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Impact of Intake Manifold Geometry on Power and Torque: A Simulation-Based Study

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ABSTRACT

The internal combustion engine (ICE) remains pivotal in motorcycle technology, primarily due to its efficiency, energy density, and established infrastructure, despite the rise of electric vehicles. This study examines the influence of intake manifold design parameters on the performance of a single-cylinder internal combustion engine (ICE), with a specific focus on brake power and brake torque at high engine speeds. A comprehensive parametric analysis was conducted using a 1D simulation model in Ricardo Wave, evaluating the effects of manifold length, diameter, and bending angle on engine performance metrics. The results demonstrate that the optimized intake manifold design yields a 7.75% improvement in brake power and a 6.5% enhancement in brake torque at 10,000 RPM compared to the baseline configuration. Mid-range values for manifold length and diameter were found to achieve optimal airflow dynamics, effectively minimizing pressure losses. Additionally, a bending angle of 70° exhibited superior stability in power delivery at elevated engine speeds. These findings underscore the critical role of intake manifold geometry optimization in achieving enhanced engine performance under high-speed operating conditions.

1. Introduction

The internal combustion engine (ICE) remains a dominant force in the global motorcycle landscape, converting fuel energy into mechanical work through controlled combustion within cylinders [1]. While electric vehicles are gaining traction, ICEs continue to be a cornerstone of motorcycle technology due to their versatility, energy density, and established infrastructure [2]. The efficiency of this conversion process, measured by the ratio of usable work output to fuel energy

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input, significantly impacts vehicle performance, fuel economy, and environmental impact [3,4]. Modern ICEs incorporate advanced technologies such as electronic fuel injection, variable valve timing, and turbocharging to optimize performance, reduce emissions, and meet stringent environmental regulations [5]. However, the pursuit of greater efficiency, lower emissions, and alternative fuel compatibility persists as a focal point for ongoing research and development.

The intake system plays a pivotal role in ICE performance by delivering a clean, controlled air-fuel mixture to the combustion chambers [6]. The intake manifold, a key component of this system, distributes air evenly to the cylinders [7-10]. However, the airflow within the manifold is subject to pressure losses due to factors like friction, changes in cross-sectional area, and bends [11]. This pressure drop diminishes the amount of air entering the cylinders, leading to reduced air-fuel mixture quality and consequently lower engine power and torque [12,13]. Additionally, to compensate for the reduced air intake, the engine's control system may increase fuel injection, potentially resulting in incomplete combustion, higher fuel consumption, and increased emissions [14].

The investigation into different intake manifold materials has shown that optimizing thermal and static properties can lead to lower air intake temperatures and improved engine performance [15]. Studies on exhaust manifold design have highlighted the importance of optimal divergence and temperature distribution for enhancing low-end engine speed performance [16]. Additionally, CFD simulations of Tesla turbines driven by internal combustion engine flue gas have provided insights into performance optimization [17]. Optimizing intake manifold design to minimize pressure drop is crucial for enhancing engine performance, and fuel economy, and reducing environmental impact [18,19]. By carefully considering factors such as runner length, diameter, and shape, engineers can improve airflow characteristics and mitigate pressure losses [20-22]. Moreover, advanced technologies like variable geometry intake manifolds offer the potential to further enhance performance by adapting the intake system to different engine operating conditions [4].

To address these challenges and optimize engine performance, this research focuses on investigating the impact of intake manifold design on pressure drop and its subsequent effects on engine power and torque. By understanding the intricate relationship between intake manifold geometry, airflow dynamics, and engine performance, this study aims to develop design strategies that minimize pressure drop and maximize engine power and torque. This study distinguishes itself by integrating a comprehensive parametric analysis of intake manifold length, diameter, and bending angle with advanced optimization methodologies to achieve significant enhancements in brake power and torque. The findings offer valuable insights with practical implications for the development of high-performance engines, particularly within the context of the local motorsport industry.

2. Methodology

2.1 Research Methodology

For this research, a 1D engine simulation model was developed and analysed using Ricardo Wave, a specialized software for simulating engine performance and airflow dynamics. The 1D simulation approach focuses on capturing the flow characteristics and thermodynamic interactions along predefined paths within the intake manifold system, providing a computationally efficient yet accurate method for parametric analysis. Unlike 3D computational fluid dynamics (CFD) simulations, which resolve full spatial details, 1D simulations offer an effective means to study the relationships between geometric parameters and engine performance metrics such as power and torque [6,23,24].

