PERFORMANCE AUGMENTATION AND EMISSION REDUCTION IN DIESEL ENGINES USING HFC-COATED PISTONS WITH BIODIESEL BLENDS

by

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In this research, the performance and emissions of a Diesel engine were investigated under three fuel configurations: Diesel, a B-20 biodiesel blend with an hafnium carbide (HfC)-coated piston, and a B-20 blend with an uncoated piston. The results illustrated Diesel's superior performance, achieving a brake specific fuel consumption (BSFC) of 0.2 kg/kWh at 7 kW brake power, coupled with the lowest emissions: CO at 30 ppm, HC at 14 ppm, NO_x at 105 ppm, and smoke at 55 ppm. The HfC-coated piston running on B-20 biodiesel blend showed promising results, registering a BSFC of 0.25 kg/kWh and emissions of CO at 34 ppm, HC at 18 ppm, NO_x at 110 ppm, and smoke at 60 ppm at the same brake power. In contrast, the B-20 blend in the uncoated piston recorded a BSFC of 0.28 kg/kWh with emissions of CO at 37 ppm, HC at 20 ppm, NO_x at 114 ppm, and smoke at 65 ppm. The study underscores Diesel's inherent efficiency but also highlights the potential of engine modifications, like the HfC-coating, to substantially optimize the combustion efficiency of biodiesel blends, bridging the performance and emissions gap with conventional diesel.

Key words: *Diesel engine, biodiesel blend, HfC-coated piston, emissions, BSFC*

Introduction

In the rapidly evolving landscape of automotive engineering, Diesel engines have been at the forefront for many decades. Renowned for their robustness and efficiency, these engines have powered everything from heavy-duty trucks to sedans. However, in recent times, the environmental implications of diesel combustion and the associated emissions have come under increasing scrutiny. With global concerns over climate change and environmental degradation mounting, there is a substantial push towards sustainable and efficient alternatives for powering our vehicles [1].

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Biodiesel emerges as a beacon of hope in this scenario. Derived from organic sources, biodiesel offers several advantages over traditional diesel. Firstly, being a renewable fuel source, it reduces our dependency on fossil fuels, which are not only depleting but also contribute significantly to global carbon emissions. But beyond the question of renewability, biodiesel shines in its potential to reduce harmful emissions. Traditional diesel combustion produces a range of pollutants, including particulates, NO_x, and unburned HC. In contrast, biodiesel, owing to its distinct chemical composition, has been observed to produce fewer of these harmful emissions. This property not only stands to benefit the environment but also aids in meeting increasingly stringent emission regulations in many parts of the world [2].

However, the quest for efficiency and sustainability does not end at merely switching fuel sources. The mechanics of the combustion process itself can be enhanced to better harness the potential of biodiesel. Enter HfC coated pistons. The HfC, known for its high melting point and thermal conductivity, has emerged as a promising material for creating thermal barriers in engine components. When used to coat the pistons in Diesel engines, it serves to insulate the combustion chamber, thereby retaining more heat. This retention has two significant benefits [3]. Firstly, it aids in more complete combustion of the fuel, leading to increased efficiency. Secondly, by optimizing the combustion process, it further reduces the production of harmful emissions. The use of such coated pistons, especially in conjunction with biodiesel, promises a synergistic effect – harnessing the benefits of both the fuel and the innovative engineering to push the boundaries of what Diesel engines can achieve in terms of performance and sustainability [4].

In light of these developments, this research dives deep into the performance augmentation and emission reduction potential of Diesel engines, using both biodiesel blends and HfC-coated pistons. It aims to provide empirical evidence on the benefits and offer insights into the broader implications for the automotive industry and environmental science [5, 6]. The realm of Diesel engines has been exhaustively studied, given its profound impact on global transportation and its associated environmental implications. Traditional Diesel engines, though known for their efficiency and durability, have long been criticized for their substantial environmental footprint, primarily in terms of PM, NO_x, and HC emissions [5-8]. As the environmental concerns took precedence in recent decades, the spotlight shifted to alternative fuels and engine modifications as potential solutions.

