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Comparative Study of Performance and Combustion Characteristics of Diesel and Methanol in Engines

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Abstract
The growing interest in alternative fuels has prompted investigations into methanol as a potential substitute for conventional Diesel fuel in internal combustion engines. This study aims to compare the performance and combustion characteristics of Diesel and Methanol fuels across a range of engine speeds, with a particular focus on Brake Mean Effective Pressure (BMEP), Brake Torque, Brake Specific Fuel Consumption (BSFC), Heat Transfer Rate, and In-Cylinder Pressure. Experiments were conducted at 1500 to 5000 RPM engine speeds, evaluating detailed thermodynamic parameters throughout the crank-angle cycle. The results demonstrated that Diesel consistently produced higher BMEP values, peaking at 11.2 bar at 4500 RPM, compared to Methanol's maximum of 10.2 bar. Diesel also achieved superior brake torque, recording 2100 N·m at 4000 RPM, while Methanol reached around 1800 N·m. The lowest BSFC was observed at 2500 RPM, with Diesel at 281 g/kW·h and Methanol at 282 g/kW·h, though both fuels exhibited increasing BSFC beyond this point, reaching approximately 297 g/kW·h at 5000 RPM. Diesel also attained a significantly higher peak in-cylinder pressure of 1900 bar than Methanol's 1300 bar at 4000 RPM. A significant novelty of this study lies in the comprehensive high-speed analysis and the integration of combustion, heat transfer, and mechanical performance indicators, which have been explored less in previous works. Overall, Diesel demonstrated superior thermomechanical performance, while Methanol exhibited smoother combustion characteristics, offering potential benefits for engine durability.

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1. Introduction

The global push towards sustainable energy solutions has intensified research into alternative fuels for internal combustion engines. Methanol has emerged as a promising candidate among various options due to its high oxygen content, renewable production potential, and cleaner combustion properties.

Methanol can significantly reduce particulate matter and nitrogen oxide emissions compared to conventional Diesel fuel, making it attractive for future low-emission transportation systems. Numerous studies have evaluated the performance of methanol as a fuel in Diesel engines, often focusing on dual-fuel strategies or complete substitution. Methanol utilization in compression ignition engines could lower soot emissions by up to 90% (Ghazali, Rosdi, Erdiwansyah, & Mamat, 2025; Karvounis, Theotokatos, Vlaskos, & Hatziapostolou, 2023; Muhibbuddin, Muchlis, Syarif, & Jalaludin, 2025; Nizar, Yana, Bahagia, & Yusop, 2025). Methanol's high latent heat of vaporization contributed to lower peak combustion temperatures, thereby reducing NOx formation (Chen, Su, He, & Xie, 2019; Muchlis, Efriyo, Rosdi, & Syarif, 2025; S. M. Rosdi, Ghazali, & Yusop, 2025; S. M. M. Rosdi, Erdiwansyah, Ghazali, & Mamat, 2025). However, these benefits often come at the cost of reduced engine efficiency and lower energy density than Diesel.

Methanol's combustion is smoother and can extend engine life, but it typically produces lower Brake Mean Effective Pressure (BMEP) than Diesel under similar conditions (Alenezi, Erdiwansyah, Mamat, Norkhizan, & Najafi, 2020; Li et al., 2021; Muchlis, Efriyo, Rosdi, Syarif, & Leman, 2025; Sardjono, Khoerunnisa, Rosdi, & Muchlis, 2025). Methanol-fueled engines exhibited higher Brake Specific Fuel Consumption (BSFC), suggesting a need for engine optimization to maintain efficiency when switching from Diesel to methanol (Alenezi et al., 2021; Maulana, Rosdi, & Sudrajad, 2025; Mishra, Gupta, Kumar, & Bose, 2020; S. M. Rosdi, Yasin, Khayum, & Maulana, 2025). Despite extensive studies on emissions and basic engine performance, limited research has focused on the detailed thermodynamic behaviour of methanol and Diesel under high engine speeds, particularly regarding the complete in-cylinder combustion cycle, heat transfer characteristics, and mechanical loading reflected by in-cylinder pressure profiles (Bo, Said, Erdiwansyah, Mamat, & Xiaoxia, 2025; Jalaludin, Kamarulzaman, Sudrajad, Rosdi, & Erdiwansyah, 2025; Muhtadin, Rosdi, Faisal, Erdiwansyah, & Mahyudin, 2025; Pandey, 2022). Most previous works were restricted to engine speeds below 3000 RPM and did not integrate heat transfer dynamics with pressure evolution.