The simulation was conducted under full-load engine operating conditions, ensuring realistic representation of high-performance scenarios. Key intake manifold parameters, including length, diameter, and bending angle, were systematically varied to evaluate their individual and combined impacts on engine performance. The study specifically targeted optimizing peak brake torque at high engine speeds, as this is critical for high-RPM applications such as motorsport. By refining the geometry of sub-components within the intake manifold system, the research aimed to minimize pressure drops, enhance airflow dynamics, and maximize overall engine performance. The detailed flow of this research methodology is illustrated in Figure 1.

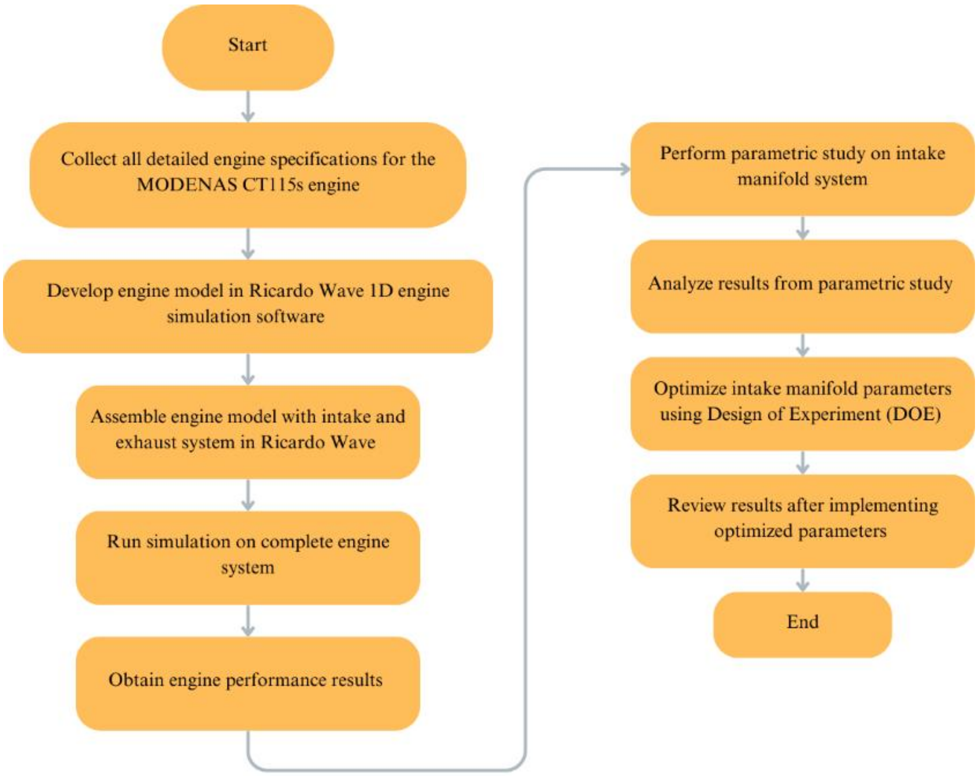

Fig. 1. Methodology flowchart

2.2 Intake Manifold Modelling

The precise geometry of the intake manifold was carefully measured as shown in Table 1 and used to construct a 1D model in Ricardo Wave, accurately replicating the physical characteristics of the system. This 1D intake manifold model was then integrated with a validated single-cylinder engine model within Ricardo Wave to simulate engine performance. The simulation setup followed established practices widely used in prior research, ensuring methodological consistency and reliable analysis. This approach enabled a comprehensive investigation into the impact of intake manifold geometry on key performance metrics such as brake power and torque, aligning with methodologies employed by previous researchers [7,20,25].

Table 1
1D simulation setup

Data Type Collected	Input Data Collected
Ambient Air Temperature	25°C
Ambient Air Pressure	101.325 kPa
Air Composition	78% N_2, 22% O_2
Intake Duct Wall Friction	0.02
Atmospheric Pressure	101.325 kPa
Wall Temperature	300°C

2.3 Parametric Study of Intake Manifold System

A parametric study was conducted on the reference intake manifold system to investigate and identify the relationship between changes in design parameters and engine performance. This study aimed to determine an appropriate range for these design parameters and provide guidance for subsequent optimization. Table 2 displays the design parameter values analysed.