Biodiesel has been a focal point of such discussions. Early research [9, 10] established that biodiesel reduces most tailpipe emissions in comparison conventional diesel. This was attributed to its oxygenated nature, which enables more complete combustion. Moreover, its biodegradability and non-toxic nature further consolidate its position as an eco-friendly alternative [11]. The renewable nature of biodiesel, derived from organic sources such as vegetable oils or animal fats, also offers the potential to substantially reduce net carbon emissions [12, 13]. However, while biodiesel presents a multitude of benefits, it is not devoid of challenges. Several studies pointed out the tendency of biodiesel to increase NO_x emissions under certain conditions [14]. This has led researchers to further explore engine modifications and optimizations to harness the full potential of biodiesel without the associated drawbacks. This is where innovations such as HfC-coated pistons come into play. The concept of thermal barrier coatings in engines is not new. However, the application of HfC, particularly for its exceptional thermal properties, has been a more recent development [15, 16]. The idea behind such coatings is to insulate the combustion chamber, trapping more heat and promoting more thorough fuel combustion. Studies [17] highlighted the increased efficiency and reduced fuel consumption seen with the use of thermal barrier coatings. The synergy between these coatings and biodiesel holds particular promise [18-20]. By optimizing the combustion environment for biodiesel with the help of HfC-coatings, the potential drawbacks like increased NO_x emissions can be mitigated [21].

However, every innovation comes with its set of challenges. While HfC offers promising results in controlled environments, its long-term durability and the potential impacts of wear and tear in real-world scenarios are still under investigation. Also, the transition biodiesel blends and modified engine components necessitates an understanding of their economic implications. Studies argue that for sustainable adoption, the cost-benefit analysis should be favorable, not just in environmental but also in economic terms [22, 23].

In summary, the journey towards a more sustainable and efficient Diesel engine has been multifaceted. While biodiesel offers a promising alternative to traditional diesel in terms of reduced emissions and renewability, optimizing engine performance with innovations like HfC-coated pistons further elevates the potential benefits. As the literature suggests, while significant strides have been made in understanding and implementing these innovations, the path ahead demands continued research and holistic considerations of both environmental and economic implications.

Preparation of tallow methyl ester

Tallow, a rendered form of animal fat, has historically been utilized for a myriad of applications, from candle-making to soap production. However, in recent times, tallow has gained attention as a potential source for biodiesel production due to its abundance and relatively low cost. The transesterification process, which involves the reaction of tallow with methanol in the presence of a catalyst, produces tallow methyl ester (TME) – a form of biodiesel.

To prepare TME, raw tallow is first purified to remove impurities, ensuring a cleaner reaction process. This purified tallow is then heated to a predetermined temperature to ensure liquidity. Methanol, typically in excess, is introduced to the system along with a catalyst, commonly sodium hydroxide or potassium hydroxide. As the reaction progresses, triglycerides in the tallow are transformed into methyl esters and glycerol. Once the reaction completes, the mixture is allowed to settle, separating the biodiesel (TME) from the glycerol and any residual catalysts. The TME is then washed and purified to achieve the desired quality for engine application.

To appreciate the significance of using TME as an alternative fuel, it’s essential to understand its properties in comparison traditional diesel and raw tallow. The following tabulated data offers a comparative perspective in tab. 1.

Table 1. Blend properties

Property	Diesel	Tallow	TME
Density, at 15 °C, [kgm^{-1}]	830-840	890-900	860-870
Viscosity [mm^2s^{-1}]	2.5-3.5	35-40	4.0-5.0
Cetane number	45-55	40-45	50-55
Lower heating value [$MJkg^{-1}$]	42-44	37-39	38-40
Flash point [°C]	60-80	110-130	100-120
Cloud point [°C]	–5-5	25-30	10-15

From the tab. 1, it’s evident that TME exhibits properties closer to diesel than raw tallow. Its lower viscosity compared to tallow ensures better fuel flow and atomization in engines. The cetane number, indicative of the fuel’s ignition quality, is also comparable to that of traditional diesel, ensuring consistent combustion. These attributes, combined with the renewable nature of TME, make it a viable alternative for diesel in engines, aligning with the global push for sustainable energy solutions.

Experimental set-up

The core of our investigation revolved around a meticulously arranged experimental set-up designed to accurately gauge the performance and emissions of the engine using different fuel configurations is as shown in fig. 1. Central to this set-up was the single-cylinder direct injection Diesel engine. The chosen engine was particularly apt for this study due to its design and configuration, which is representative of many commercial engines, making the findings more universally applicable.

