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Comparative Analysis of Engine Performance and Emissions Using Experimental and GT-POWER Simulation

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Abstract
Internal combustion engines' performance and emission characteristics are critical for improving efficiency and environmental sustainability. This study aims to validate the predictive accuracy of GT-POWER simulation software by comparing it with experimental data across multiple engine parameters, including brake efficiency, brake power, brake torque, specific CO and CO_2 emissions, and in-cylinder heat transfer. The engine was tested at various speeds ranging from 1000 to 6000 rpm, and simulation data were generated using GT-POWER under equivalent conditions. Experimental results showed that the maximum brake efficiency occurred at 2000 rpm, reaching 27.3%, while the GT-POWER simulation predicted 26.3%. The peak brake power was 87 kW (experiment) and 84 kW (simulation) at 1600 rpm. Brake torque peaked at 71 bar (experiment) and 66 bar (simulation) at 2000 rpm. Emission results indicated a decrease in brake-specific CO from 75 g/kW·h at 1000 rpm to 21 g/kW·h (experiment) and 16 g/kW·h (simulation) at 6000 rpm. Similarly, CO_2 emissions dropped from 60 g/kW·h to 15 g/kW·h (experiment) and 14 g/kW·h (simulation). In-cylinder heat transfer showed a maximum of 43 kW (experiment) and 38 kW (simulation), with the most significant discrepancies at higher engine speeds. The novelty of this study lies in its multi-variable validation approach and inclusion of thermal behaviour through in-cylinder heat transfer analysis, which is rarely addressed in simulation studies. The results confirm that GT-POWER accurately captures performance trends, particularly within the 1600–2000 rpm range, though refinements are needed for thermal modelling at high speeds.

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1. Introduction

Internal combustion engines (ICEs) remain the dominant power source in transportation and industrial applications due to their high energy density and well-established infrastructure. However, increasing concerns over fuel efficiency, emissions, and environmental sustainability have pushed researchers and manufacturers to optimize engine performance and reduce exhaust pollutants. Advanced simulation tools, such as GT-POWER, have become integral in evaluating and predicting engine behaviour under various operating conditions without relying solely on time-consuming and expensive physical experiments. Numerous studies have applied GT-POWER modelling to simulate engine performance parameters, including power output, efficiency, torque, and emissions. For instance, the effectiveness of GT-POWER in predicting brake power and torque in a turbocharged gasoline engine has been demonstrated, and its use for simulating diesel engine performance under variable load conditions has been validated (Ahmadipour, Aghkhani, & Zareei, 2021; Almardhiyah, Mahidin, Fauzi, Abnisa, & Khairil, 2025; Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Yana, Mufti, Hasiany, Viena, & Mahyudin, 2025). Similarly, GT-POWER was used to analyze combustion and emission characteristics when using alternative fuels (Gani, Saisa, et al., 2025; Jena, Raj, Tirkey, & Kumar, 2023; Mufti, Irhamni, & Darnas, 2025; Pranoto, Rusiyanto, & Fitriyana, 2025).

Despite these advancements, many of the existing studies focus on isolated parameters such as brake power or NOx emissions, often neglecting the broader spectrum of performance indicators and their interdependencies (Irhamni, Kurnianingtyas, Muhtadin, Bahagia, & Yusop, 2025; Maghfirah, Yusop, & Zulkifli, 2025; Rahimi, Bortoluzzi, & Wahlström, 2021; Selvakumar, Maawa, & Rusiyanto, 2025). Furthermore, fewer studies provide detailed comparisons across multiple parameters, including brake efficiency, torque, power in both HP and kW, brake-specific emissions, and in-cylinder heat transfer within a single, integrated validation framework. In-cylinder heat transfer, in particular, is a crucial yet underexplored parameter in GT-POWER validation (Gani, Zaki, Bahagia, Maghfirah, & Faisal, 2025; Klingbeil & Lavertu, 2020; Muhibbuddin, Hamidi, & Fitriyana, 2025; Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025). Accurate modelling of thermal losses is essential for performance prediction, thermal management, and durability assessments. Only a limited number of studies have addressed in-cylinder heat transfer validation due to its complexity and dependency on dynamic boundary conditions and transient combustion phenomena (Fonseca, Olmeda, Novella, & Valle, 2020; Gani, Mahidin, Erdiwansyah, Sardjono, & Mokhtar, 2025; Jalaludin, Kamarulzaman, Sudrajad, Rosdi, & Erdiwansyah, 2025; Muhtadin, Rosdi, Faisal, Erdiwansyah, & Mahyudin, 2025).

