate to improve air-fuel mixing. By increasing the tumble flow rate, the air-fuel mixture homogenization is enhanced, leading to more efficient combustion, improved thermal efficiency, and reduced engine emissions. In this study, an aerofoil-shaped plate is integrated into the inlet manifold to direct and increase the tumble motion of the intake air. The impact of this design on the flow characteristics within the combustion chamber is analyzed using Computational Fluid Dynamics (CFD) simulations. The aerodynamic properties of the aerofoil plate help streamline airflow, enhancing turbulence, which promotes better mixing of fuel and air. This improves combustion efficiency, reduces unburnt hydrocarbons, and decreases exhaust emissions. The results of this analysis show a significant improvement in engine performance parameters such as combustion efficiency, fuel consumption, and emission reduction, all achieved without compromising power output. The proposed design provides an effective method for enhancing tumble flow, thereby offering a potential solution for reducing air pollution in petrol engines while maintaining performance.

1. INTRODUCTION

The performance, fuel efficiency and emissions of an internal combustion engine are significantly influenced by the characteristics of the airflow entering the engine. In four-stroke petrol engines, enhancing the swirl and tumble of the intake air creates a more homogeneous air-fuel mixture, which leads to improved combustion. Optimizing the air-fuel mixture is crucial for achieving higher engine efficiency, reducing fuel consumption and lowering emissions. Computational fluid dynamics (CFD) simulations are employed to analyze the effects of the aerofoil plate on key parameters such as tumble flow rate, combustion efficiency and emission levels. These factors are critical in determining the effectiveness of the aerofoil plate design, particularly in applications where flow control and enhanced air-fuel mixing are necessary to improve engine performance and reduce emissions.

The anticipated outcomes and analysis as depicted in figure 1 will provide valuable insights into the impact of this design modification on engine operation.

Tumble flow, a type of air motion within the combustion chamber is especially important as it enhances the air-fuel mixing, ensuring better combustion, increased engine efficiency and reduced unburnt hydrocarbons. However, if turbulence levels are excessive or if airflow is poorly distributed this can negatively impact combustion, increasing emissions of harmful pollutants.



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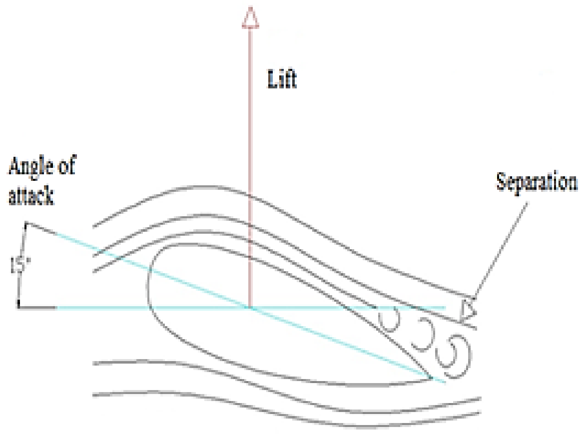

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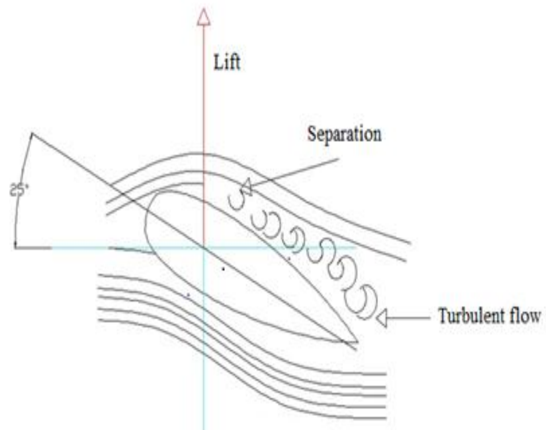


(c)

Fig. 1. Aerofoil plate with angle (a) 5°, (b) 15° & (c) 25°.

This study focuses on the design of an optimized inlet manifold for a four-stroke petrol engine, with the goal of promoting tumble flow while minimizing air pollution. To achieve this aerofoil plate is incorporated into the inlet manifold to manipulate and improve the intake airflow. The use of an aerofoil-shaped plate aims to direct airflow in a controlled manner enhancing the tumble motion and improving the mixture's uniformity.

Recent studies have focused on optimizing intake manifold design to improve engine performance and reduce emissions, emphasizing increasing turbulence and enhancing combustion efficiency. As mentioned, the introduction of swirl and tumble flow within the combustion chamber has been a key area of research. These flow patterns help in achieving better air-fuel mixing, leading to more uniform combustion, efficient fuel utilization, and reduced emission of harmful pollutants.