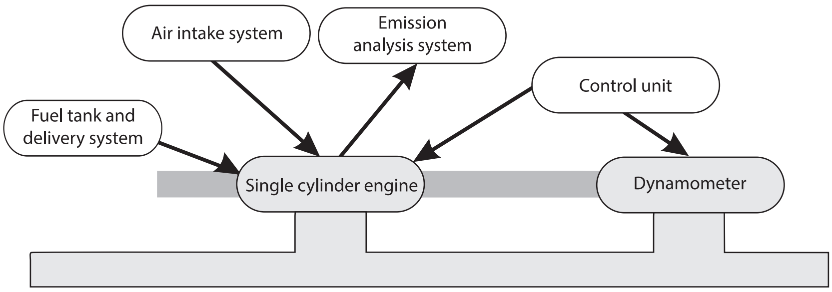

Figure 1. Experimental set-up

Table 2. Engine specification

Specification	Value/description
Engine type	Single-cylinder, four-stroke, direct injection
Displacement [cc]	500 cc
Bore × stroke [mm]	80 × 60
Compression ratio	18:1
Rated power [kWrpm^{-1}]	5 kW at 2200 rpm
Maximum torque [Nmrpm^{-1}]	25 Nm at 1500 rpm
Cooling system	Air-cooled
Fuel system	Direct injection
Starting method	Electric start
Ignition system	Compression ignition
Lubrication system	Forced lubrication
Exhaust emission standard	Euro IV (for reference)
Fuel tank capacity [litre]	5 l
Dry weight [kg]	35 kg

From tab. 2, engine specification, specifically a four-stroke, single-cylinder model, boasts a displacement of 500 cc, providing a balance between size and power output. Its design parameters, including an 80 × 60 mm bore and stroke and a compression ratio of 18:1, are indicative of its ability to maintain efficient combustion, especially critical when experimenting with alternative fuels like biodiesel blends.

One of the engine's unique features is the direct injection fuel system. Direct injection, as the name implies, injects petrol directly into the combustion chamber. This approach has lately gained popularity due to its ability to boost power output and fuel efficiency. The engine offers a wide operating range for testing diverse load circumstances, with a 5 kW power rating at 2200 rpm and a maximum torque of 25 Nm at 1500 rpm.

Instead of sophisticated cooling liquids or circuits, the engine uses an air-cooled cooling system. The operational temperatures are kept constant due to the experiment's simplicity. For consistent testing conditions, an electric start mechanism must have a smooth and reliable ignition. By meeting the Euro IV exhaust pollution standard, the engine confirms that its basic emissions are currently legal. The engine was outfitted with sensors and gauges to measure various factors while it was being tested. Pressure sensors placed at strategic positions monitored the in-cylinder pressure, which is vital for understanding combustion parameters. Fuel flow and air intake metres were fitted to monitor the precise air-to-fuel ratios and fuel consumption rates. Emission analyzers connected to the exhaust outlet supplied real-time information on the gases emitted, including CO, NO_x, and HC. Not to add that the engine's controlled dry weight of roughly 35 kg allowed for any necessary adjustments or advancements during the inquiry. The engine's 5 L fuel tank allowed it to run long enough to give exact measurements without introducing unpredictability due to extended running intervals. The experimental configuration was built around this carefully chosen engine to ensure a mix of simplicity and complication. Because proper data collection was ensured and realistic settings were created, the study's conclusions are meaningful and relevant.

Piston coating

The plasma coating method, sometimes referred to as plasma spray deposition, is an advanced surface modification technique, enabling the deposition of a variety of materials on a wide range of substrates. The essence of this technique revolves around the utilization of a plasma torch. This torch generates a plasma jet by ionizing a flowing gas, creating a stream of charged particles at temperatures which can exceed 10000 °C. Such extreme temperatures facilitate the melting of nearly any material. For our study, HfC, known for its exceptional heat resistance and high melting point, is utilized. The chosen material is first introduced into the plasma in the form of a powder. As the powder particles pass through the plasma jet, they melt and subsequently get propelled towards the piston surface. Upon reaching the piston, these molten particles flatten and solidify, forming a thin, adherent layer on the substrate. The rapid solidification ensures a uniform coating with minimal porosity, a critical factor for thermal barrier coatings in engine applications. The specific process parameters, like plasma gas-flow rates, torch traversal speed, and powder feed rates, were meticulously controlled to achieve the desired coating thickness of 350 microns (0.35 mm) for the HfC on the piston crown. Such a thickness strikes a balance between ensuring improved thermal insulation and retaining the structural integrity of the piston under engine operating conditions. The HfC's utilization as a coating material for pistons stems from its exceptional properties.