Moreover, discrepancies often exist between experimental and simulated results, especially at high engine speeds where real-world physical losses and combustion instabilities are more prominent (Gani et al., 2023; Iqbal, Rosdi, Muhtadin, Erdiwansyah, & Faisal, 2025; Liu et al., 2022; NOOR, Arif, & Rusirawan, 2025). These discrepancies highlight the need for a comprehensive model validation to pinpoint the limits and strengths of simulation tools like GT-POWER in various engine regimes. To address these gaps, this study conducts a detailed comparative analysis between experimental and GT-POWER simulated results for a spark-ignition engine tested across a wide range of engine speeds (Khanyi, Inambao, & Stopforth, 2025; Nizar, Yana, Bahagia, & Yusop, 2025; Rosdi, Ghazali, & Yusop, 2025; Sumarno, Fikri, & Irawan, 2025). The analysis covers seven key performance and emission indicators: brake efficiency, brake power (HP and kW), brake torque, brake-specific CO and CO_2 emissions, and in-cylinder heat transfer (Maulana, Rosdi, & Sudrajad, 2025; Muchlis, Efriyo, Rosdi, & Syarif, 2025; Rosdi, Yasin, Khayum, & Maulana, 2025; Wang, Shuai, Li, & Yu, 2021).

Through this multi-parameter approach, the study aims to validate the accuracy of GT-POWER in simulating real engine behaviour while identifying specific speed ranges where deviations occur. Special attention is given to thermal behaviour, offering insights into the model's limitations and potential areas for refinement. Ultimately, this research contributes to the advancement of simulation-based engine development by providing a robust validation framework that supports performance optimization and emission reduction strategies while highlighting the model's capability and shortcomings in replicating complex engine dynamics.

2. Methodology

Fig. 1 illustrates a structured and systematic methodology employed in this research study to validate and assess engine performance and emission characteristics using experimental data and simulation software (GT-POWER). The flowchart depicts sequential stages, facilitating a comprehensive approach to achieving reliable and precise research outcomes. The study begins with an exhaustive literature review and problem identification stage. During this phase, relevant existing studies and technical documents are thoroughly reviewed to identify research gaps, explicitly focusing on engine performance parameters, emissions, and heat transfer characteristics that require further exploration. Subsequently, the second stage, experimental setup and engine testing involves detailed planning and preparation of the physical engine test conditions. Here, the engine is tested under various predefined speeds, ranging from 1000 to 6000 rpm. This step ensures accurate and real-world data is collected for subsequent analysis and validation processes.

The third stage involves the GT-POWER simulation setup, configuring equivalent engine operating conditions within the GT-POWER environment. This simulation software is utilized to theoretically predict engine performance and emission parameters, allowing for an efficient comparison with experimental outcomes. Next, the research progresses to the data collection stage, integrating experimental and simulation data. The meticulous gathering of datasets for both scenarios is critical for ensuring accuracy and reliability, facilitating a robust comparative framework. The fifth stage is the comparative analysis, representing the research's core analytical part. Here, several key performance and emission parameters are scrutinized thoroughly:

a) Brake Efficiency: Evaluates the effective conversion of fuel energy into mechanical work.
b) Brake Power (HP & kW): Assesses engine output power capabilities at varying speeds.
c) Brake Torque: Measures the twisting force produced by the engine, essential for vehicle propulsion.
d) Brake Specific CO & CO_2 Emissions: Determining the environmental impact through emission rates per unit power output is crucial for sustainability assessments.
e) In-Cylinder Heat Transfer: Analyzes thermal energy transfer inside the cylinder, which affects efficiency, durability, and engine cooling strategies.

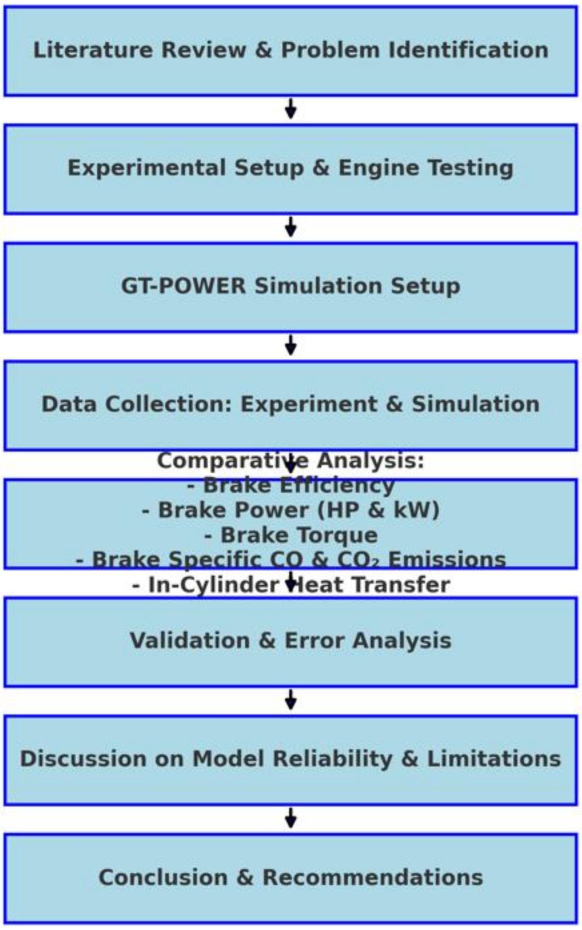

Fig. 1. Research Methodology Flowchart

Disc discrepancies between experimental results and simulation predictions are systematically examined in the validation and error analysis phase. This stage identifies the accuracy of GT-POWER, quantifying deviations and assessing their implications on reliability. The subsequent stage addresses the discussion on model reliability and limitations. Here, the model's predictive capabilities, strengths, and potential shortcomings are evaluated in detail. Specifically, it identifies operational ranges where