Table 2
Design Parameter values for parametric study

Factor's Name	Factor's Symbol	Existing value	Level 1	Level 2	Level 3	Level 4
Length (mm)	L	90	50	150	200	250
Diameter (mm)	D	21.5	10	30	40	50
Bending Angle (°)	ϴ	81	70	90	100	110

2.4 Optimization of Intake Manifold System

To identify the optimal values for the three design parameters that yield the most significant performance improvements, optimization was performed using the Design of Experiment (DOE) method. First, parameters were created in the case setup menu to specify the design parameters of the intake manifold system in the engine model. The targets for this optimization were set to enhance peak torque and airflow rate at mid and high engine speeds (RPM).

2.5 Validation of Engine Model Results

The accuracy of the 1D simulation model developed for the MODENAS CT115s engine was rigorously validated by comparing simulation results with experimental data obtained from the MODENAS R&D Centre. Figure 2 and Figure 3 illustrate this comparison for brake power and brake torque, respectively. The validation results indicate that the discrepancies between the simulated and experimental data were consistently within 10%, underscoring the reliability and robustness of the simulation model in capturing the engine's performance characteristics. This level of accuracy aligns with industry standards for simulation validation, further supporting the credibility of the study's findings.

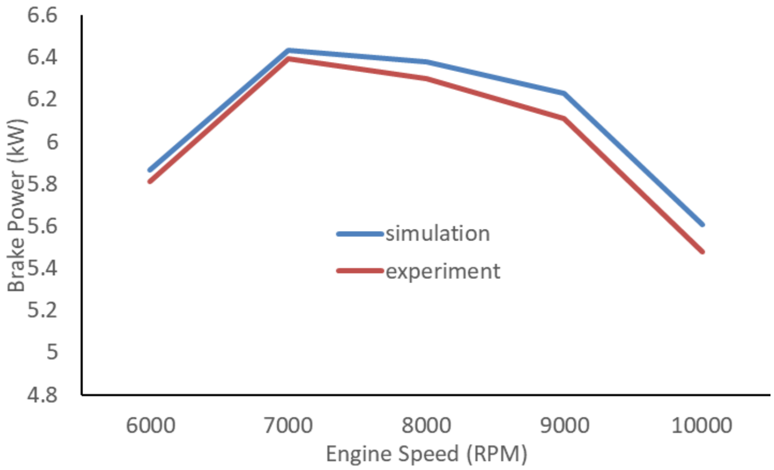

Fig. 2. The comparison between existing simulation and experimental result of brake power

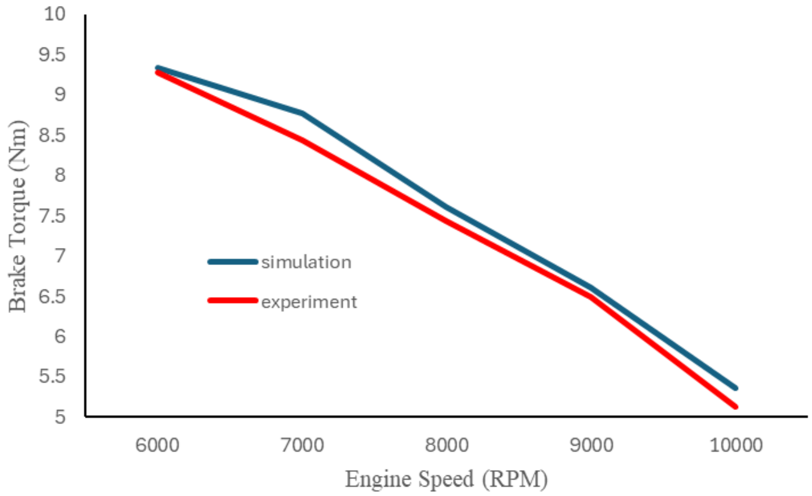

Fig. 3. The comparison between existing simulation and experimental result of brake torque

3. Results

3.1 Parametric Study on Intake Manifold System

In this research, a parametric study was conducted to examine and understand the relationship between variations in design parameters and engine performance, ensuring their interactions are clearly defined.

