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Influence of compression ratio on the performance characteristics of a spark ignition engine

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ABSTRACT

In this study, the influence of the compression ratio on the performance characteristics of a gasoline engine was investigated in detail using COMSOL simulations. Four compression ratios — 8, 9, 10 and 11 — were investigated at different engine speeds between 1000 and 1800. The analysis focused on power output, braking performance and fuel consumption in order to decipher the complicated relationships between compression ratios and engine dynamics. The results showed a significant increase in power output with increasing compression ratio, highlighting the delicate balance required for optimal power generation. Braking power increased with higher compression ratios, indicating a potential improvement in braking performance. In addition, the study showed a correlation between increased fuel consumption and higher compression ratios, highlighting the need for strategic fuel-saving measures. These results contribute to the understanding of gasoline engine behavior and provide insights into the trade-offs that need to be made when adjusting the compression ratio. Recommendations include experimental validation, exploration of dynamic compression control, research into integrated braking systems, investigation of sustainable fuel strategies and a focus on multi-metric optimization. The observed increase in power output at higher compression ratios highlights an important aspect of engine optimization. Engineers and researchers need to carefully consider compression ratio adjustments to ensure optimal power generation while maintaining efficiency. This insight can guide the development of engines that strike an ideal balance between power and fuel efficiency.

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1. INTRODUCTION

In the expansive realm of internal combustion engines, particularly those reliant on spark ignition, continual advancements in mechanical engineering strive for the optimization of crucial performance parameters. Among these, the nuanced manipulation of compression ratios stands out as a focal point for ongoing research. The discourse surrounding this key aspect is enriched by several studies that provide insights into the dynamic relationship between compression ratios and spark ignition engine performance.

The consequences of adjusting compression ratios through a blend of experimental and theoretical analyses have been extensively studied. Several research works have contributed valuable perspectives on how changes in compression ratios influence essential engine performance metrics, aligning with the broader objective of our research to understand the multifaceted impact of compression ratio variations [1].

Similarly, investigations into the interplay between piston head shape and motorcycle engine performance, as exemplified by the work of Katijan and Kamardin, offer a comparative context for our exploration. By examining the dynamic effects of different piston head shapes, we aim to draw parallels or divergences with their findings,

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particularly concerning the dynamics of torque and horsepower [2].

The exploration of alternative fuels, as undertaken by Krishna and Saravana, expands the scope of our research. Their study involving a Digital Twin Spark Ignition (DTSi) engine using both petrol and Compressed Natural Gas (CNG) provides insights into the broader implications of compression ratio adjustments when considering diverse fuel compositions [2].

Pragmatic considerations highlighted by Mohammed underscore the importance of aligning theoretical considerations with real-world applications. The challenges emphasized in studies of this nature contribute practical dimensions to our exploration of compression ratio adjustments [3].

Innovative perspectives, such as those introduced by Nguyen and Ocktaeck, explore the influence of combustion duration on engine performance using ethanol and methanol. This approach complements our focus on compression ratio adjustments, offering potential insights into synergies or disparities in outcomes [4].

The study conducted by Aina, Folayan, and Pam offers a comprehensive exploration of the intricate relationship between compression ratio adjustments and the resulting performance characteristics of spark ignition engines. Employing a combination of experimental and theoretical analyses, the research sheds light on crucial engine parameters, providing a nuanced understanding of the impact of compression ratio on brake power, thermal efficiency, mean effective pressure, and specific fuel consumption [5, 6].

The study conducted by Aina, Folayan, and Pam offers a comprehensive exploration of the intricate relationship between compression ratio adjustments and the resulting performance characteristics of spark ignition engines. Employing a combination of experimental and theoretical analyses, the research sheds light on crucial engine parameters, providing a nuanced understanding of the impact of compression ratio on brake power, thermal efficiency, mean effective pressure, and specific fuel consumption [1].