simulation closely mirrors experimental outcomes (e.g., the 1600–2000 rpm range) and highlights areas requiring further model calibration, particularly at higher engine speeds.
Finally, the research culminates in a conclusion and recommendations phase. Based on the comprehensive analysis and discussions from the preceding stages, informed conclusions are drawn about GT-POWER's applicability in predicting engine performance and emissions. Recommendations aim to improve future modelling accuracy and guide further research to optimize internal combustion engine performance and environmental compatibility. Overall, **Fig.1** provides a clear, structured representation of the research approach, enhancing understanding of the sequential activities and analytical depth undertaken to achieve the study's objectives.

3. Result & Discussion

Fig. 2 illustrates the relationship between engine speed (rpm) and brake efficiency (%) based on experimental data and GT-POWER simulation results. Overall, the brake efficiency trend increases with engine speed up to a certain point and slightly decreases thereafter. The comparison demonstrates a close agreement between the experimental and simulation outcomes across all engine speeds tested. At 1200 rpm, the brake efficiency is approximately 15.8% in the experimental result and 14.5% in the GT-POWER simulation. As the engine speed increases to 1400 rpm, brake efficiency rises to 21.5% (experiment) and 20.2% (GT-POWER), indicating a more efficient energy conversion at higher speeds. This positive trend continues at 1600 rpm, where the brake efficiency reaches 24.3% experimentally and 23.5% in simulation. At 1800 rpm, both values improve to 26.1% (experiment) and 25.4% (GT-POWER), showing the closest match in the entire range, with only 0.7% deviation. The maximum brake efficiency is observed at 2000 rpm, with 27.3% for the experiment and 26.3% for the GT-POWER model. However, a slight decline is noted at 2200 rpm, where brake efficiency drops marginally to 26.6% (experiment) and 25.9% (GT-POWER). These results indicate that the engine performs most efficiently in the 1800–2000 rpm range, and the GT-POWER simulation closely replicates the experimental findings with deviations below 1%, confirming the model's reliability in predicting brake efficiency behaviour under varying engine speeds.

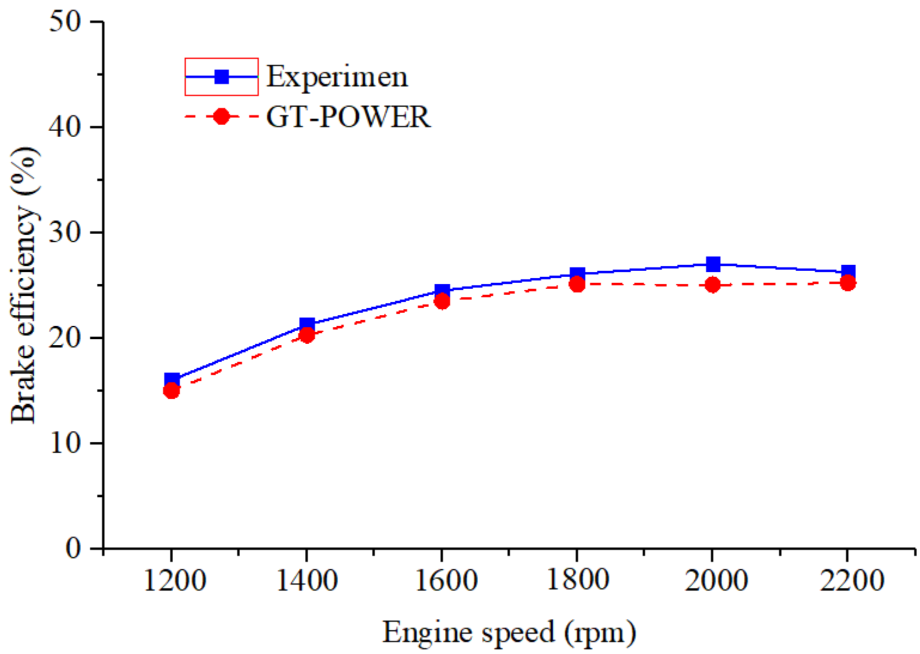

Fig. 2. Brake Efficiency Comparison Experiment vs GT-POWER

Fig. 3 compares brake power (HP) as an engine speed (rpm) function between experimental data and GT-POWER simulation. The graph reveals a clear parabolic trend, where brake power increases with engine speed up to a peak and decreases significantly at higher speeds. The comparison helps assess the

GT-POWER model's accuracy in replicating real engine performance. At 1200 rpm, the brake power is measured at approximately 54 HP in the experiment, while the GT-POWER simulation estimates it slightly lower at 50 HP. As the engine speed increases to 1400 rpm, both results show a significant rise in brake power, reaching 74 HP (experiment) and 71 HP (GT-POWER), respectively. The maximum brake power is observed at 1600 rpm, where the experiment shows 78 HP and the GT-POWER simulation shows 75 HP, indicating a minor deviation of 3 HP between the two. This peak marks the most efficient operating point in terms of power output.