3.1.1 Intake manifold length

Figure 4 illustrates the relationship between brake power (in kW) and engine speed for various intake manifold lengths: the existing 90mm and alternative lengths of 50mm, 150mm, 200mm, and 250mm. As engine speed increases from 6000 RPM to approximately 8000 RPM, brake power rises for all manifold lengths, peaking at different points. The 90mm and 200mm manifolds exhibit the highest brake power, peaking at around 6.9 kW and 7.0 kW, respectively. The 150mm manifold shows a slightly lower peak, while the 50mm and 250mm manifolds demonstrate the lowest brake power across the engine speed range, with the 250mm length showing a sharp decline beyond 8000 RPM.

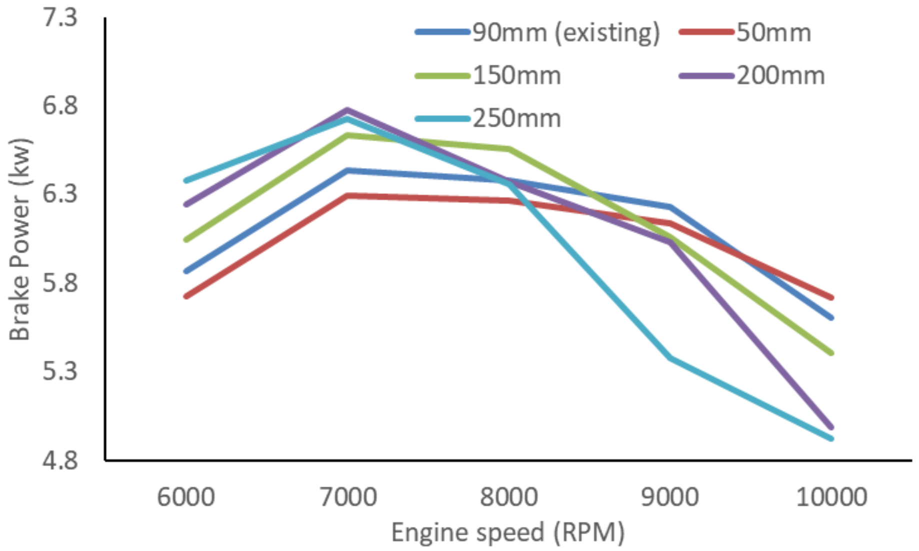

Fig. 4. Brake Power vs. Engine Speed of varies intake manifold length

Overall, the graph indicates that manifold length significantly influences engine performance, with mid-range lengths performing better than both shorter and longer ones. Figure 5 shows that brake torque follows a similar trend to brake power, with shorter lengths showing better performance at high RPM.

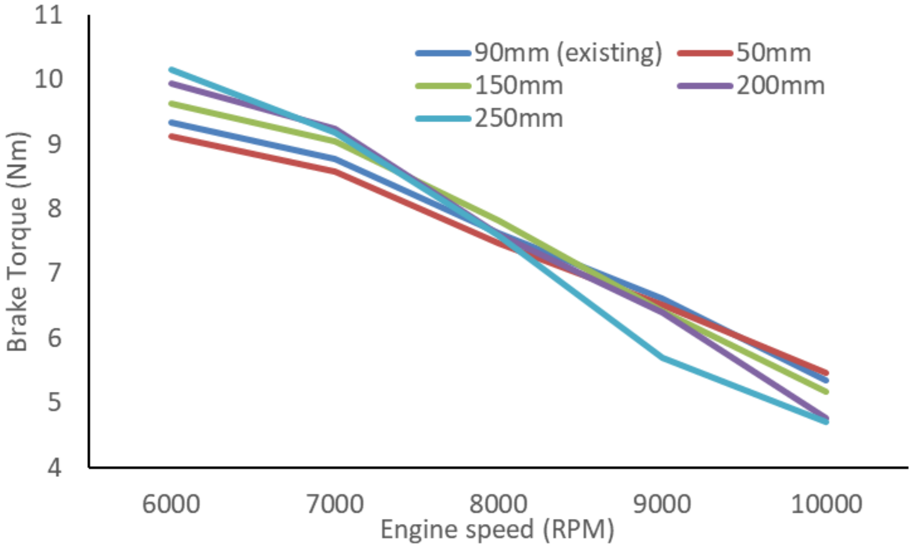

Fig. 5. Brake Torque vs. Engine Speed of varies intake manifold length

3.1.2 Intake manifold diameter

The two graphs illustrate the impact of intake manifold diameter on brake power and brake torque across a range of engine speeds. Figure 6 shows that brake power increases with engine speed up to a peak around 8000 RPM for all diameters, then decreases as engine speed approaches 10000 RPM. The existing 21.5mm manifold diameter delivers the highest brake power, closely followed by the 30mm, 40mm, and 50mm diameters, while the 10mm diameter consistently results in significantly lower brake power. Similarly, Figure 7 indicates that brake torque generally decreases with increasing engine speed for all diameters. The 21.5mm diameter maintains the highest brake torque across the RPM range, with the 30mm, 40mm, and 50mm diameters closely trailing, and the 10mm diameter producing the lowest brake torque.