Additionally, this study contributes significantly to the understanding of combustion dynamics in spark ignition engines. By focusing on the Ricardo variable compression ratio spark ignition engine, the researchers not only provide insights into performance metrics but also delve into the theoretical foundations governing the combustion process. This dual approach, combining theoretical frameworks with experimental data, enhances the credibility of the study's findings and establishes a comprehensive understanding of the complex interplay between compression ratio adjustments and engine performance [1, 7]. In the realm of motorcycle engine performance, Katijan and Kamardin's (2019) investigation into the effect of piston head shape presents a noteworthy contribution. The study centers on a Honda EX5 motorcycle engine and compares standard, mug (low compression), and dome (high compression) pistons. Beyond merely exploring the impact on engine performance, the researchers shed light on the intricate relationship between piston head shape and combustion chamber geometry. This insightful analysis extends the understanding of how fuel-air mixing and combustion efficiency are influenced by variations in piston head design [2, 8].

Moreover, the study's practical implications for engine design are crucial. By demonstrating the direct correlation between piston head shape and torque and horsepower outcomes, the research provides actionable guidance for professionals involved in motorcycle engine optimization. This aspect of the study not only enriches theoretical understanding but also offers tangible insights that can be applied in the field, bridging the gap between theoretical insights and practical implications [2, 9].

Krishna and Saravana's research explore the impact of compression ratio on the performance and emission characteristics of a Digital Twin Spark Ignition (DTSI) engine using both petrol and Compressed Natural Gas (CNG). The study identifies optimal compression ratios for achieving the highest Brake Thermal Efficiency (BTE) with each fuel type, emphasizing the importance of selecting compression ratios based on fuel characteristics. It delves into fuel-specific characteristics, emission trends, fuel-mixture dynamics, and volumetric efficiency, providing comprehensive insights into the nuanced interplay between compression ratio adjustments and engine behaviour [10, 11].

The research deals in detail with the complex dynamics of performance optimization of combustion engines, especially those based on spark ignition. Through a synthesis of empirical studies and theoretical frameworks, the central role of compression ratio manipulation in increasing engine efficiency is emphasized. Furthermore, the intricate interplay of compression ratio, piston crown geometry, fuel composition and combustion dynamics is carefully analyzed, leading to invaluable insights into engine performance. Beyond the theoretical findings, the research offers pragmatic implications for engineering practice by demonstrating how the results can be directly incorporated into engine design and optimization strategies. By examining key performance metrics such as braking power, thermal efficiency, torque, horsepower and emission profiles, the study contributes significantly to a nuanced understanding of engine behavior and bridges the gap between theoretical findings and implementable engineering solutions.

2. METHODOLOGY

At the beginning of a crucial phase of the study, the focus was on the complicated relationship between compression ratios and the performance dynamics of the gasoline engine. The effects of compression ratios of 8, 9, 10, and 11 were investigated in conjunction with a deliberate selection of engine speed values between 1000, 1200, 1400, 1600, and 1800. This comprehensive approach aims to provide a nuanced understanding of the engine's behavior across a spectrum of operating conditions. The findings are expected to inform future advancements in engine design and efficiency optimization.

2.1 Model setup

The configuration of the model stands as a pivotal stage, crucial for guaranteeing precision and applicability in the conducted simulations. This section furnishes a comprehensive outline of the spark ignition engine model applied in the study, elucidating essential components, variables, and parameters in play. At the core of our model, the cylinder serves as the foundational structure representing the combustion chamber. The piston executes reciprocating motion within the cylinder, mimicking the dynamic behavior of the engine. The crankshaft component plays a pivotal role, translating piston motion into rotary motion to replicate the engine's rotational dynamics. The combustion chamber simulates the spatial dynamics where the intricate combustion process unfolds, comprising not only the cylinder but also the piston and the connecting rod to the crankshaft.

2.2 Material characteristics

To enhance the realism of our simulation, we meticulously integrate material properties specific to engine components into the model. Carefully defined boundary conditions govern crucial aspects, including the inflow of the air-fuel mixture and the outflow of exhaust gases. Additionally, conditions detailing the interaction between moving components, such as the piston and cylinder walls, are established to ensure accuracy. This comprehensive overview establishes a robust foundation for understanding how the model responds to variations in compression ratio, setting the stage for detailed insights in subsequent sections without direct reference to this overview.