Beyond this point, brake power begins to decline. At 1800 rpm, the experiment recorded 61 HP, while GT-POWER showed 56 HP. At 2000 rpm, the drop continues to 44 HP (experiment) and 39 HP (GT-POWER), and finally, at 2200 rpm, brake power sharply falls to 19 HP in the experiment and 15 HP in the simulation. This analysis suggests that the experimental and simulation results follow a similar trend, although the GT-POWER model consistently underestimates brake power by a small margin. The most significant differences occur at higher engine speeds, which may be attributed to increased thermal losses, friction, or modelling assumptions not captured accurately by the simulation. Overall, the GT-POWER simulation effectively predicts the general behaviour of brake power but could benefit from further calibration at higher rpm ranges to improve accuracy.

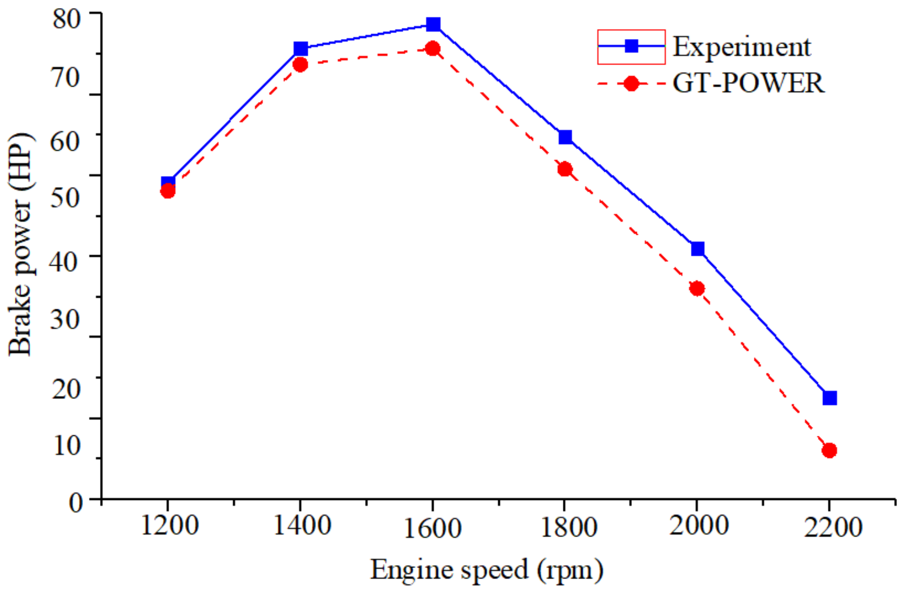

Fig. 3. Brake Power Comparison Experiment vs GT-POWER

Fig. 4 shows the variation of brake power in kilowatts (kW) concerning engine speed (rpm), comparing the results from experimental measurements and GT-POWER simulation. The trend follows a typical performance curve, with brake power increasing and engine speed reaching a peak point, followed by a steady decline. The graph provides insights into the engine’s power-generating characteristics and the simulation’s accuracy in replicating engine behaviour. At 1200 rpm, the experimental brake power is approximately 58 kW, while the GT-POWER model estimates it at 56 kW. This is followed by a sharp increase as the engine speed reaches 1400 rpm, where brake power rises to 83 kW (experiment) and 80 kW (GT-POWER). The highest brake power is recorded at 1600 rpm, with the experimental result showing 87 kW, while the GT-POWER simulation estimates it slightly lower at 84 kW, a slight deviation of only 3 kW, indicating good agreement near the engine’s optimal performance range.