The 10mm diameter intake manifold exhibits lower power and torque because its smaller size restricts airflow into the engine. Adequate air intake is crucial for efficient combustion in an internal combustion engine. When the diameter of the intake manifold is too small, it limits the volume of air that can enter the cylinders. This results in a less efficient combustion process due to insufficient air mixing with the fuel, leading to less power and torque production. The smaller diameter increases air resistance, reduces volumetric efficiency, and leads to a rich fuel mixture, all contributing to the significantly reduced engine performance observed with the 10mm diameter. These results suggest that a 30mm diameter offers comparable performance to the existing 21.5mm manifold, the smaller 10mm diameter is markedly less effective in both brake power and torque.

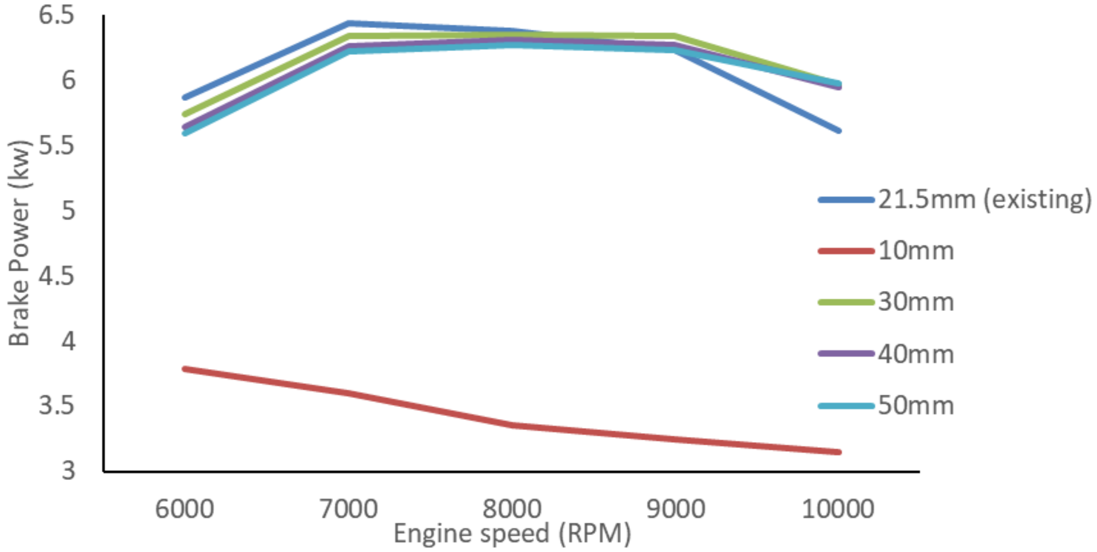

Fig. 6. Brake power vs. Engine Speed of varies intake manifold diameter

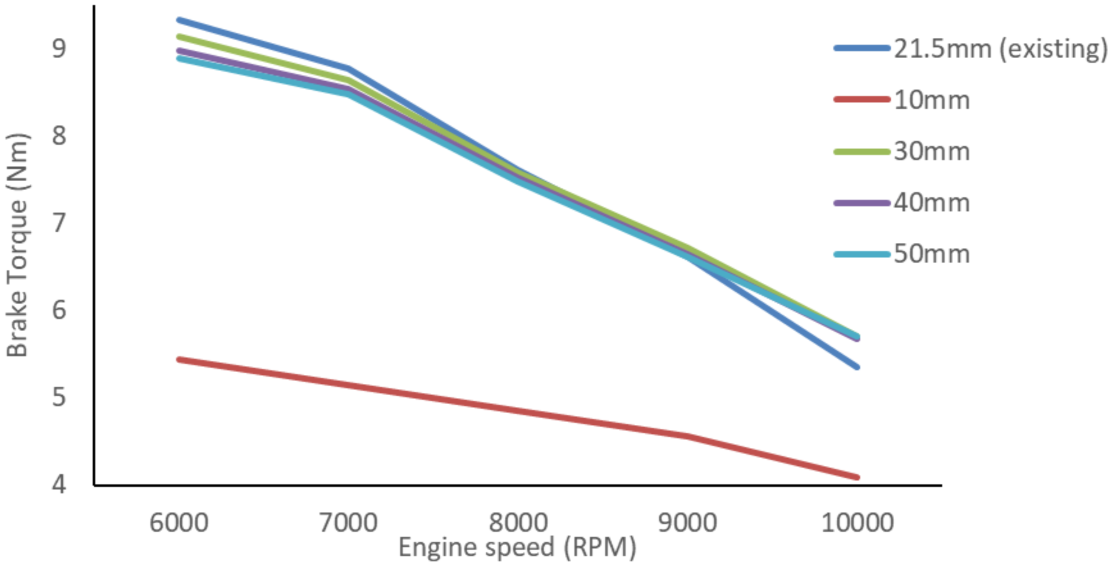

Fig. 7. Brake torque vs. Engine Speed of varies intake manifold diameter

3.1.3 Intake manifold bending angle

Figure 8 illustrates the relationship between brake power (in kW) and engine speed for various intake manifold bending angles: 70°, 81° (existing), 90°, 100°, and 110°. As engine speed increases from 6000 RPM to around 7000 RPM, brake power also rises, peaking at approximately 6.45 kW for all angles. Beyond 7000 RPM, brake power decreases for all angles, with the 70° angle showing slightly higher performance compared to the others. Figure 9 depicts the relationship between brake torque (in Nm) and engine speed (in RPM) for the same intake manifold bending angles. Brake torque decreases steadily from around 9.5 Nm at 6000 RPM to about 5.5 Nm at 10,000 RPM for all angles. The performance trend is consistent across the different bending angles, with minimal variation in brake torque. Both graphs indicate that while the bending angle has a noticeable impact on brake power at peak performance, its effect on brake torque is less pronounced across the engine speed range.