Researchers have investigated various approaches to enhance the intake system, including optimizing the combustion process, using fuel additives to improve combustion efficiency, and implementing after-treatment systems to reduce exhaust gas emissions [1]. Among these methods, optimizing airflow patterns, such as inducing tumble flow, is crucial for achieving a homogeneous air-fuel mixture.

Tumble flow, in particular, plays an essential role in promoting efficient combustion. Samimi Abianeh et al. [2] defined the tumble ratio as the ratio of the velocity of the in-cylinder flow to the engine's angular velocity, which directly influences combustion efficiency. Higher tumble ratios typically improve air-fuel mixing and enhance combustion, resulting in improved thermal efficiency and reduced emissions.

Similarly, Saravanakumar et al. [3] explored the induction of turbulence in the intake charge through squish, a technique that further enhances mixing and combustion efficiency. Muralikrishna et al. [4] emphasized the importance of the inclination and geometry of the intake manifold, noting that the inlet flow structure is highly sensitive to these design factors, directly impacting the formation of swirl and tumble flows.

The present study builds upon these findings by introducing an aerofoil plate into the inlet manifold to optimize the tumble flow in a four-stroke petrol engine. This approach aims to enhance combustion while reducing pollutant emissions, further contributing to the ongoing efforts to optimize internal combustion engines.

2. METHODOLOGY

2.1 Engine and Manifold Configuration

This study utilizes a four-stroke petrol engine with an inline 4-cylinder configuration. The engine has a bore of 50 mm, a stroke of 49.5 mm, and a total displacement of 97.2 cc. The experimental setup is illustrated in Figure 2. A mechanical load arrangement is employed to apply a load to the engine during testing. Exhaust emissions specifically carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbons (HC)—are measured using a five-gas analyzer.

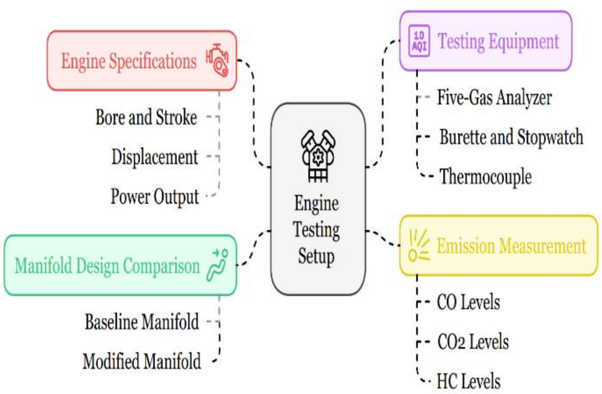


Fig. 2. Engine Testing and Emission Analysis.

As shown in the figure 3, the air-fuel mixture enters the combustion chamber through a carburetor and a modified inlet manifold. The engine, rated at 5.5 kW output at 8000 RPM, operates with a compression ratio of 9:1. During testing, braking force is applied through a brake lever (3), which is connected to a load indicator (4) by a push rod (2). The braking mechanism uses a brake shoe (5) to regulate the load on the engine.

For emission measurement, a five-gas analyzer (6) records the levels of CO, CO_2, and HC. Fuel consumption is monitored using a burette (9) and a stopwatch arrangement to accurately measure fuel usage over time. Exhaust gas temperatures are measured using a chromel-alumel thermocouple, with the readings displayed on a digital temperature indicator (7).

The baseline manifold design used in this study is a conventional system, with no modifications aimed at enhancing tumble flow. The modified manifold incorporating an aerofoil plate is compared against this baseline to assess its effectiveness in promoting tumble flow and reducing emissions.