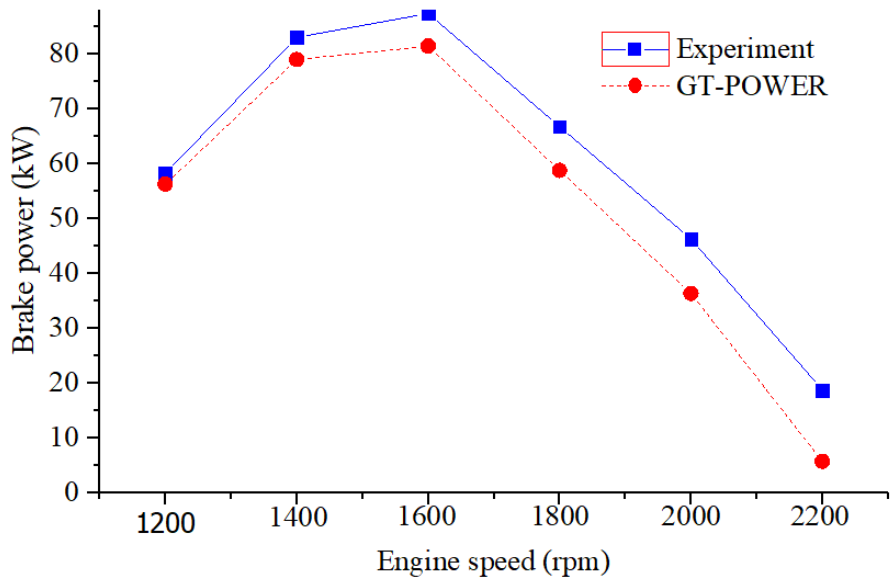

Fig. 4. Brake Power Comparison in kW Experiment vs GT-POWER

As the engine speed continues to increase, the brake power declines. At 1800 rpm, it drops to 70 kW in the experiment and 64 kW in the GT-POWER simulation. This trend continues at 2000 rpm, with values of 49 kW (experiment) and 42 kW (GT-POWER). Finally, at 2200 rpm, brake power decreases significantly to 28 kW (experiment) and 20 kW (GT-POWER). These findings confirm that both experiment and simulation capture the general trend of brake power variation with engine speed. However, the GT-POWER simulation consistently underestimates brake power, particularly at higher engine speeds. This could be due to assumptions made in heat transfer, friction losses, or combustion modelling in the GT-POWER environment, which may need further calibration. Despite these discrepancies, the GT-POWER model demonstrates reasonable accuracy, especially in the low to mid-speed range (1200–1600 rpm), making it a reliable tool for preliminary performance analysis.

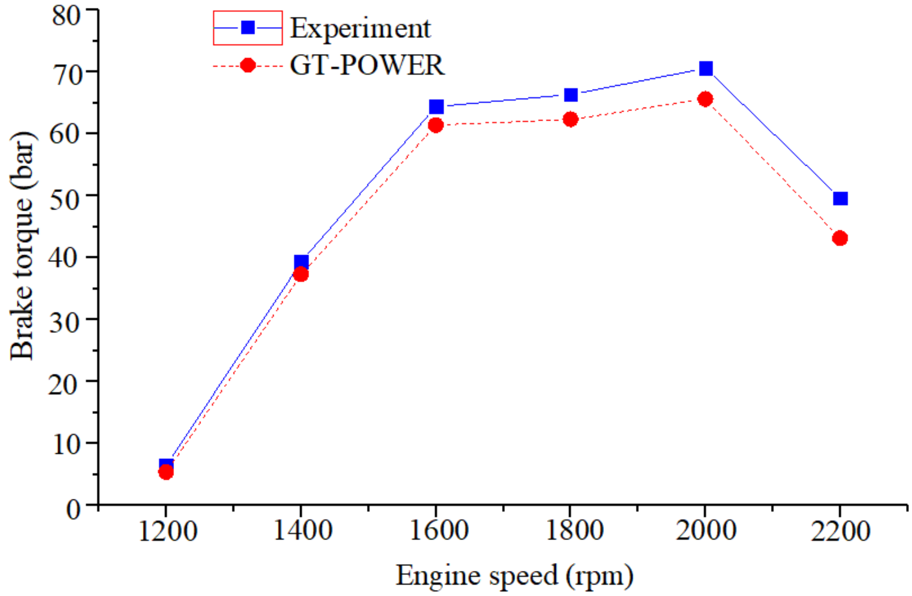

Fig. 5. Brake Torque Comparison Experiment vs GT-POWER

Fig. 5 compares brake torque (bar) versus engine speed (rpm) for experimental and GT-POWER simulation results. The curve shows a typical trend where torque increases with engine speed, reaches a plateau, and decreases at higher speeds. This figure highlights how closely the GT-POWER simulation replicates the torque behaviour of the actual engine under test conditions. At the initial speed of 1200 rpm, the brake torque is around 6 bar for both the experimental and simulation results, showing excellent agreement. As engine speed increases to 1400 rpm, the torque sharply rises to 41 bar (experiment) and 39 bar (GT-POWER), reflecting a steep torque buildup due to improved combustion dynamics. At 1600 rpm, torque increases and reaches 65 bar experimentally and 62 bar in the GT-POWER model. This increasing trend stabilizes at 1800 rpm, with the values being 67 bar (experiment) and 63 bar (GT-POWER). The peak brake torque is achieved at 2000 rpm, reaching 71 bar in the experiment and 66 bar in the simulation, representing the most efficient torque generation point.

At 2200 rpm, a significant decrease in torque is observed, falling to 49 bar (experiment) and 44 bar (GT-POWER), indicating reduced efficiency likely due to increased internal friction, thermal losses, or less optimal combustion conditions at higher speeds. Overall, GT-POWER simulation aligns closely with experimental data, particularly in the low to mid-range engine speeds (1200–1800 rpm), while a slightly larger deviation appears at higher speeds. The maximum difference between experimental and simulated torque occurs at 2000 and 2200 rpm, with gaps of 5 bar each. These discrepancies could be due to simplifications in the simulation model or unaccounted physical losses. Despite minor differences, the GT-POWER model effectively captures the overall trend of brake torque, making it a valuable tool for performance prediction and engine tuning.