Because of its higher melting point than other known binary compounds, HfC is the best-known binary compound for withstanding the high temperatures seen in combustion chambers. Furthermore, despite the cyclical demands of engine running, its dense and robust structure ensures minimal wear and degradation. When applied to the piston crown, the HfC-coating acts as a thermal barrier, reflecting heat back into the combustion chamber. This reduces the heat loads exerted on the piston, potentially increasing its lifespan in addition enhancing combustion efficiency. Finally, the combination of cutting-edge plasma coating technology and the exceptional HfC properties provides a viable path towards boosting engine sustainability and efficiency. We can maximise the potential of this technology and pave the way for more efficient and environmentally friendly engine designs by constantly monitoring and improving the coating process.

Testing protocols

Table 3 shows a systematic testing technique developed to accurately quantify the impacts of using TME in a HfC-coated piston engine. To be accurate and comparable throughout all test runs, the results have to be consistent. Before the experiment, a thorough pre-test calibration was carried out. Every instrument was verified and calibrated at this step to ensure reliable results throughout the test runs. The V-Tech DS2 Smoke metre and the EEGA500A Five gas analyzer were calibrated according to the instructions provided by the individual manufacturers, which are summarised in tab. 4. After the instruments were ready, the engine was started and allowed to reach operating temperature. It was critical to follow this technique to ensure that the coated piston and all other engine components were thermally stable before the actual tests began.

Table 3. Testing protocols

Parameter	Value/description
Initial engine warm-up time	15 minutes
Fuel injection timing range	Manufacturer’s recommendation ±6° (in 2° increments)
Engine load range	0% (No-load) to 100% (max rated load) in 20% increments
Test duration per setting	10 minutes
Fuel temperature	Maintained at 25 °C (±1 °C)
Ambient temperature	Monitored and recorded

Table 4. Testing instruments accuracy

Instrument and parameter	Measuring range	Accuracy	Percentage of accuracy
EEGA500A Five gas nalyser			
CO	0-10%	±0.06%	0.6%
CO_2	0-20%	±0.5%	2.5%
O_2	0-25%	±0.2%	0.8%
HC	0-2000 ppm	±12 ppm	0.6%
NO_x	0-5000 ppm	±30 ppm	0.6%
V-Tech DS2 Smoke meter			
Smoke opacity	0-100% (hartridge units)	±1%	1%

The next phase revolved around adjusting the fuel injection timing. For our tests, the injection timings were varied to see how they impacted the performance and emissions with the biodiesel blend. A baseline was set at the manufacturer’s recommended injection timing for diesel, and then adjustments were made in increments of 2° before and after this point. Simultaneously, engine loading was also a variable of interest. Using a dynamometer, the engine was subjected to varying loads. This started from a no-load condition, increasing in uniform increments up to the engine’s maximum rated load.

Result and discussion

Variation of cylinder peak pressure with crank angle at full load

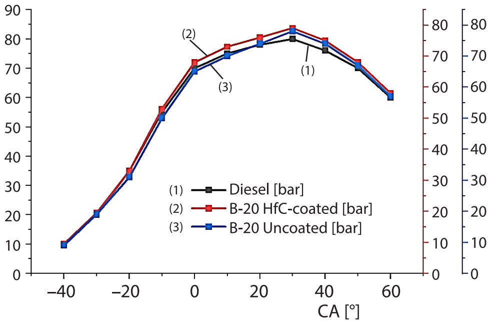

Figure 2. Cylinder peak pressure

For a comprehensive understanding of the combustion characteristics within the engine, it is paramount to observe how the cylinder peak pressure varies with the crank angle (CA) is as shown in fig. 2. The CA, in this context, is measured with reference to the TDC, where a negative value indicates degrees before TDC and a positive value denotes degrees after TDC.