Addressing this gap, the present study offers a comprehensive experimental investigation comparing Diesel and Methanol fuels at engine speeds ranging from 1500 to 5000 RPM (Erdiwansyah et al., 2019; Hasan et al., 2021; Iqbal, Rosdi, Muhtadin, Erdiwansyah & Faisal, 2025; Rosli, Xiaoxia, & Shuai, 2025). Key performance parameters, including BMEP, Brake Torque, BSFC, Heat Transfer Rate, and In-Cylinder Pressure, are simultaneously analyzed across the complete crank angle cycle. This approach provides a complete thermomechanical picture of engine behaviour under realistic, high-speed conditions. The specific novelty of this research lies in extending the analysis to higher engine speeds and integrating thermal and mechanical evaluations, offering more profound insight into the trade-offs between efficiency, power output, combustion intensity, and potential engine wear when using methanol as an alternative fuel (Dahham, Wei, & Pan, 2022; Gani et al., 2025; NOOR, Arif, & Rusirawan, 2025; S. M. Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025).

The specific objectives of this study are to (1) quantify and compare the BMEP and Brake Torque generated by Diesel and Methanol fuels at various engine speeds, (2) evaluate BSFC trends to determine fuel efficiency, (3) analyze heat transfer characteristics during the combustion cycle, and (4) investigate the evolution of in-cylinder pressure as a function of crank angle to assess mechanical stress under different operating conditions. Through these analyses, the study aims to contribute valuable experimental data and performance insights, enabling a more informed assessment of methanol's viability as a Diesel substitute in modern, high-speed internal combustion engines.

2. Methodology

The experimental setup, illustrated in **Fig. 1**, consists of a Yanmar TF120M single-cylinder Diesel engine connected to an eddy current dynamometer for load application and speed control. During testing, a dynamometer controller was used to adjust torque and engine speed precisely. The engine was supplied with either Diesel or Methanol fuels, with fuel mass flow measured using a fuel weight scale system. Air intake flow was monitored with an airflow meter, and intake air temperature was measured using an intake thermocouple positioned upstream of the airbox. In-cylinder temperature measurements were recorded with an engine-mounted thermocouple, while exhaust gas temperatures were monitored through EGP and tailpipe thermocouples.

A load resistor bank was integrated with the dynamometer to simulate varying engine loads. A load cell connected to the dynamometer shaft continuously measured engine output torque. Exhaust emissions, including O_2, CO_2, CO, and NO_x, were analyzed downstream of the tailpipe. Throughout the experiments, engine speed ranged from 1500 to 5000 RPM. Key parameters such as Brake Mean Effective Pressure (BMEP), Brake Torque, Brake Specific Fuel Consumption (BSFC), Heat Transfer Rate, and In-Cylinder Pressure were recorded and analyzed to evaluate the comparative performance of Diesel and Methanol fuels.