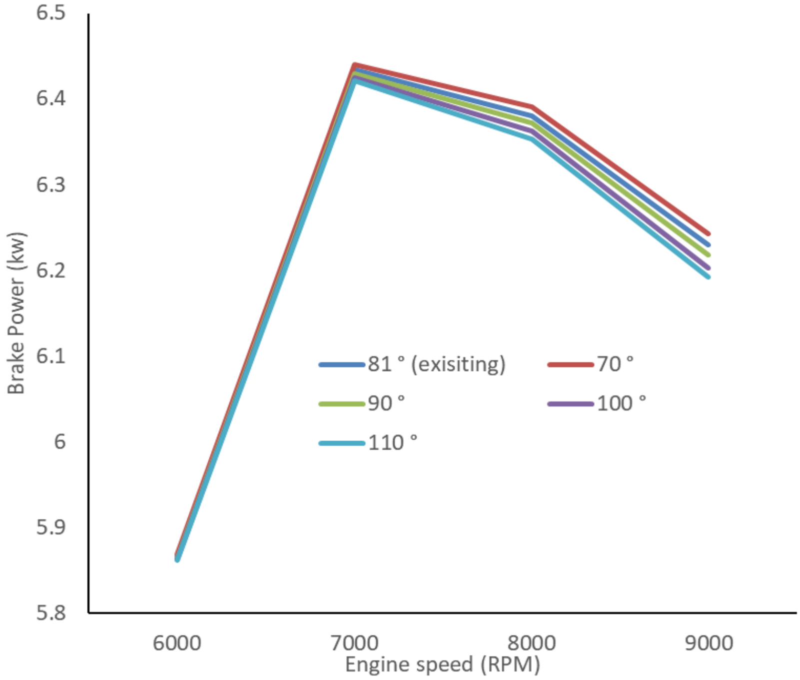

Fig. 8. Brake power vs. Engine Speed of varies intake manifold bending angle

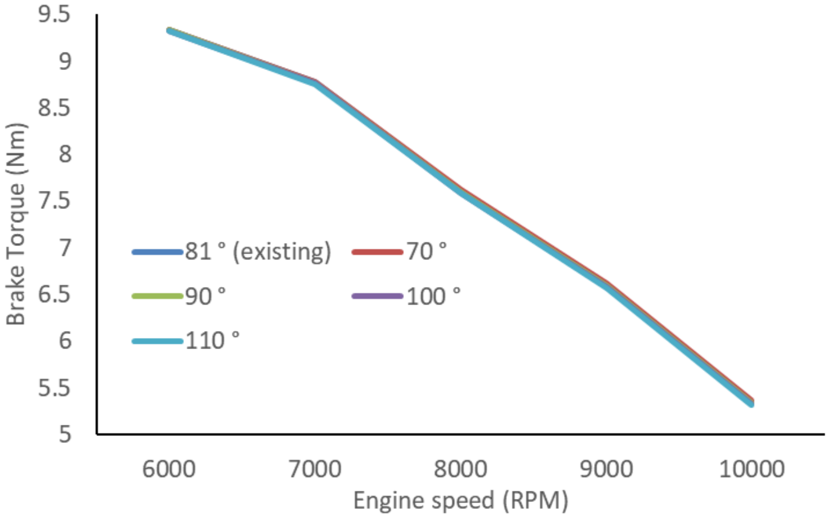

Fig. 9. Brake torque vs. Engine Speed of varies intake manifold bending angle

3.1.4 Optimization results of intake manifold

After conducting a comprehensive study on different intake manifold lengths, diameters, and bending angles, the best configuration was selected and designated as the optimized intake manifold. The two graphs below illustrate the performance differences between the optimized and existing intake manifolds.

Figure 10 shows the relationship between brake power (in kW) and engine speed for both the existing and optimized intake manifolds. As engine speed increases from 6000 RPM to 7000 RPM, brake power also rises, peaking at approximately 6.45 kW for the existing manifold and slightly higher for the optimized manifold. Beyond 7000 RPM, brake power decreases for both configurations, but the optimized manifold consistently delivers higher brake power across the