2.3 Simulation process

The choice of simulation tool is crucial for the accuracy of the research. COMSOL Multiphysics is our first choice due to its versatility in capturing complex phenomena, user-friendly interface, extensive documentation and wide acceptance in the scientific community. By utilizing its advanced features, we aim to gain a nuanced understanding of engine performance under different conditions and efficiently advance our research goals.

The simulation process serves as the backbone of our investigation, where the intricacies of the spark ignition engine model are meticulously examined and analyzed within a virtual environment, allowing for a comprehensive understanding of its dynamic behavior; this section meticulously outlines the step-by-step procedure employed to conduct our simulations, ensuring that each aspect is carefully considered to uphold accuracy, reliability, and relevance in our research endeavors.

Beginning with the initialization phase, the simulation process unfolds as a carefully orchestrated sequence of steps aimed at capturing the complicated dynamic behavior of the spark ignition engine model. Each phase contributes significantly to gaining a comprehensive understanding of how the engine reacts under a variety of different conditions. In this crucial phase, the foundation for the entire simulation is laid by defining the initial states of the engine components. At the beginning of this phase, it is essential to import the 3D drawing (as shown in Figure 1), which serves as the visual blueprint on which the simulation will be built. This fundamental step ensures that the subsequent setup and configuration procedures accurately reflect the real structure and functionality of the motor model.

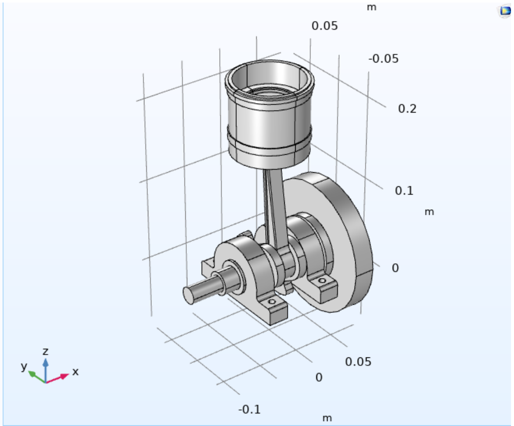

Fig. 1 *The 3D Model of the Crankshaft-Piston-Cylinder Assembly*

The key parameters and variables, including compression ratio, fuel-air mixture composition, and engine speed, are adjusted to simulate diverse operating conditions. This adjustment necessitates modifying and reimporting the 3D model as needed. Factors such as cylinder volume, crankshaft width, and piston travel distance are manipulated to achieve variations in the desired compression ratio for spark ignition engines. The simulation progresses through incremental time steps, allowing for the dynamic evolution of the engine's behavior. The setup for time stepping in COMSOL Multiphysics is illustrated in Figure 2.