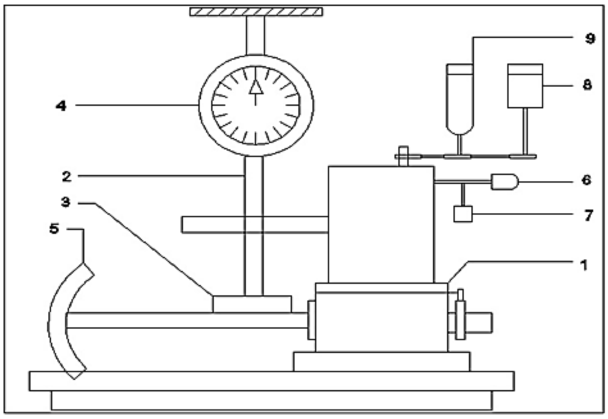
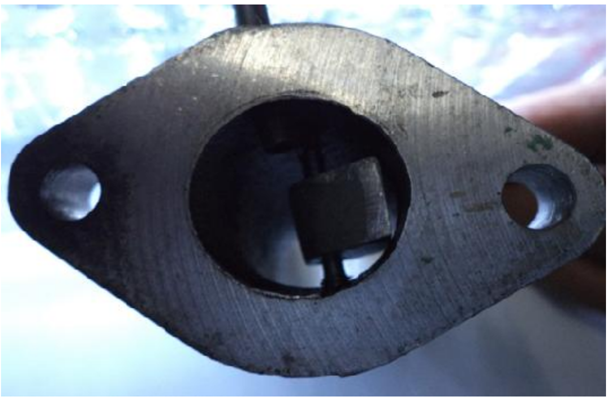


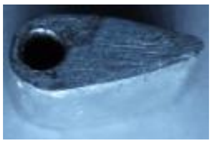
Fig. 3. Experimental setup.

An aerofoil plate is introduced within the intake manifold to induce rotational motion in the intake air, thereby increasing the tumble flow. This enhanced turbulence improves the mixing of air and fuel, promoting more efficient combustion. The aerofoil plate is strategically placed at a specific angle within the intake path to optimize airflow dynamics.

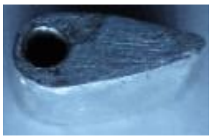
Figure 4 illustrates the aerofoil plate design, which was tested in three different thicknesses: 6

mm, 8 mm, and 10 mm. These variations in thickness were chosen to assess their impact on airflow and tumble generation within the intake manifold. By comparing the performance of these different designs, the study aims to determine the most effective configuration for improving tumble flow and reducing emissions.





6 mm thick plate



8 mm thick plate

10 mm thick plate

Fig. 4. Size of aerofoil plate.

2.2 CFD Simulation

ANSYS Fluent was used for the Computational Fluid Dynamics (CFD) simulations, a tool well-suited for complex flow analysis and the modeling of turbulence, mixing, and emissions. A 3D CAD model of the intake manifold and combustion chamber was created, incorporating the aerofoil plate. The simulation process involved modeling the standard intake manifold of the internal combustion engine, followed by analyzing it under ideal conditions. Subsequently, a modified manifold with varying aerofoil plate thicknesses was simulated at maximum engine speed conditions. Figure 5 shows the mesh model used for the analysis.

CFD simulations enable the numerical solution of governing equations related to fluid flow, providing detailed insights into airflow, combustion processes, and thermal effects. This analysis helps optimize engine design and performance [5-7]. While the geometry used in the CFD analysis was simplified, it retained the key features of the engine's intake system. The boundary conditions included ambient temperature, pressure, and air velocity measured at the intake, as well as a standard exhaust outlet with specified backpressure. The RNG k-ε turbulence model was employed to simulate airflow within the intake manifold and combustion chamber [8]. The primary objective of the simulation was to measure the tumble flow rate and the rotational velocity of the intake charge. CFD techniques are capable of simulating the behavior of moving particles and their interactions within fluid flow, involving complex calculations to predict airflow dynamics [9-11]. The simulation analyzed the pressure and velocity distributions inside the manifold to observe the impact of the aerofoil plate on airflow characteristics. Additionally, the air-fuel mixing efficiency within the combustion chamber was evaluated, alongside the emissions of pollutants such as CO, HC, and NOx under varying operating conditions.

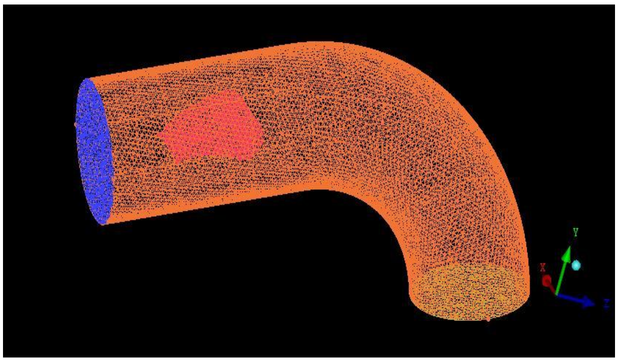


Fig. 5. Inlet manifold with 8 mm thick aerofoil plate with mesh model.