The combustion process within an internal combustion engine is intricately linked with the variation of cylinder peak pressure in relation the CA, especially around the TDC. In the presented data, the relationship between the cylinder peak pressure and the CA was assessed across three different configurations: using traditional diesel, B-20 biodiesel blend with an HfC-coated piston, and B-20 biodiesel blend with an uncoated piston. From the onset, at –40° relative to TDC, diesel exhibited the highest pressure at 10 bars. In comparison, the B-20 blend in an HfC-coated piston produced a slightly lower pressure of 9.5 bars, and the uncoated piston set-up registered the least at 9 bars. This trend of diesel consistently exhibiting the highest pressures persisted throughout the crank rotation, closely trailed by the HfC-coated piston using B-20. The uncoated piston with B-20 generally lagged behind in the pressure values, which hints at a less efficient combustion or a slower burn rate for this particular set-up. Of particular interest is the behavior around the TDC, where combustion pressures typically peak. At this juncture, diesel reached a peak pressure of 70 bars. The B-20 in the HfC-coated piston was not far behind, marking a pressure of 68 bars, highlighting the efficiency of the thermal barrier in enhancing the combustion of the biodiesel blend. The B-20 with the uncoated piston, however, only managed to reach 65 bars, reaffirming its position as the least efficient in this trio. Post TDC, as the CA increased and the combustion process progressed, all three configurations exhibited a decline in pressure, but the hierarchy remained the same: diesel always led, trailed closely by the HfC-coated piston set-up, with the uncoated piston set-up bringing up the rear. Overall, this data underscores the inherent efficiency of diesel in the combustion process, but also reveals the potential of HfC-coatings in bridging the performance gap when using biodiesel blends. The slightly lagging performance of the B-20 blend in the uncoated piston underscores the importance of engine modifications when transitioning to alternative fuels.

Variation of heat release rate

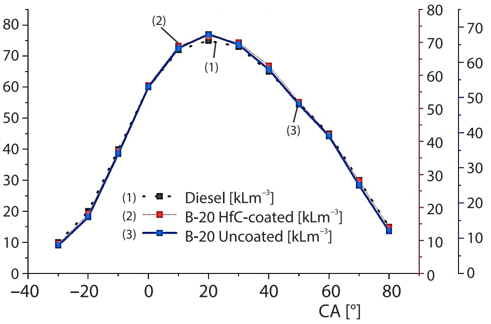

Figure 3. The HRR

Heat release rate (HRR) is a pivotal parameter in engine research, shedding light on combustion efficiency and dynamics within the engine's cylinder is as shown in the fig. 3. Let's examine the data comparing the HRR concerning crank angle for diesel, B-20 blend with an HfC-coated piston, and B-20 with an uncoated piston.

When examining this data, we can identify several noteworthy trends. At the outset, –30° from TDC, Diesel recorded the highest HRR at 10 kL/m^3. The HfC-coated piston with the B-20 blend showed a marginally lower value of 9 kL/m^3, while the uncoated piston's reading was the lowest at 8 kL/m^3. As the CA approached TDC, there was a sharp increase in HRR across all configurations, underlining the combustion's peak phase. Diesel, once again, exhibited the highest values throughout, reaching a maximum HRR of 75 kL/m^3 shortly after TDC. The B-20 blend in the HfC-coated piston showcased a pattern quite similar to diesel, albeit with slightly lower values, peaking at 72 kL/m^3. This suggests that the thermal barrier provided by the HfC coating aids in efficient combustion of the biodiesel blend, almost matching diesel's performance. On the other hand, the B-20 blend in the uncoated piston had the most subdued curve, reaching its peak at 68 kL/m^3. Post the peak, as the CA continued its rotation, there was a subsequent decline in the HRR for all set-ups. This decline is characteristic of the post-combustion phase, where the majority of the fuel has been combusted, and the expansion phase of the piston begins. This data offers vital insights into combustion dynamics. Diesel's inherent efficiency in the combustion process is evident, but it's also clear that the HfC coating plays a significant role in optimizing the combustion of the B-20 biodiesel blend. The uncoated piston configuration's slightly subdued performance underscores the importance of synergizing fuel choices with appropriate engine modifications.