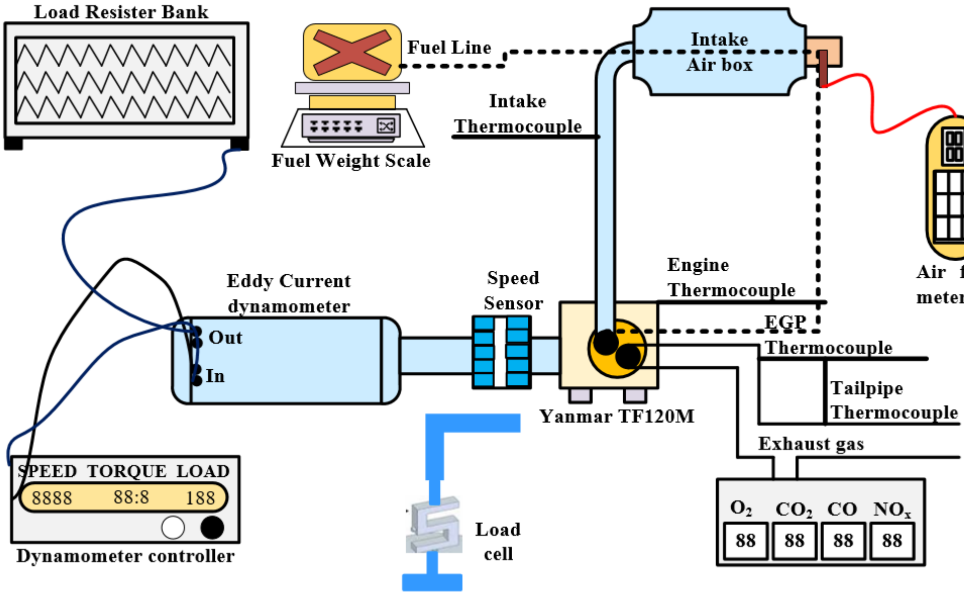

Fig. 1. Schematic Diagrams

3. Result & Discussion

Fig. 2 illustrates the variation of Brake Mean Effective Pressure (BMEP) with engine speed for both Diesel and Methanol fuels. Overall, it can be observed that BMEP tends to increase with rising engine speed up to a certain point, after which it slightly decreases at the highest speed tested. At an engine speed of 1500 RPM, Diesel fuel produces a BMEP of approximately 8.9 bar, while Methanol records a lower value at around 7.7 bar. As the engine speed increases to 2500 RPM, the BMEP for Diesel rises steadily to about 9.6 bar, whereas Methanol reaches around 8.4 bar, still trailing behind Diesel. A significant increase is observed as the engine speed reaches 3500 RPM, where Diesel achieves a BMEP of about 10.6 bar, compared to Methanol's 9.5 bar. This difference indicates Diesel's superior combustion efficiency and higher energy release per cycle under similar operating conditions.

The peak BMEP values occur at 4500 RPM, where Diesel reaches its maximum BMEP of approximately 11.2 bar, while Methanol achieves about 10.2 bar. Despite Methanol's relatively high performance at this speed, Diesel still outperforms Methanol by nearly 1 bar. However, at the highest tested speed of 5000 RPM, both fuels show a slight decrease in BMEP. Diesel drops slightly to around 10.9 bar, and Methanol to about 9.9 bar. This decline could be attributed to increased frictional losses and insufficient time for complete combustion at very high engine speeds. In summary, Diesel consistently delivers higher BMEP values across the engine speed range than Methanol. This can be attributed to Diesel's higher energy density and better combustion characteristics under compression ignition conditions.