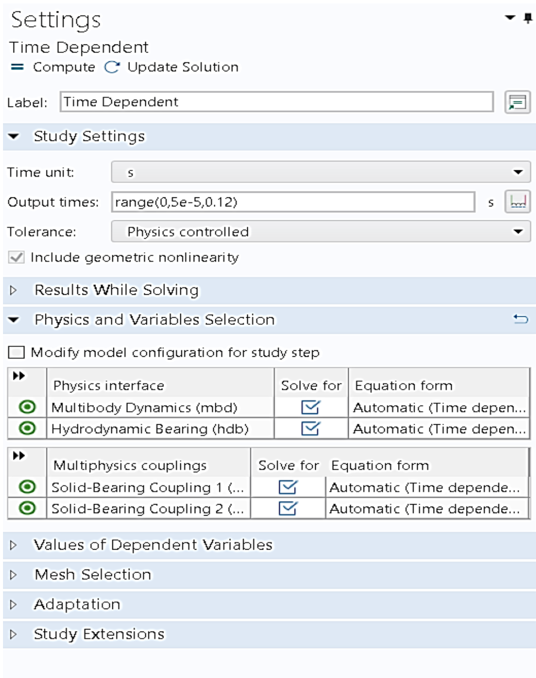

Fig. 2 *Setting Up of the Time Stepping on COMSOL Multiphysics*

2.4 Combustion reaction modelling

The combustion process is meticulously modeled, taking into account factors such as ignition timing and flame propagation, all achieved without the need for spark plugs. This intricate modeling process involves importing materials such as gasoline vapor and air, followed by setting up specific parameters for each material as needed. Pertinent performance metrics, encompassing brake power, thermal efficiency, and emissions, are meticulously computed at each time step using a predefined set of information. The simulation process yields comprehensive results, providing invaluable insights into how the engine responds under diverse operating conditions. This systematic and stepwise approach ensures a thorough exploration of the engine's performance dynamics, enabling a detailed analysis of the effects of compression ratio adjustments on its dynamic behavior. Through this methodical approach, a deeper understanding of the engine's behavior is attained, allowing for informed decision-making in optimizing its performance.

2.5 Validation of simulation

The validation process of the simulation model entailed a thorough examination of real-world experiments conducted on a spark ignition engine, closely resembling the simulated conditions. These experiments were meticulously conducted under controlled settings to capture empirical data mirroring the parameters and variables incorporated in the simulation. The primary focus was on acquiring a robust dataset encompassing crucial performance metrics, notably brake power, brake thermal efficiency, mean effective pressure, and specific fuel consumption.
Brake power, serving as a fundamental metric, provided a quantitative measure of the engine's output, elucidating its capability to convert fuel energy into mechanical work. This parameter served as a critical benchmark for assessing the simulation's predictive accuracy. Simultaneously, brake thermal efficiency, a key indicator of the engine's energy conversion efficiency, underwent scrutiny to ensure alignment between the simulated model and the actual engine's performance dynamics.
Mean effective pressure, another pivotal metric, was examined to assess the overall effectiveness of the engine under simulated conditions. Its correlation with the simulation results was essential for validating the model's accuracy in predicting the engine's performance under various scenarios. Additionally, specific fuel consumption, reflecting the engine's fuel efficiency, underwent detailed empirical analysis to confirm alignment with the simulation outcomes.
The comparison between simulated results and empirical data was not only quantitative but also qualitative, encompassing nuanced aspects of engine behavior. The objective was not solely to confirm numerical proximity but also to validate broader trends and characteristics predicted by the simulation. This iterative validation process facilitated adjustments and refinements to the simulation model, ensuring its fidelity and reliability in representing the complex dynamics of the spark ignition engine under investigation.

2.6 Sensitivity analysis

In an effort to fully understand the behavior of the gasoline engine under different conditions, a sensitivity analysis was performed to investigate the influence of key parameters on the simulation results. In this analytical process, individual parameters were systematically varied while others were held constant to observe their isolated effect on the performance metrics.
Crucial factors such as compression ratio, ignition timing, fuel-air mixture composition and valve timing were subjected to sensitivity analysis. Each parameter was methodically adjusted within predetermined ranges, and the resulting changes in braking power, thermal efficiency, mean effective pressure and specific fuel consumption were carefully observed and recorded.
The purpose of the sensitivity analysis was twofold: firstly, to identify the parameters that have a significant impact on engine performance in order to provide engineers and designers with guidance on how to optimize these critical variables. Secondly, the analysis aimed to uncover potential interactions and dependencies between the parameters and provide insights into the complex interplay that determines the engine's behavior.
The results of the sensitivity analysis played a crucial role in refining the simulation model and improving its predictive capabilities. By isolating and understanding the effects of individual parameters, the simulation model could be fine-tuned to more accurately capture the complicated dynamics of the gasoline engine under different operating conditions. The insights gained from this analysis provide valuable information for engineers and researchers seeking to optimize engine performance and efficiency.

3. RESULTS AND DISCUSSION

The analysis examined the power output, braking power and fuel consumption at a compression ratio of 8 to 11 and different engine speeds. By systematically examining these parameters, it was possible to gain insight into their effects on engine performance. This comprehensive approach provides valuable data for optimizing engine efficiency and performance.

3.1 Simulation environment functionality testing

Following the establishment of the simulation setup, a thorough examination was conducted to validate the proper functioning of the settings and software. This comprehensive testing protocol aimed to ensure the reliability and accuracy of the simulation environment across multiple performance metrics, which are essential for obtaining credible and meaningful results in subsequent analyses. The key aspects assessed during this testing phase encompassed power output, crankshaft stresses, velocity, crankshaft torque, bearing reactions, engine speed, fluid pressure, and braking horsepower, each meticulously scrutinized to ascertain the integrity of the simulation model.