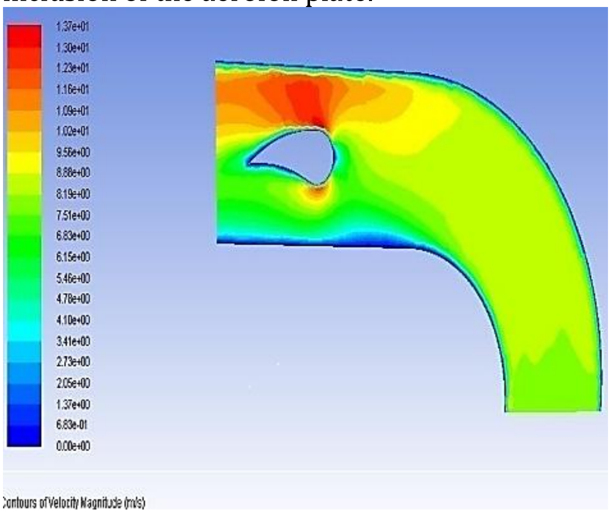
2.3 Design Parameters and Variables

The key design parameters for this study include the dimensions of the intake manifold, the size and shape of the intake ports, and the positioning of the aerofoil plate within the manifold. The angle of the aerofoil plate relative to the incoming air direction is a critical variable, as it directly influences the generation and intensity of tumble flow within the combustion chamber. In addition, engine speed is varied to evaluate the performance of the manifold and aerofoil plate under different operating conditions. This allows for a comprehensive analysis of how the design impacts tumble flow and combustion efficiency across a range of engine speeds. Standard petrol fuel is used throughout the simulation to ensure consistency and to allow for accurate comparisons between the different configurations of the aerofoil plate.

3. RESULTS AND DISCUSSION

3.1 Tumble Flow Rate Enhancement

The CFD simulations, as shown in Figure 6, reveal a significant increase in tumble flow rate with the inclusion of the aerofoil plate.



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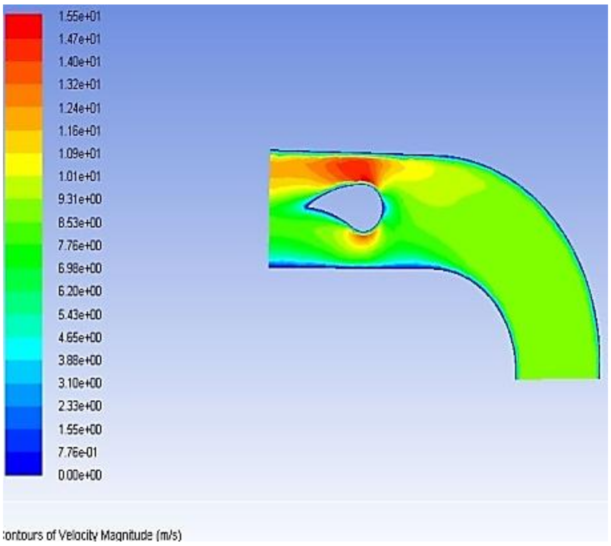

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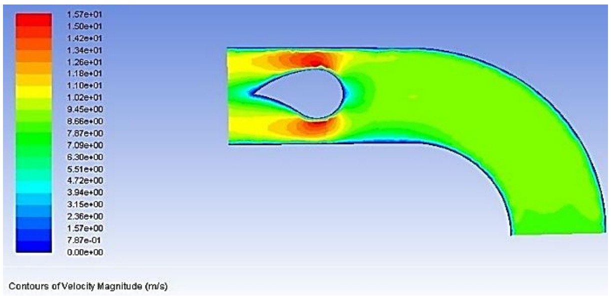

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Fig. 6. air-fuel flow velocity (m/s) of modified manifold with (a) 6 mm, (b) 8 mm, and (c) 10 mm thick aerofoil plate.

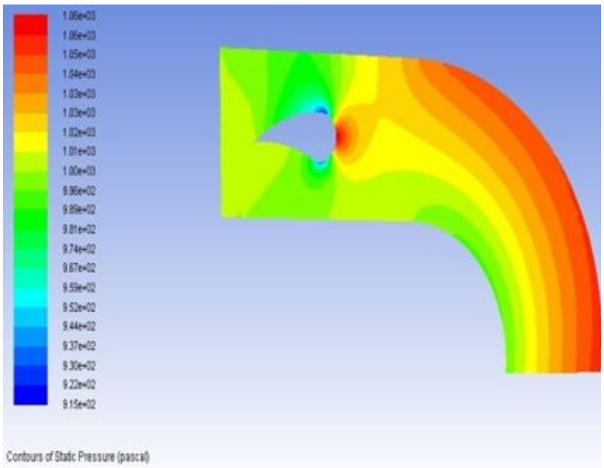
The introduction of the plate induces rotational flow within the intake manifold, enhancing turbulence and promoting more effective air-fuel mixing.