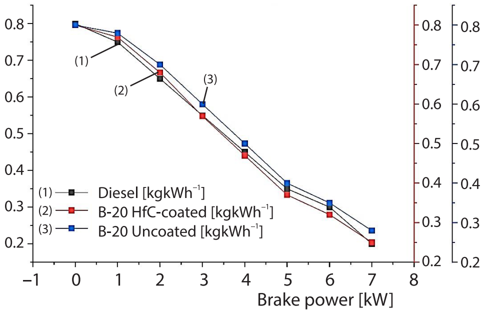

Figure 4. Maximum rate of pressure rise

Variation of maximum rate of pressure rise

The maximum rate of pressure rise within the cylinder can provide insights into combustion behavior, smoothness, and potential for knock. When correlated with brake power, it can yield insights into the engine's operational efficiency and behavior under varying loads. Let's explore a set of data in the fig. 4, comparing these parameters for diesel, B-20 with an HfC-coated piston, and B-20 with an uncoated piston.

Starting at idle, with a brake power of 0 kW, the maximum rate of pressure rise is zero across all configurations – an expected result as there's minimal fuel being burned and the engine is not delivering any power. However, as brake power increases, signifying an increase in engine load, the rate of pressure rise escalates. For traditional diesel, the curve is the steepest. At 7 kW, diesel achieves a maximum rate of pressure rise of 8 bar per CA, indicating efficient combustion and rapid pressure development in the cylinder. The B-20 blend in the HfC-coated piston, while following a similar trend, has values slightly below the Diesel in the entirety of the power range. Peaking at 7.6 bar per CA at 7 kW, it suggests that the thermal barrier coating is aiding in maintaining efficient combustion characteristics, albeit not as aggressively as diesel. On the other hand, the B-20 blend in the uncoated piston consistently lags behind the other two configurations. It only reaches 7.1 bar per CA at 7 kW. This could imply that, without the aid of the HfC-coating, the combustion of the biodiesel blend is not as efficient or rapid, leading to a slower rate of pressure rise. In essence, while diesel remains a dominant player in terms of combustion dynamics, the HfC-coated piston plays a significant role in enhancing the behavior of the biodiesel blend. The slightly lagging values for the uncoated piston version highlight the importance of using advanced engine modifications to optimize alternative fuel performance.

Variation of ignition delay

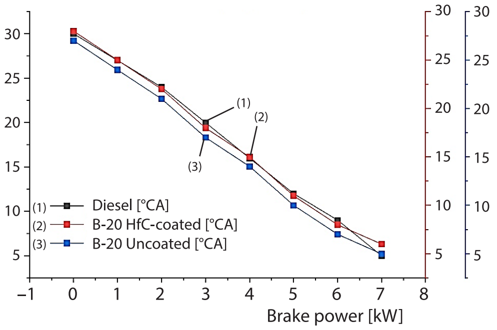

Figure 5. Ignition delay

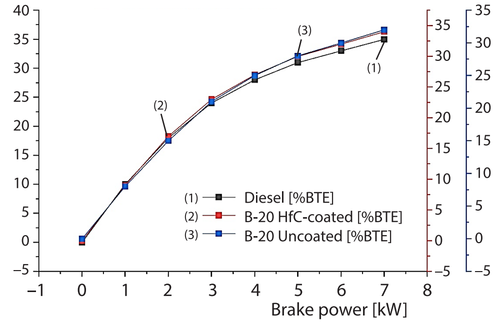

Figure 6. The BTE

Ignition delay, which denotes the time interval between the start of injection and the start of combustion, is a crucial parameter. It can provide insights into the fuel's auto-ignition characteristics and the overall combustion quality. Let's delve into data illustrating the variation of ignition delay with respect to brake power for diesel, B-20 with an HfC-coated piston, and B-20 with an uncoated piston in the fig. 5.

Starting at zero brake power or idle, the ignition delay is typically at its highest. This is because lower temperatures and pressures inside the cylinder at idle prolong the time it takes for the fuel to auto-ignite. In this scenario, diesel exhibits the longest ignition delay of 30° CA. The B-20 blend in an HfC-coated piston is not far behind, with a delay of 28° CA, while the uncoated piston set-up records 27° CA. As the brake power and, by extension, the load on the engine increase, the cylinder's internal temperatures and pressures also rise. This typically leads to shorter ignition delays. Once again, Diesel consistently showcases shorter ignition delays across the power spectrum compared to its biodiesel counterparts. The HfC-coated piston, with the B-20 blend, trails Diesel closely throughout, signifying the coating's positive impact in improving biodiesel's combustion characteristics.