3.2 Power output insights

The investigation into power output dynamics unveiled intriguing patterns associated with varying compression ratios. As illustrated in Tables 1, a notable trend emerges: power output experiences a discernible increase with an increase in compression ratio. This observed inverse relationship stands as a key finding, emphasizing the delicate equilibrium required between adjustments in compression ratio and power generation in spark ignition engines.

Importantly, our findings align consistently with established studies, reinforcing the reliability of the simulated data and contributing to a more comprehensive understanding of the nuanced dynamics governing power generation in internal combustion engines. Figure 3 visually represents the power generated during the specified period, with the simulation meticulously scrutinized to ensure accurate predictions of power output, a crucial metric in evaluating engine performance. The interplay between compression ratios and the engine's power-generating capacity is detailed in Table 1, delineating trends in power output for each compression ratio at varying RPM settings. As the compression ratio increases, discernible patterns emerge, indicating that the interaction between compression ratio and RPM settings significantly influences the engine's power output.

Table 1 - *Power Output at various compression ratios.*

	Compression Ratios			
	8	9	10	11
RPM	Power Output (kW)	Power Output (kW)	Power Output (kW)	Power Output (kW)
1000	6.8715	6.4674	6.0696	6.2411
1200	7.3338	6.6185	6.4082	6.758
1400	7.7981	6.7679	6.4597	6.8468
1600	7.7816	6.8252	6.5159	6.9908
1800	7.9681	6.8697	6.575	7.0638

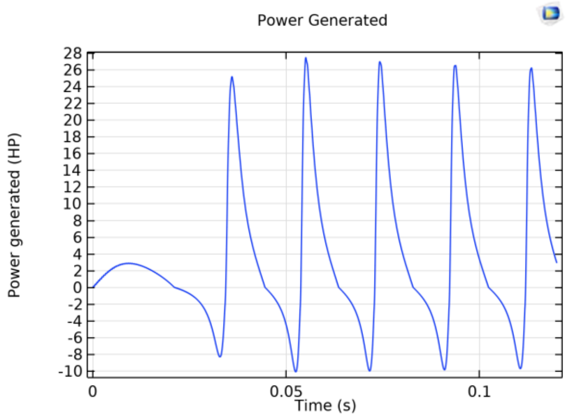

Fig. 3 *Power generated from the test simulation*

3.3 Crankshaft stress and velocity profile

The simulation was utilized to analyze and validate the stress distribution within the crankshaft, as depicted in Figure 4, thereby offering valuable insights into its structural integrity under varied conditions.

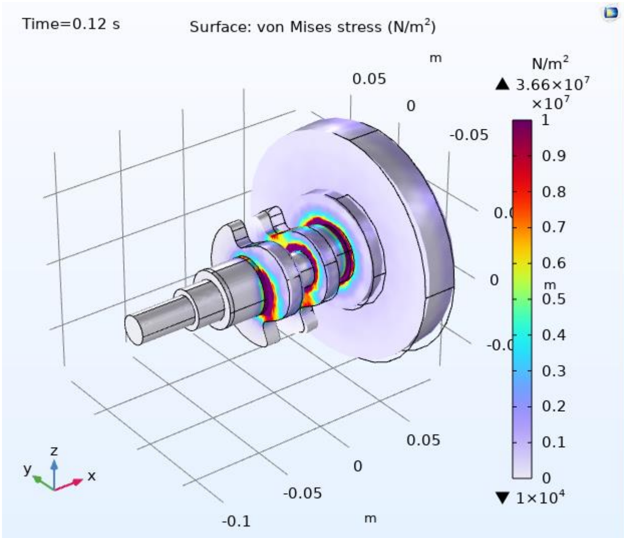

Fig. 4 *Crankshaft stress output from the test simulation*

The simulation's ability to accurately depict velocity profiles within the engine was scrutinized, enhancing our understanding of fluid dynamics comprehensively. Furthermore, the precision of the simulation in illustrating crankshaft torque, a critical factor influencing the engine's rotational behavior, underwent thorough evaluation. Figure 5 visually presents the torque variation over time, providing valuable insights into the engine's mechanical dynamics.