Fig. 6 compares Brake Specific Carbon Monoxide (CO) emissions, expressed in g/kW·h, as a function of engine speed ranging from 1000 to 6000 rpm. This parameter reflects the mass of CO emitted per unit of engine power produced, offering valuable insight into the engine's combustion efficiency and emission performance under different operating conditions. At 1000 rpm, the CO emission is very high, exceeding 75 g/kW·h in both experimental and simulation results. This is typical at low engine speeds, where incomplete combustion and lower in-cylinder temperatures increase CO formation. As engine speed increases to 2000 rpm, a notable reduction is observed, with CO emissions dropping to 47 g/kW·h (experiment) and 45 g/kW·h (GT-POWER). This downward trend continues at 3000 rpm, with values decreasing to 32 g/kW·h (experiment) and 29 g/kW·h (simulation). These results indicate improved combustion efficiency as speed rises, likely due to more favourable turbulence and air-fuel mixing.

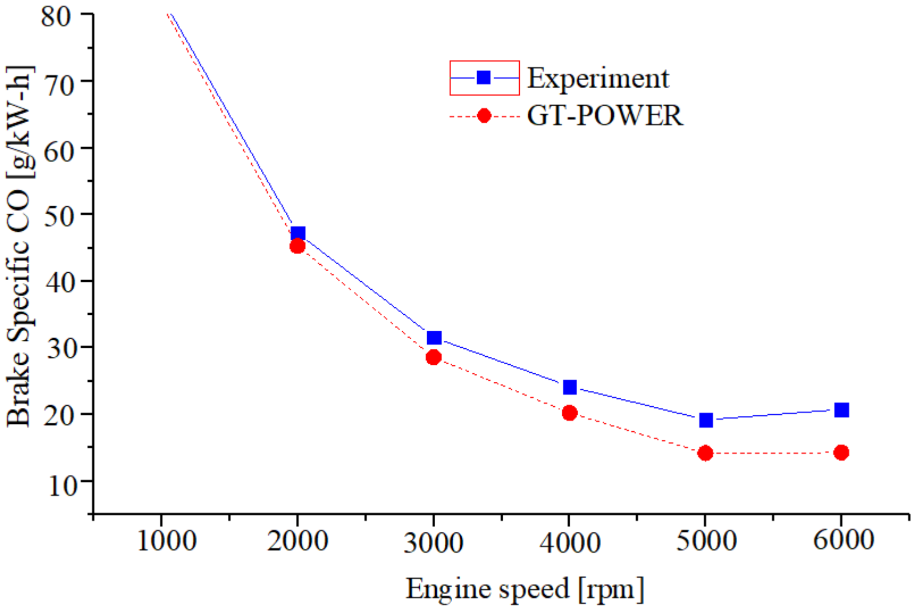

Fig. 6. Brake Specific CO Emission Comparison Experiment vs GT-POWER

At 4000 rpm, brake-specific CO emissions decline to 24 g/kW·h (experiment) and 20 g/kW·h (GT-POWER). The lowest emission values are observed at 5000 rpm, where CO output reaches 19 g/kW·h experimentally and 16 g/kW·h in simulation. A slight increase is then recorded at 6000 rpm, with the experiment showing 21 g/kW·h and GT-POWER remaining stable at 16 g/kW·h. The trends demonstrate that GT-POWER follows the experimental pattern across the entire engine speed range, with slightly lower predicted emissions, especially at higher rpm. These discrepancies may be attributed to GT-POWER's idealized combustion model, which may not fully account for transient effects or varying in-cylinder temperatures during engine operation. Overall, the GT-POWER simulation proves to be a reliable tool for predicting CO emission behaviour, and both data sets confirm that higher engine speeds tend to reduce brake-specific CO emissions due to complete combustion.

Fig. 7 compares Brake Specific Carbon Dioxide (CO_2) emissions, expressed in g/kW·h, as a function of engine speed ranging from 1000 to 6000 rpm, based on experimental measurements and GT-POWER simulation. CO_2 emissions are directly proportional to the amount of fuel combusted. Hence, this parameter serves as an indicator of fuel consumption and combustion completeness. At 1000 rpm, the brake-specific CO_2 emission is at its highest, with experimental and simulation results showing values around 60 g/kW·h. This is expected, as engines typically operate with lower thermal efficiency and incomplete combustion at low speeds. A significant decrease is observed as the engine speed increases to 2000 rpm, where the CO_2 emissions fall to 30 g/kW·h for both experiment and GT-POWER. The trend continues downward at 3000 rpm, with values recorded at 19 g/kW·h (experiment) and 18 g/kW·h (GT-POWER), reflecting improved combustion and fuel utilization.