The B-20 with an uncoated piston, however, consistently registers the longest delays, indicating a less efficient combustion behavior. By the time brake power reaches 7 kW, Diesel's ignition delay has shortened dramatically to 5° CA. The B-20 blend in the HfC-coated piston records 6° CA, and the uncoated version clocks in at 5° CA, although it took a longer path to reach this value. While diesel inherently exhibits superior combustion characteristics, it's evident that the HfC coating can substantially improve biodiesel's ignition behavior. The slightly elongated delays for the uncoated piston configuration reiterate the importance of engine modifications and enhancements when transitioning to alternative fuels.

Variation of brake thermal efficiency

Brake thermal efficiency (BTE) offers a measure of how effectively the engine converts the fuel's chemical energy into useful work. A higher BTE indicates a more efficient conversion process. Let's examine data showcasing the variation of BTE with brake power for diesel, B-20 with an HfC-coated piston, and B-20 with an uncoated piston.

At a glance, it's evident that as brake power (and engine load) increases, the BTE also tends to improve. This trend is common across most internal combustion engines, where they operate more efficiently under certain load conditions. The data indicates diesel as the leader in terms of efficiency throughout the brake power range, topping off at a BTE of 35% at 7 kW. The B-20 blend in the HfC-coated piston follows closely, suggesting that the coating plays a vital role in optimizing the combustion process, and thereby, the efficiency of the biodiesel blend. This set-up achieves a BTE of 34% at the 7 kW mark. The B-20 with an uncoated piston, although displaying the same general trend, consistently falls behind the other two configurations, reaching a maximum BTE of 32% at 7 kW. This efficiency gap between the configurations becomes especially prominent in the mid-range brake powers (3-5 kW), where the engine's operating conditions are often seen as more *optimal*.

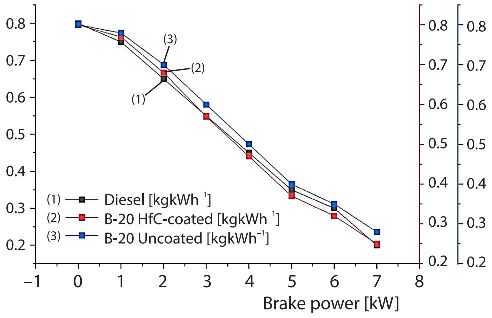

Figure 7. The BSFC

Variation of brake specific fuel consumption

The BSFC is a critical metric in engine research, denoting how much fuel is consumed per unit of power produced. Lower BSFC values indicate greater fuel efficiency. Let's analyze data detailing the variation of BSFC concerning brake power for diesel, B-20 with an HfC-coated piston, and B-20 with an uncoated piston in the fig. 7.

Observing the data, it becomes apparent that as the brake power (or load) on the engine increases, the BSFC decreases, indicating better fuel efficiency. This trend is consistent across most internal combustion engines. Diesel, renowned for its energy density and efficient combustion, consistently records the lowest BSFC values across the brake power range, making it the most fuel-efficient among the three. It drops to an impressive 0.2 kg/kWh at the maximum brake power of 7 kW. The B-20 blend in the HfC-coated piston follows closely behind diesel, with the thermal barrier coating aiding in more efficient combustion of the biodiesel blend. The B-20 in the HfC-coated piston reaches a BSFC of 0.25 kg/kWh at 7 kW. In contrast, the B-20 with an uncoated piston consistently records higher BSFC values compared to its counterparts, suggesting it's the least fuel-efficient among the three. Its BSFC stands at 0.28 kg/kWh when the brake power is at 7 kW. These findings underline the inherent efficiency of diesel. Still, they also showcase how engine modifications, like the HfC-coating, can significantly enhance the performance of alternative fuels, bringing them closer to conventional fuels in terms of efficiency. The uncoated piston's comparatively higher BSFC values emphasize the potential performance drawbacks when transitioning to biodiesel blends without appropriate engine modifications.

Variation of emissions

The emissions from an internal combustion engine, including CO, HC, NO_x, and smoke PM, can provide significant insights into combustion quality, efficiency, and environmental impact. Let's delve into data comparing these emission parameters in relation brake power for diesel, B-20 with an HfC-coated piston, and B-20 with an uncoated piston is as shown below in fig. 8.