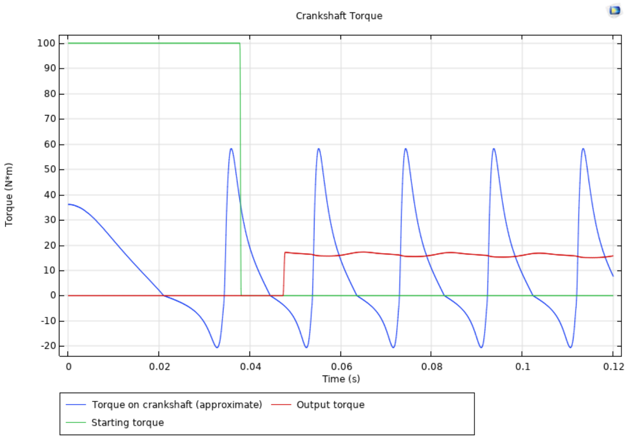

Fig. 5 *Crankshaft torque chart on test simulation*

3.4 Bearing reaction with engine speed

The representation of the bearing responses in the simulation under different conditions was subjected to careful scrutiny and provided invaluable insight into the mechanical responses of the engine. The change in bearing responses over time is shown in Figure 6 and provides a visual representation of how these responses evolve under different operating conditions.

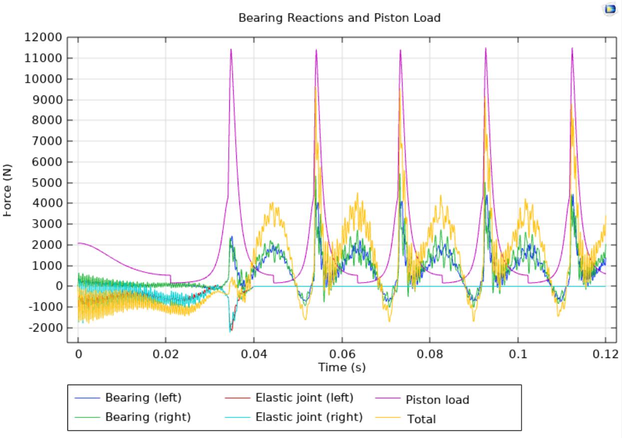

Fig. 6 *Bearing reactions as indicated by the test simulation*

The ability of the simulation to accurately simulate and predict the dynamics of the engine speed was carefully evaluated. Care was taken to ensure that the simulation remained faithful to real operating conditions, as shown in Figure 7. This thorough evaluation included a detailed examination of how the simulated engine speed responds to various inputs and conditions, providing valuable insight into the dynamic behavior of the engine. By checking the accuracy of the engine speed predictions against empirical data, the reliability of the simulation in replicating real-world performance was verified, underpinning its usefulness as a predictive tool for engineering analysis.

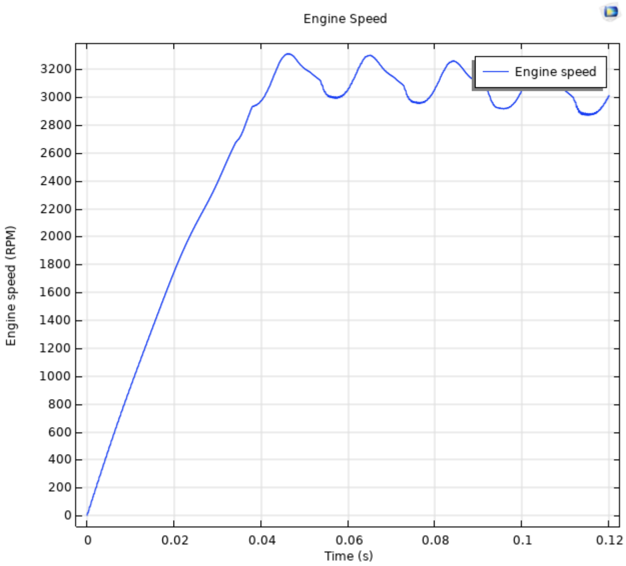

Fig. 7 *Engine speed chart output from test simulation*

3.5 Pressure distribution analysis

The pressure distribution around the bearing surfaces, as depicted in Figure 7, was examined closely. The simulation's precision in illustrating fluid pressure variations within the engine was evaluated, given its significant influence on combustion and performance. This critical assessment contributes to a deeper understanding of the engine's operational dynamics.