entire RPM range. The optimized intake manifold shows a significant improvement in brake power at 10000 rpm which is 7.75%. This improvement can be attributed to the enhanced airflow dynamics provided by the optimized manifold design, which allows for more efficient combustion.

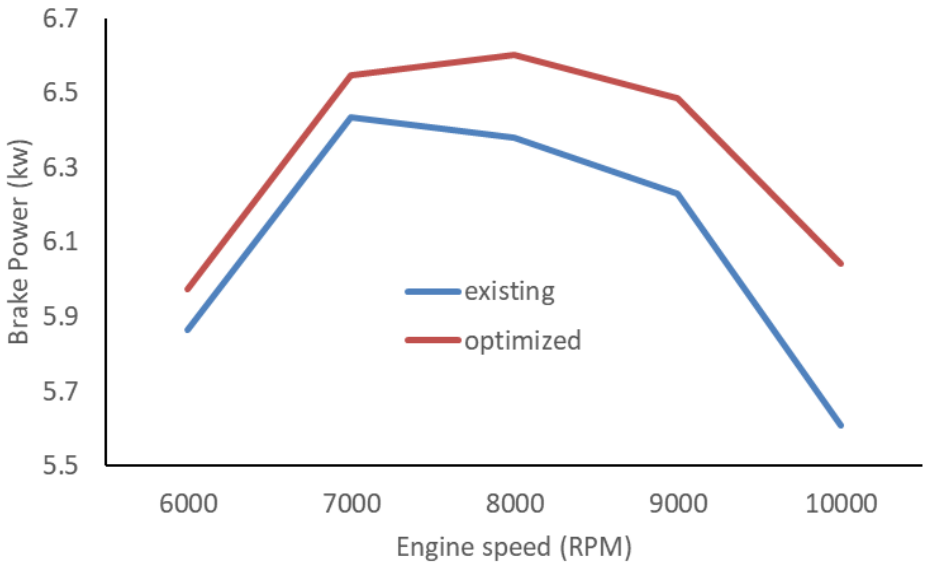

Fig. 10. Brake power vs. Engine Speed comparison of the existing and optimized intake manifold

Figure 11 illustrates the relationship between brake torque (in Nm) and engine speed for both the existing and optimized intake manifolds. Brake torque decreases steadily from around 9.5 Nm at 6000 RPM to about 5.5 Nm at 10,000 RPM for both configurations. However, the optimized manifold maintains a higher brake torque throughout the RPM range compared to the existing manifold. The optimized intake manifold shows a significant improvement in brake torque at 10000 rpm which is 6.5%. This enhancement is due to the optimized manifold's ability to better manage airflow and fuel mixture, resulting in more effective power delivery.