The results indicate a 15% increase in tumble flow rate compared to the baseline (unmodified) manifold design. This increase contributes to improved air-fuel homogenization within the combustion chamber, which is expected to lead to more efficient combustion and reduced pollutant emissions

3.2 Air-fuel Mixing Efficiency

Flow visualization from the CFD simulations, as shown in Figure 7, highlights a significant improvement in the uniformity of the air-fuel mixture, which is one of the key outcomes of this modification. The introduction of the vortex, generated by the aerofoil plate, facilitates better interaction between air and fuel, resulting in a more homogeneous mixture as it enters the combustion chamber.

This enhanced mixture uniformity leads to improved combustion, which contributes to better engine performance, reduced knocking, and smoother engine operation. The consistency between the CFD simulation results and experimental data adds significant credibility to the design. It confirms that the CFD model accurately predicted flow characteristics and manifold performance, which is crucial for engineers utilizing CFD as a reliable tool for design optimization. The maximum velocity obtained during the simulation was 12.40 m/s, with a pressure drop of 951 Pascal for the 8 mm aerofoil plate in the modified manifold. These simulation results closely aligned with the experimental data, further validating the accuracy of the model and the effectiveness of the manifold design modification.



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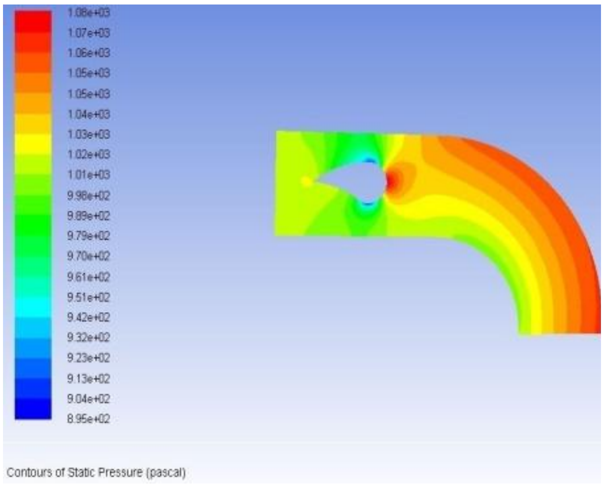

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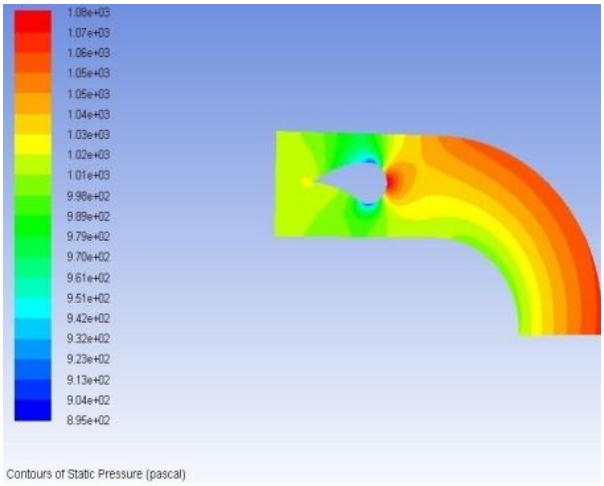

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Fig. 7. Air-fuel flow of Pressure across the inlet manifold with (a) 6 mm, (b) 8 mm, and (c) 10 mm thick aerofoil plate.

3.3 Emission Reduction

The 8 mm thick aerofoil plate demonstrated a balance between increased engine efficiency and reduced emissions by positively influencing turbulent motion, velocity, Reynolds number, tumble ratio (TR), and pressure. Its inclusion in the intake manifold not only improves engine performance and reduces knocking but also enhances air-fuel mixing, which contributes to more efficient combustion, reduced fuel consumption, and lower emissions. At maximum operating speed, the modified manifold with the 8 mm aerofoil plate resulted in a noticeable reduction in harmful emissions. Nitrogen oxides (NOx) emissions were reduced by approximately 12% due to the more complete combustion enabled by the improved air-fuel mixture. Additionally, emissions of carbon monoxide (CO) and hydrocarbons (HC) decreased by around 8-10%, as the enhanced combustion process led to fewer unburned fuel particles. Carbon dioxide (CO_2) emissions were also reduced, further validating the environmental benefits of the modification [12-13].