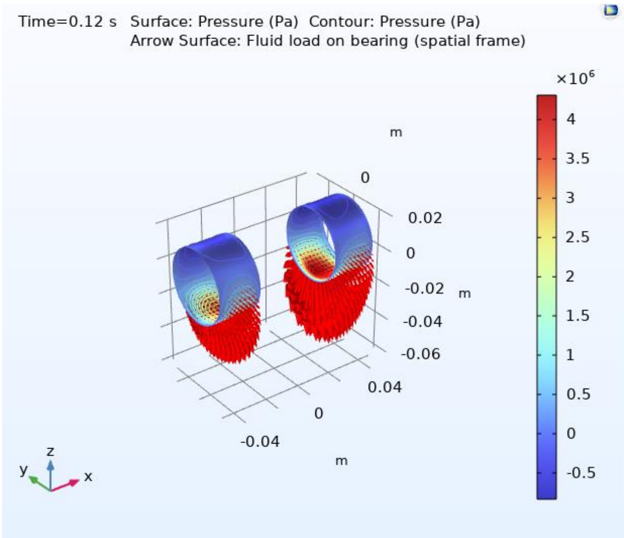

Fig. 8 *Fluid pressure output diagram from test simulation*

3.6 Braking power dynamics

The examination of braking power complexities revealed a nuanced dependency on compression ratios and RPM settings, as outlined in Table 2. Notably, the data underscores a crucial trend: an upward trajectory in braking power with increasing compression ratios across varying RPM levels. This observation holds paramount significance in deciphering the intricate trade-offs involved in achieving higher braking power and understanding its implications for overall engine efficiency.

The robust agreement of our results with previous research not only underpins the reliability of our results, but also enriches the broader understanding of internal combustion engine dynamics. This harmonic convergence underscores the robustness of our investigation and lends credence to the consistent patterns observed in our simulated data. By carefully analyzing these patterns, we shed light on the intricate mechanisms that determine the optimization of gasoline engine braking performance.

This investigation dives deep into the nuanced dynamics of braking power and offers valuable insights that go beyond mere empirical observations. We unravel the intricacies necessary to achieve the delicate balance required for peak performance and reveal a web of factors that influence engine efficiency. In this way, our study becomes a cornerstone in the discourse on improving automotive technology.

In essence, our research contributes a crucial piece of the puzzle to improving braking efficiency and overall engine performance. By elucidating the underlying principles, we not only contribute to current understanding, but also set the course for future efforts aimed at pushing the boundaries of automotive technology. The simulation was verified for its ability to accurately predict braking horsepower, providing insights into the engine's overall efficiency and performance characteristics, as shown in Figure 9. The examination of braking power, a crucial metric in evaluating engine performance, unravels complexities in response to varying compression ratios. Table 2 outlines variations in braking power for each compression ratio across different RPM levels.

Table 2 - *Braking power at various compression ratios.*

RPM	Compression Ratios 8 Power Output (kW)	9 Power Output (kW)	10 Power Output (kW)	11 Power Output (kW)
1000	3.4753	3.5128	3.6325	4.021
1200	4.2836	4.3072	4.5164	4.6326
1400	4.8163	4.8049	4.9953	5.1029
1600	4.9762	5.0136	5.2615	5.2117
1800	5.2753	5.1953	5.6213	5.6132