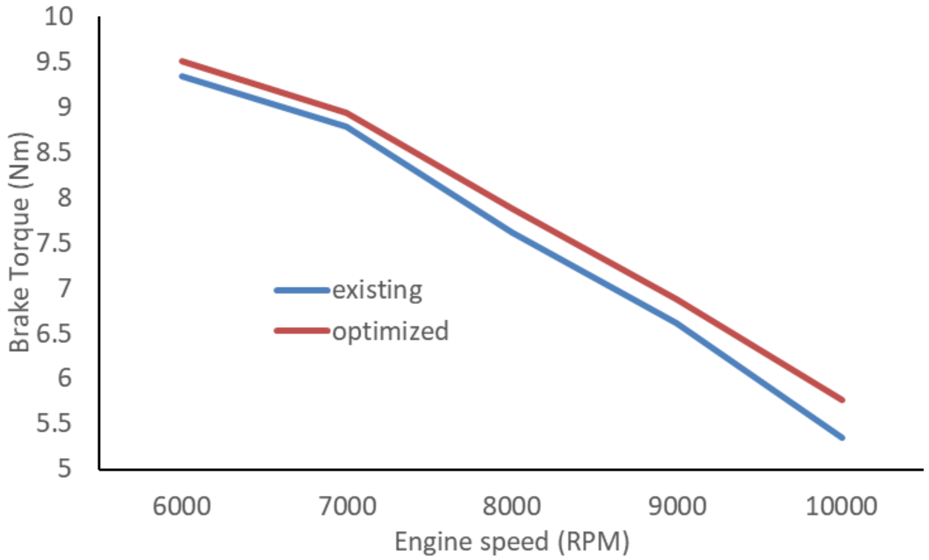

Fig. 11. Brake torque vs. Engine Speed comparison of the existing and optimized intake manifold

4. Conclusions

This study comprehensively analysed the effects of intake manifold geometry on the performance of a single-cylinder internal combustion engine (ICE) using a 1D Ricardo Wave simulation. The research focused on optimizing brake power and brake torque at high engine speeds by varying manifold parameters, including length, diameter, and bending angle. The findings provide significant insights into the relationship between these design parameters and engine performance.

The results indicate that manifold length has a substantial influence on engine performance. Among the tested lengths of 50 mm, 90 mm, 150 mm, 200 mm, and 250 mm, the mid-range lengths of 90 mm and 200 mm demonstrated superior performance, with the 90 mm length achieving a brake power of approximately 7.0 kW and a brake torque of 9.5 Nm at 10,000 RPM. Shorter lengths, such as 50 mm, exhibited better high-RPM performance but compromised efficiency at lower speeds, while longer lengths, such as 250 mm, suffered from excessive airflow resistance, reducing power output and torque.

The diameter of the intake manifold also plays a critical role in determining engine performance. The existing diameter of 21.5 mm yielded the highest brake power and torque, closely followed by the 30 mm diameter. Smaller diameters, such as 10 mm, significantly restricted airflow, leading to reduced performance, while larger diameters, such as 40 mm and 50 mm, introduced turbulence that offset potential gains in airflow efficiency. These findings highlight the importance of selecting an optimal diameter to balance airflow and minimize pressure losses.

Similarly, the bending angle was found to affect airflow dynamics and engine efficiency. Angles of 70°, 81°, 90°, 100°, and 110° were tested, with the existing 81° and 70° angles performing best across the RPM range. The 70° angle showed slightly better stability and achieved the highest brake power at 10,000 RPM due to reduced pressure losses. In contrast, larger angles, such as 100° and 110°, introduced increased resistance, which negatively impacted both power and torque.

The optimized intake manifold design, which combines a length of 90 mm, a diameter of 21.5 mm, and a bending angle of 70°, demonstrated significant improvements in performance. Compared to the baseline design, the optimized manifold achieved a 7.75% increase in brake power (7.75 kW at 10,000 RPM) and a 6.5% improvement in brake torque (6.5 Nm at 10,000 RPM). These enhancements underscore the importance of optimizing intake manifold geometry, particularly for applications requiring high-speed engine performance, such as motorsport.

In conclusion, this study provides valuable insights into the critical role of intake manifold geometry in enhancing ICE performance at high RPMs. The results contribute to the understanding of airflow dynamics and offer practical implications for the development of high-performance engines. This research serves as a foundation for future studies on advanced intake manifold designs and their applications in high-speed engine optimization.

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