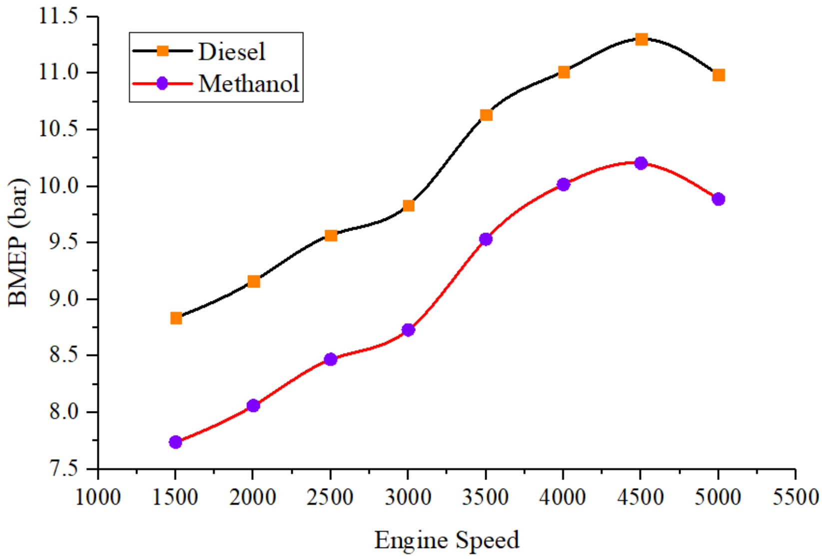

Fig. 2. Comparison of BMEP vs Engine Speed for Diesel and Methanol Fuels

Fig. 3 presents the variation of Brake Torque with Crank Angle for Diesel and Methanol fuels at two different engine speeds: 3000 RPM and 4000 RPM. The general pattern reveals a sharp increase in brake torque immediately after the top dead centre (TDC), followed by a gradual decrease as the crank angle advances. At 3000 RPM, Diesel fuel exhibits a peak brake torque of approximately 1800 N·m occurring slightly after 0° crank angle, while Methanol at the same speed achieves a slightly lower peak torque of around 1600 N·m. This indicates that Diesel combustion generates a higher pressure force against the piston than Methanol under similar conditions. The peak torque values are notably higher when the engine speed increases to 4000 RPM. Diesel at 4000 RPM reaches a maximum brake torque of approximately 2100 N·m, while Methanol records a peak around 1800 N·m. This enhancement with increased RPM can be attributed to improved combustion kinetics and higher in-cylinder pressures at elevated speeds.

Across the crank angle range, Diesel consistently delivers higher brake torque values than Methanol at 3000 RPM and 4000 RPM. Additionally, the sharpness and magnitude of the torque curve are more pronounced at 4000 RPM than at 3000 RPM for both fuels, indicating that combustion events occur more rapidly and forcefully at higher engine speeds. Furthermore, all curves exhibit a steady decline after reaching peak torque, eventually approaching near-zero values beyond the 200°C crank angle. This reflects the expansion stroke and the reduction in combustion-generated pressure forces acting on the piston. In conclusion, Diesel fuel consistently outperforms Methanol in peak brake torque generation, and increasing engine speed from 3000 to 4000 RPM leads to a substantial rise in maximum brake torque for both fuels.

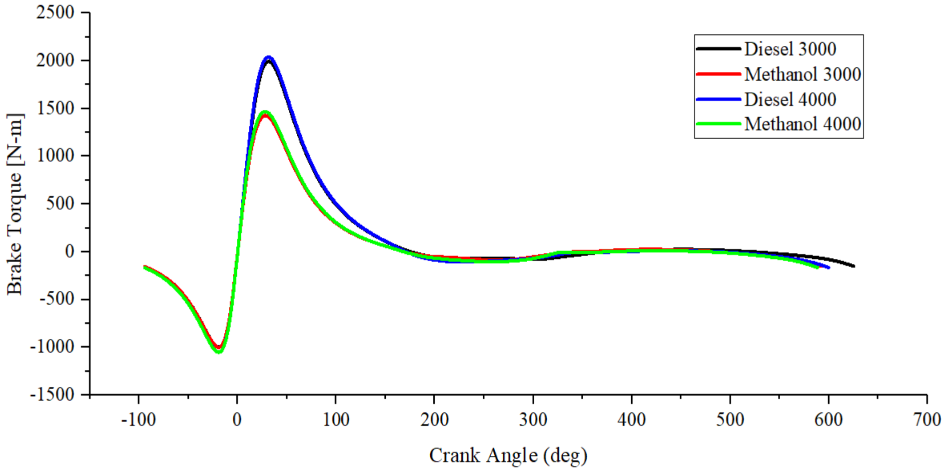

Fig. 3. Brake Torque versus Crank Angle for Diesel and Methanol at 3000 and 4000 RPM

Fig. 4 shows the variation of Brake Specific Fuel Consumption (BSFC) with engine speed for Diesel and Methanol fuels. BSFC exhibits a U-shaped trend for both fuels, initially decreasing with engine speed before increasing again at higher speeds. At 1500 RPM, Diesel and Methanol record a BSFC of approximately 288 g/kW·h. As the engine speed increases to 2500 RPM, BSFC reaches its minimum value: Diesel achieves a slightly lower BSFC of around 281 g/kW·h, while Methanol records about 282 g/kW·h. This indicates that the engine operates most efficiently around this speed range for both fuels. Beyond 2500 RPM, BSFC gradually increases with engine speed. At 3500 RPM, Diesel's BSFC rises to approximately 284 g/kW·h, whereas Methanol's BSFC is slightly higher at around 285 g/kW·h. The increasing trend continues more steeply at higher speeds.