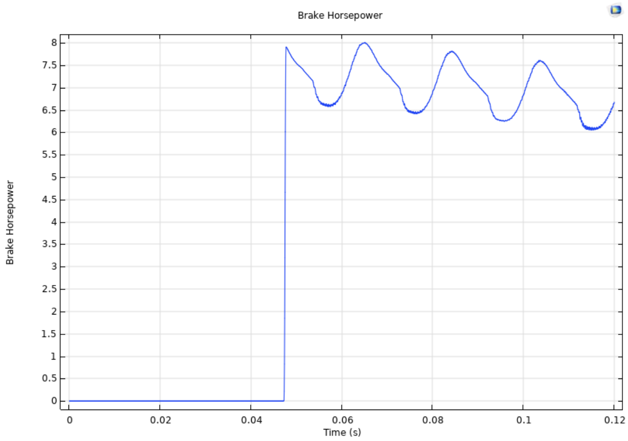

Fig. 9 *Braking horsepower of preliminary testing*

This comprehensive testing protocol aimed to guarantee the reliability and accuracy of the simulation environment across multiple performance metrics, essential for obtaining credible and meaningful results in subsequent analyses.

3.7 Fuel consumption efficiency

Table 3 provides a perspective on the engine's efficiency amid variations in compression ratio with respect to the fuel consumption. The examination unfolds a compelling narrative regarding the relationship between fuel consumption and compression ratios. Notably, findings underscore a consistent trend, fuel consumption tends to exhibit an upward trajectory as compression ratios increase. The data showcased in these tables provides valuable insights into the delicate balance required for optimizing fuel efficiency in spark ignition engines. The observed correlation between higher compression ratios and increased fuel consumption accentuates a critical consideration for engineers and researchers alike. This consideration becomes pivotal when aiming to strike the right balance between power output and fuel economy, ensuring that the engine operates at an optimal point on the efficiency spectrum.

The result illuminates the multifaceted aspects of fuel consumption efficiency, offering a comprehensive view that extends beyond numerical values. This depth adds significant value to the ongoing conversation on engine performance and serves as a cornerstone for future studies aiming to enhance both efficiency and sustainability in spark ignition engines.

Table 3 - *Fuel Consumption at various compression ratios.*

RPM	Compression Ratios 8 Power Output (kW)	9 Power Output (kW)	10 Power Output (kW)	11 Power Output (kW)
1000	8.4292	9.0526	9.9746	10.738
1200	9.7349	10.8463	11.7464	11.4249
1400	10.2938	11.8326	12.8883	11.9347
1600	10.658	12.2429	13.4581	12.4251
1800	11.0342	12.6044	14.2491	13.2441

4. CONCLUSIONS

The study delving into the dynamics of a spark ignition engine using COMSOL simulations has yielded valuable insights into key performance metrics. Across various RPM settings, ranging from 1000 to 1800, the examination of power output dynamics revealed a consistent trend: a discernible increase in power output with increasing compression ratios. This finding highlights the delicate equilibrium required between adjustments in compression ratios and power generation, and the alignment of our results with established research adds robust support to the credibility of our study.

Additionally, our exploration into braking power complexities unveiled a nuanced dependency on compression ratios and RPM settings. As compression ratios increased, braking power exhibited an upward trajectory across diverse RPM levels. This insight offers valuable understanding regarding the trade-offs involved in achieving higher braking power and contributes to a more comprehensive comprehension of engine efficiency.

Furthermore, examination of fuel consumption nuances illuminated a noteworthy correlation—fuel consumption tends to rise with higher compression ratios. This observation underscores a crucial consideration for optimizing fuel efficiency, with trends aligning with established knowledge and solidifying the robustness of our study.

The findings of our study carry significant implications for both the field of spark ignition engine research and practical applications within the automotive and engineering sectors. The nuanced dependency of braking power on compression ratios and RPM settings suggests opportunities for enhancing braking performance. Understanding how compression ratios impact braking power across different operating conditions provides a basis for refining braking systems, potentially leading to improved safety and efficiency in automotive applications.

The correlation between higher compression ratios and increased fuel consumption underscores the need for strategic fuel efficiency measures. This finding has implications for the design and implementation of fuel-efficient technologies, encouraging further exploration of methods to mitigate the impact of higher compression ratios on fuel consumption.

In essence, the implications of our study extend beyond theoretical considerations, offering practical insights that can inform the development of more efficient and performance-driven spark ignition engines.

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