At 4000 rpm, CO_2 emissions further decrease to approximately 14 g/kW·h (experiment) and 13 g/kW·h (GT-POWER), marking the lowest emissions in this range. At 5000 rpm, the emissions slightly stabilize at 13 g/kW·h (experiment) and 12 g/kW·h (GT-POWER) before rising slightly again at 6000 rpm to 15 g/kW·h and 14 g/kW·h, respectively. The similarity of both curves across the entire speed range highlights the accuracy of the GT-POWER simulation in predicting brake-specific CO_2 emissions. The deviations between experimental and simulation data remain within a narrow margin (usually within 1 g/kW·h), indicating excellent model calibration and reliability. In summary, CO_2 emissions per unit of brake power decrease as engine speed increases, reflecting more efficient combustion. Both datasets confirm that optimal combustion and fuel efficiency are achieved in the 3000–5000 rpm range, with only a slight increase at maximum rpm due to increased load and possibly richer air-fuel mixtures.

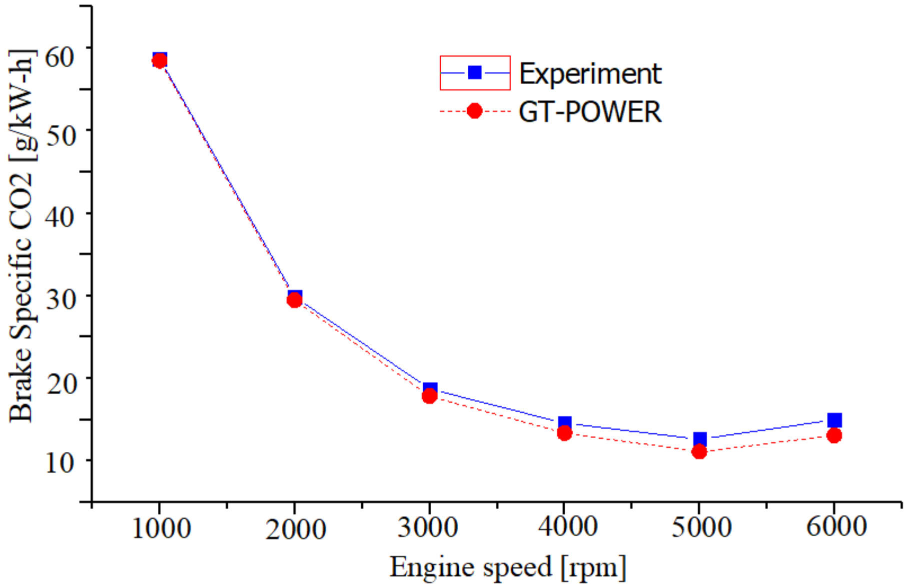

Fig. 7. Brake Specific CO_2 Emission Comparison Experiment vs GT-POWER

Fig. 8 illustrates the variation in in-cylinder heat transfer (measured in kW) as a function of engine speed (rpm), comparing values obtained through experimental testing and GT-POWER simulation. In-cylinder heat transfer is a critical parameter that reflects the amount of thermal energy lost to the cylinder walls during combustion, influencing engine efficiency and component durability. At 1200 rpm, the in-cylinder heat transfer is approximately 40 kW based on experimental data, while GT-POWER simulation predicts a slightly lower value of 38 kW. As the engine speed increases to 1400 rpm, the experimental heat transfer peaks at about 43 kW, compared to 37 kW in the simulation. This suggests that the GT-POWER model may slightly underestimate heat transfer during low to mid-speed operations. At 1600 rpm, the experimental value decreases to 40 kW, while the GT-POWER result drops more noticeably to 33 kW. This divergence continues as engine speed increases:

a) At 1800 rpm, experimental heat transfer is 33 kW, while GT-POWER predicts 25 kW.
b) At 2000 rpm, the values are 27 kW (experiment) and 17 kW (GT-POWER).
c) Finally, at 2200 rpm, the heat transfer reduces significantly to 17 kW in the experiment and only 10 kW in the GT-POWER simulation.

The overall trend for both datasets shows a decline in heat transfer with increasing engine speed, which is typical as higher speeds reduce the heat transfer time from gases to the cylinder wall. However, GT-POWER consistently underpredicts the amount of heat transferred across the speed range. The maximum deviation occurs at 2000–2200 rpm, where the gap between simulation and experiment reaches up to 7 kW. This discrepancy could arise from simplifications in the GT-POWER heat transfer model, such as constant wall temperature assumptions, inadequate modelling of turbulence effects, or cylinder wall geometry not accurately represented. Despite the deviation in absolute values, GT-POWER successfully captures the overall downward trend, confirming its utility for trend prediction. However, it may require further calibration for accurate heat transfer estimation at higher engine speeds.