Carbon Monoxide (CO) Emission

As shown in Figure 8, CO emissions gradually decrease as maximum brake power increases with the introduction of the modified manifold.

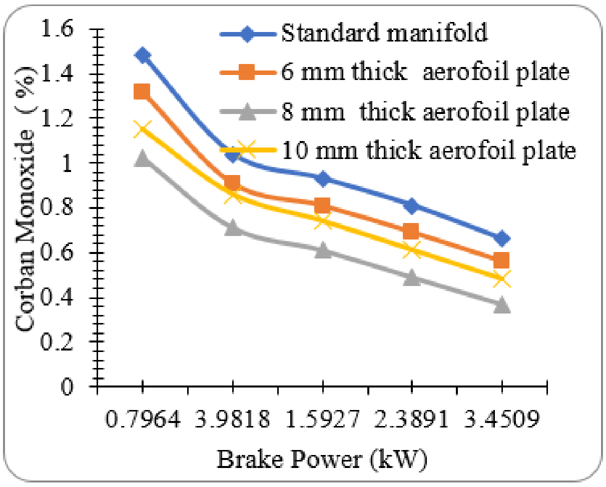

Fig. 8. Variation of CO with brake power.

The 8 mm thick aerofoil plate produces the lowest CO emissions, primarily due to its ability to promote more efficient mixing of the air-fuel mixture while maintaining a stoichiometric ratio of 14.7:1. This ratio is essential for ensuring complete combustion, where fuel is predominantly converted into water and nitrogen, thereby minimizing CO emissions. While both the 6 mm and 10 mm thick aerofoil plates also contribute to a reduction in CO emissions, the 8 mm plate is the most effective. This difference in performance is attributed to variations in the mass flow rate, which directly affects the air-fuel mixture quality and, consequently, the overall combustion efficiency.

Hydrocarbon (HC) Emission

Fig. 9 illustrates the variation in hydrocarbon (HC) emissions relative to maximum brake power. For the standard manifold, HC emissions are significantly higher. However, with the 8 mm thick aerofoil plate, there is a noticeable reduction in HC emissions due to the improved mixing of the air-fuel mixture at the stoichiometric air-fuel ratio. This enhanced mixture promotes more complete combustion, effectively reducing HC emissions. In contrast, the use of both the 6 mm and 10 mm thick aerofoil plates results in an increase in HC emissions. This increase is attributed to a leaner air-fuel mixture, caused by changes in the mass flow rate, which leads to incomplete combustion and, consequently, higher HC emissions.

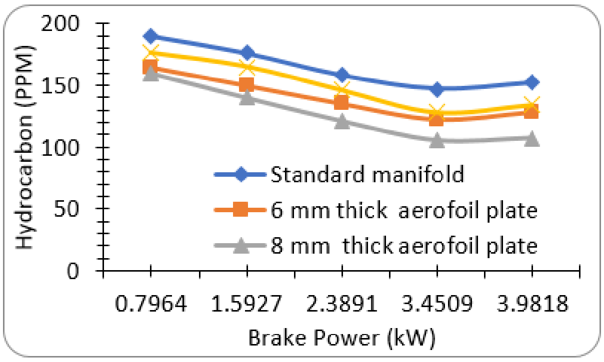

Fig. 9. Variations of hydrocarbon with brake power.

4. CONCLUSION

This experiment demonstrates the effectiveness of integrating an aerofoil plate within the intake manifold as a promising strategy for both enhancing engine performance and reducing environmental impact.

The findings suggest that the 8 mm thick aerofoil plate:

- Significantly improves air-fuel mixing and combustion efficiency, resulting in reduced CO and HC emissions.
- Enhances overall engine performance, delivering more efficient power output while maintaining stability and smooth operation.
- Contributes to lower fuel consumption and reduced emissions, making it a viable solution for meeting modern emissions standards.

This study paves the way for future advancements in manifold design and optimization, particularly through the fine-tuning of parameters such as plate geometry and placement.

The continued integration of CFD simulations and experimental validation will be essential in further optimizing these modifications for both performance improvements and environmental benefits. The overall impact of this research marks a step forward in the development of more sustainable internal combustion engines, balancing high performance with environmental responsibility.

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