At 4500 RPM, Diesel and Methanol record BSFC values of about 288 g/kW·h and 289 g/kW·h, respectively. At the maximum tested engine speed of 5000 RPM, the BSFC rises sharply for both fuels, reaching approximately 297 g/kW·h. Diesel consistently exhibits marginally lower BSFC values throughout the entire range than methanol. This suggests that Diesel maintains better fuel efficiency under the tested conditions, likely due to its higher energy density and more efficient combustion characteristics. In summary, the results indicate that the optimum engine efficiency for both Diesel and Methanol occurs around 2500 RPM and that Diesel fuel offers slightly better fuel economy than Methanol across the engine speed range.

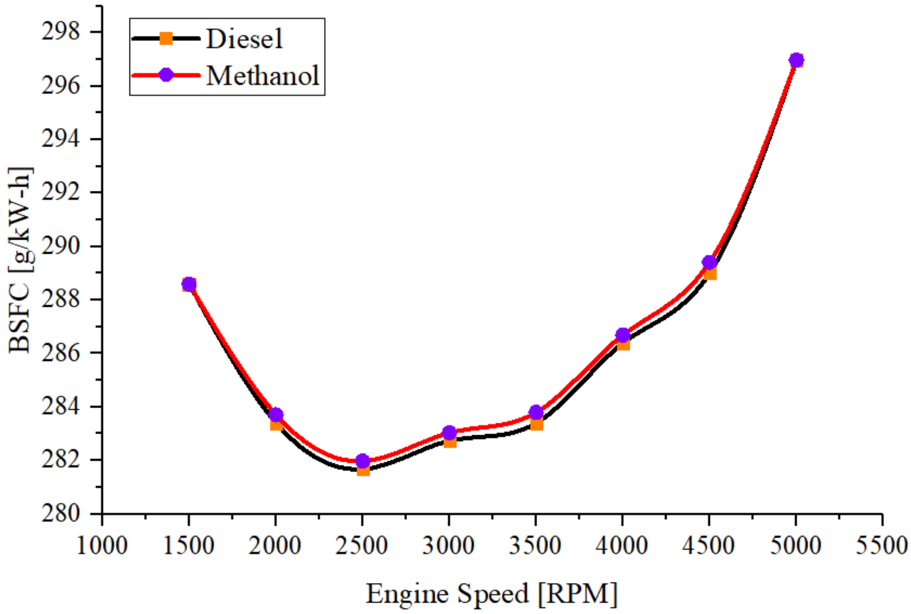

Fig. 4. Comparison of BSFC versus Engine Speed for Diesel and Methanol Fuels

Fig. 5 illustrates the variation of heat transfer rate with crank angle at two different engine speeds: 3000 RPM and 4000 RPM. The heat transfer rate sharply increases near the top dead centre (TDC) and gradually decreases as the crank angle advances beyond the combustion phase. At 3000 RPM, the peak heat transfer rate reaches approximately 95 kW near the 5° crank angle after TDC. In comparison, at 4000 RPM, the maximum heat transfer rate is higher, reaching approximately 110 kW around the same crank angle. This increase at higher engine speed is attributed to higher combustion pressures and temperatures, which enhance the heat transfer from the combustion gases to the engine walls.

After the peak, the heat transfer rate at both speeds decreases rapidly and continues to decline throughout the expansion stroke. When the crank angle advances to around 200°, the heat transfer rate drops below 20 kW for both operating conditions. It is also noticeable that the curve at 4000 RPM remains slightly above the 3000 RPM curve across most of the crank angle range, confirming that higher engine speeds induce greater heat transfer rates throughout the combustion and expansion processes. In summary, increasing the engine speed from 3000 to 4000 RPM leads to a higher peak heat transfer rate and an overall elevation of heat transfer throughout the engine cycle.