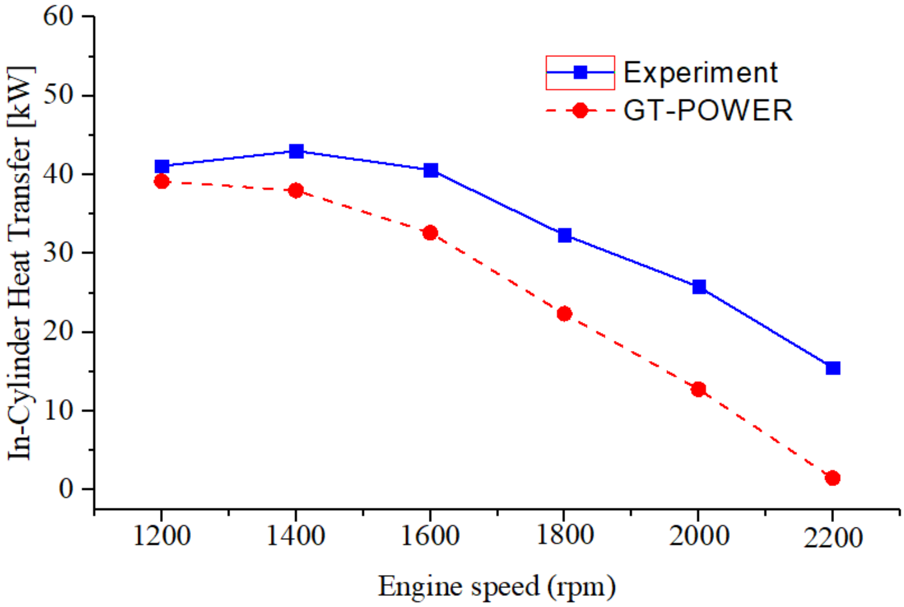

Fig. 8. In-Cylinder Heat Transfer Comparison Experiment vs GT-POWER

The novelty of this study is reflected in its comprehensive and multi-faceted comparison between experimental results and GT-POWER simulation outcomes across a wide range of engine operating parameters. Unlike previous studies that often focus on a single performance aspect such as brake power or efficiency, this research evaluates seven critical indicators: brake efficiency, brake power (in both HP and kW), brake torque, brake specific CO and CO_2 emissions, and in-cylinder heat transfer over various engine speeds. This integrated evaluation provides a more holistic perspective on the performance and emission characteristics of the engine and the fidelity of the GT-POWER simulation. A distinctive contribution of this work is identifying specific engine speed ranges between 1600 and 2000 rpm where simulation results most closely align with experimental data, as well as regions above 2000 rpm where significant deviations begin to appear, especially in thermal behaviour and emission estimates. Including in-cylinder heat transfer analysis, a parameter often overlooked in simulation validation studies, adds further novelty. The findings demonstrate that while GT-POWER is reliable in capturing general trends, its heat transfer modelling capabilities require further refinement for higher-speed accuracy.

Overall, this study offers a novel validation approach by simultaneously analyzing multiple engine performance metrics and emissions and highlighting key areas for model improvement. These insights are expected to contribute to developing more accurate simulation frameworks and better-informed strategies for internal combustion engine design and optimization.

4. Conclusion

This study has comprehensively validated engine performance and emission parameters by comparing experimental data with GT-POWER simulation results across various engine speeds. The evaluation included brake efficiency, power (in both HP and kW), brake torque, brake-specific CO and CO_2 emissions, and in-cylinder heat transfer, covering a broad spectrum of engine characteristics. The results indicate that the maximum brake efficiency was observed at 2000 rpm, reaching 27.3% (experiment) and 26.3% (GT-POWER). The highest brake power was recorded at 1600 rpm, with 78 HP / 87 kW experimentally and 75 HP / 84 kW from simulation. Similarly, brake torque peaked at 2000 rpm with 71 bar (experiment) and 66 bar (simulation). Emission analysis showed that brake-specific CO emissions dropped from 75 g/kW·h at 1000 rpm to 21 g/kW·h (experiment) and 16 g/kW·h (GT-POWER) at 6000 rpm, while CO_2 emissions decreased from 60 g/kW·h to 15 g/kW·h (experiment) and 14 g/kW·h (GT-POWER) in the same range.

For in-cylinder heat transfer, the experimental results showed a peak of 43 kW at 1400 rpm. GT-POWER consistently underpredicted this parameter with a maximum of 38 kW and a minimum of 10 kW at 2200 rpm. The deviation in heat transfer becomes more significant at higher engine speeds, indicating areas where the simulation model may require recalibration. The novelty of this study lies in its integrated multi-variable comparison and the inclusion of in-cylinder heat transfer, which is rarely validated in simulation studies. Moreover, the study identifies engine speed ranges, particularly 1600 to 2000 rpm, where GT-POWER simulations most accurately reflect experimental behaviour and highlight deviations beyond these points.

In conclusion, GT-POWER demonstrates strong predictive capability in modelling engine performance and emissions, with most deviations remaining under acceptable margins. However, the model shows limitations in accurately predicting thermal losses at high speeds. These findings improve engine simulation models and can support more accurate and efficient engine design and emission reduction strategies in future developments.

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