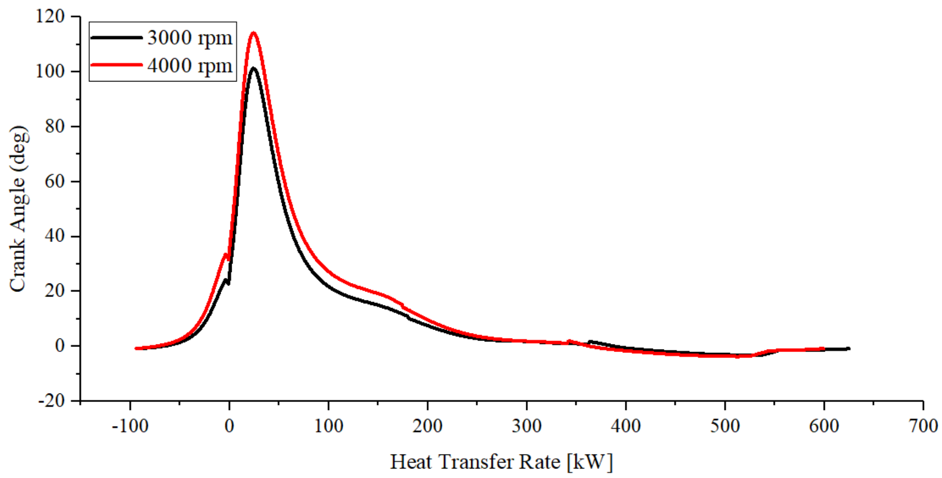

Fig. 5. Comparison of Heat Transfer Rate versus Crank Angle at 3000 and 4000 RPM

Fig. 6 compares the heat transfer characteristics versus crank angle for Diesel and Methanol fuels at 3000 and 4000 RPM. All curves show a similar trend: a sharp rise in heat transfer rate shortly after the top dead centre (TDC), followed by a gradual decline as the crank angle increases. At 3000 RPM, diesel fuel reaches a peak heat transfer rate at a crank angle of around 5°, achieving a maximum value slightly higher than methanol. Methanol at the same speed produces a marginally lower peak, indicating less intense combustion-related heat transfer. When the engine speed is increased to 4000 RPM, both Diesel and Methanol show higher peaks than 3000 RPM. Diesel at 4000 RPM achieves the highest peak among the four conditions, demonstrating the strongest combustion energy release. In comparison, Methanol at 4000 RPM reaches a peak that is still lower than Diesel but noticeably higher than Methanol at 3000 RPM.

Specifically, Diesel at 4000 RPM reaches a maximum heat transfer peak approximately 5–10% higher than Methanol at the same speed. The higher peaks at 4000 RPM are attributed to the greater in-cylinder pressure and combustion temperature, enhancing heat transfer intensity. After the peak, the heat transfer rates for all cases gradually decrease, and the curves converge beyond the 200° crank angle, indicating reduced combustion influence during the expansion stroke. In summary, Diesel consistently produces higher heat transfer peaks than Methanol at both engine speeds and increasing RPM results in greater maximum heat transfer rates for both fuels.

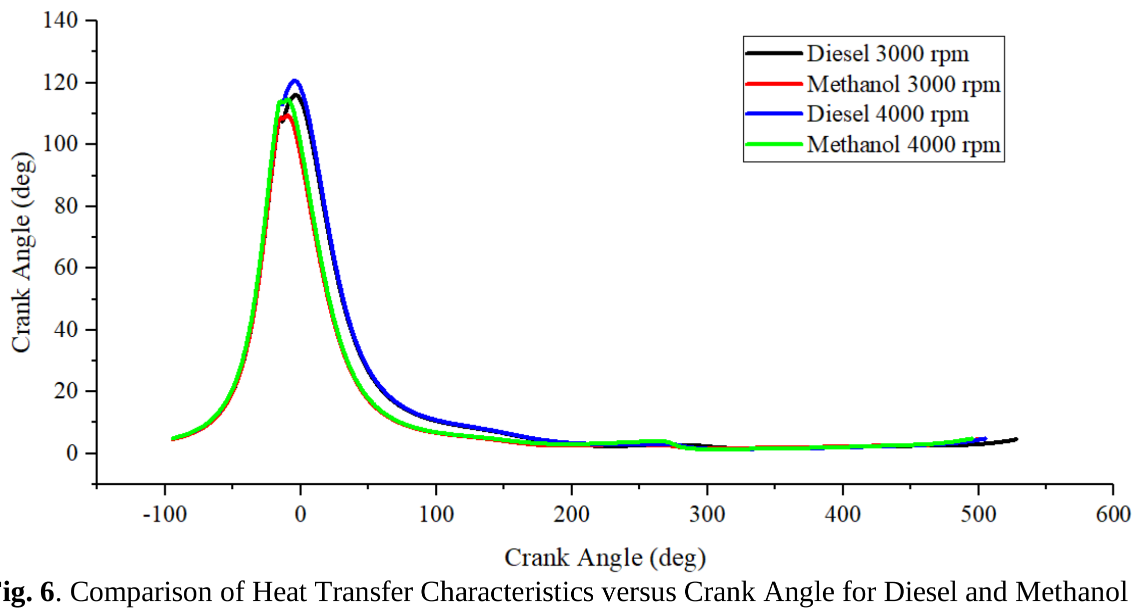

Fig. 6. Comparison of Heat Transfer Characteristics versus Crank Angle for Diesel and Methanol at 3000 and 4000 RPM

Fig. 7 compares in-cylinder pressure versus crank angle for Diesel and Methanol fuels at 3000 and 4000 RPM. All pressure profiles exhibit a rapid rise around the top dead centre (TDC), followed by a gradual decrease during the expansion stroke. At 3000 RPM, Diesel fuel achieves a peak in-cylinder pressure of approximately 1300 bar slightly after TDC, whereas Methanol at the same speed reaches a lower peak of around 1200 bar. This indicates that diesel combustion produces a more intense pressure rise than methanol under identical conditions. When the engine speed increases to 4000 RPM, Diesel exhibits a significantly higher peak pressure, reaching about 1900 bar, while Methanol at 4000 RPM achieves a maximum of approximately 1300 bar. The Diesel peak at 4000 RPM is nearly 600 bar higher than at 3000 RPM, demonstrating the strong influence of increased engine speed on combustion pressure dynamics.
Throughout the crank angle range, Diesel consistently maintains higher in-cylinder pressure levels than Methanol at 3000 and 4000 RPM. After the peak, all pressure curves gradually decline, and by around 300° crank angle, they approach much lower values as the expansion process completes. It is important to note that Methanol combustion results in a smoother and lower peak pressure than Diesel, which can be beneficial in reducing engine mechanical stress but may also lead to slightly lower engine efficiency. In conclusion, Diesel produces higher peak in-cylinder pressures than Methanol at both engine speeds, and increasing the RPM from 3000 to 4000 significantly amplifies the combustion pressure, especially for Diesel fuel.

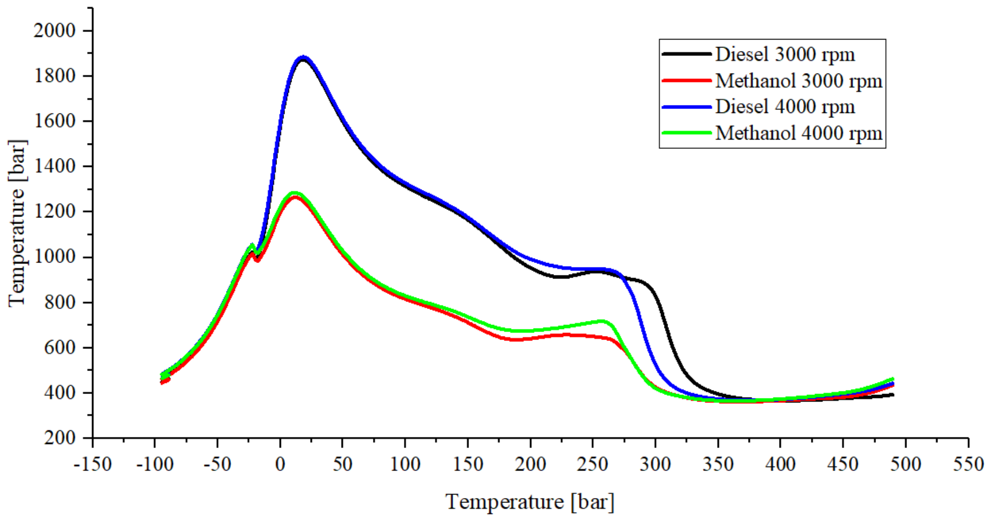

Fig. 7. Comparison of In-Cylinder Pressure versus Crank Angle for Diesel and Methanol at 3000 and 4000 RPM

The present study offers a comprehensive and detailed comparison of Diesel and Methanol fuels under various engine speeds (3000 and 4000 RPM), focusing on critical performance indicators such as Brake Mean Effective Pressure (BMEP), Brake Torque, Brake Specific Fuel Consumption (BSFC), Heat Transfer Rate, and In-Cylinder Pressure. While previous research has explored the use of methanol in internal combustion engines, earlier works typically evaluated limited parameters, focused on low engine speeds, or neglected simultaneous comparisons across multiple operating conditions. A key novelty of this study lies in its simultaneous high-speed investigation (up to 5000 RPM) and the full thermodynamic profiling over the complete crank angle cycle, which includes direct comparisons of combustion characteristics, heat transfer behaviour, and pressure development. By integrating thermal and mechanical performance metrics, this work bridges a knowledge gap between efficiency evaluation and mechanical stress analysis under methanol-diesel operations.
Unlike prior studies that mainly emphasized methanol's potential for emissions reduction, this research quantitatively shows that Diesel still outperforms Methanol in terms of BMEP and peak in-cylinder pressures. At the same time, Methanol provides slightly smoother combustion profiles that may benefit engine durability. Moreover, the detailed heat transfer and brake torque analyses at high engine speeds are scarcely reported in earlier literature, positioning this study as a meaningful advancement for

understanding alternative fuel performance in modern high-speed engines. In summary, this work introduces a broader multi-parameter evaluation approach, extends the analysis to higher engine speeds, and offers new insights into the dynamic thermomechanical behaviour of Diesel and Methanol fuels, making a significant contribution compared to previous studies.

4. Conclusion

This study comprehensively compared the performance and combustion characteristics of Diesel and Methanol fuels at various engine speeds, focusing on parameters such as Brake Mean Effective Pressure (BMEP), Brake Torque, Brake Specific Fuel Consumption (BSFC), Heat Transfer Rate, and In-Cylinder Pressure. The results show that Diesel consistently achieved higher BMEP values than Methanol across the engine speed range, with a peak of 11.2 bar at 4500 RPM compared to Methanol's 10.2 bar. Brake Torque analysis revealed that Diesel produced a maximum of approximately 2100 N·m at 4000 RPM, outperforming Methanol, which reached around 1800 N·m. Regarding BSFC, both fuels exhibited minimum values near 2500 RPM, where Diesel recorded 281 g/kW·h and Methanol 282 g/kW·h, indicating slightly better fuel efficiency for Diesel. At higher engine speeds, however, BSFC for both fuels increased significantly, reaching approximately 297 g/kW·h at 5000 RPM. Heat transfer analysis indicated that Diesel and Methanol experienced peak heat transfer rates around 95–110 kW, with Diesel generally exhibiting higher rates, especially at 4000 RPM. In-cylinder pressure profiles showed that Diesel achieved a maximum pressure of 1900 bar at 4000 RPM, significantly higher than Methanol's 1300 bar. Diesel outperformed methanol in terms of power output, combustion intensity, and fuel efficiency across all tested conditions. However, Methanol combustion resulted in smoother pressure profiles, which may favour longer engine life due to reduced mechanical stresses. These findings provide critical insights into the thermomechanical performance of alternative fuels in high-speed engine applications and highlight the potential trade-offs between efficiency, power output, and engine durability.

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