Emissions from internal combustion engines are of keen interest to researchers and environmentalists alike. These emissions can provide important clues into the combustion efficiency, environmental impact, and overall performance of the engine. The presented data offers insights into these emissions across different fuel and engine configurations – traditional diesel, a B-20 biodiesel blend with an HfC-coated piston, and a B-20 blend in an uncoated piston. Starting with idle operations, represented by a brake power of 0 kW, emissions are often at their highest. This is attributed to the less efficient and incomplete combustion processes occurring at low engine loads. In our data set, diesel consistently displayed the lowest emissions for CO,

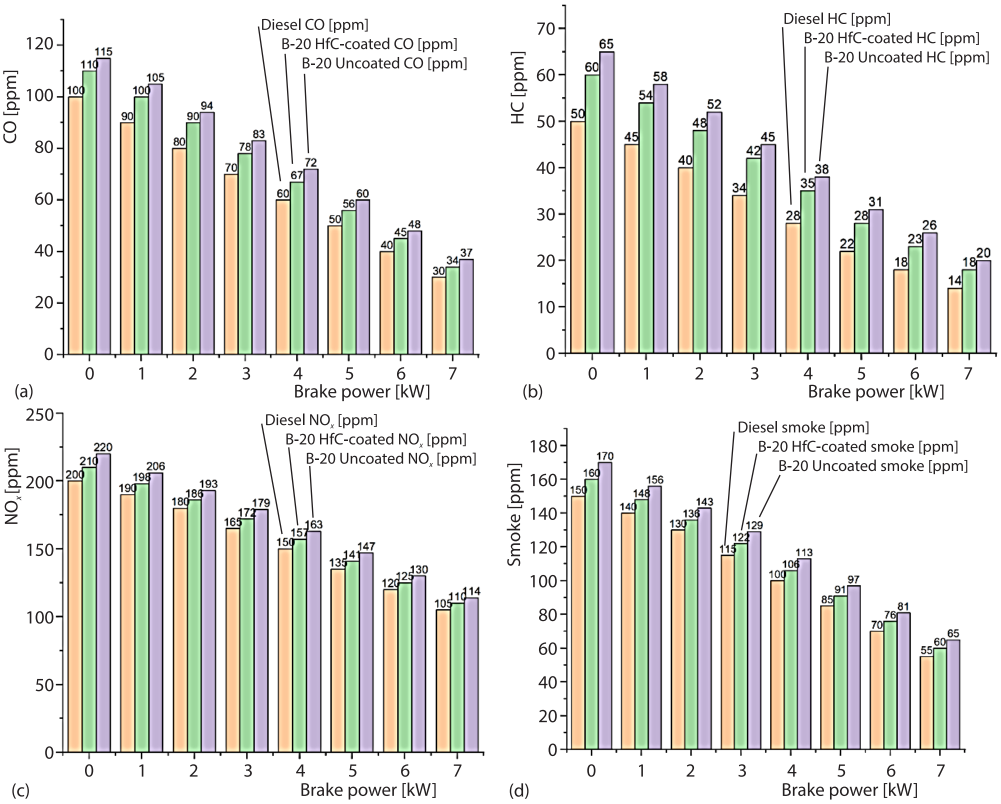

Figure 8. (a) CO, (b) HC, (c) NO$_x$, and (d) smoke emission

HC, NO$_x$, and smoke. This trend is unsurprising given Diesel's inherent properties that promote efficient combustion. Following diesel, the B-20 blend in the HfC-coated piston generally recorded slightly higher emissions. The influence of the thermal barrier coating is evident here, as it seems to enhance the combustion efficiency of the biodiesel blend. Lastly, the highest emissions across the board were observed with the B-20 blend in the uncoated piston set-up, suggesting less optimal combustion dynamics. As we moved up the brake power range, signaling increased engine loads, there was a clear and consistent reduction in emissions. Higher engine loads typically correlate with more efficient and complete combustion, which, in turn, reduces the emissions of pollutants. One thing to note is that while most emissions decline with increased engine load, certain emissions, like NO$_x$, could have a different trend due to the higher temperatures at these loads promoting their formation. In this illustrative data set, while diesel's prowess as an efficient fuel is clearly exhibited, the advantages of the HfC-coated piston in improving biodiesel combustion efficiency are also evident.

The gap in performance and emissions between the coated and uncoated piston set-ups reinforces the concept that transitioning to alternative fuels requires careful consideration of engine design and technology to harness their full potential.

Conclusion

In this comprehensive study, the emissions and performance of a Diesel engine were analyzed across three configurations: using traditional diesel, a B-20 biodiesel blend with an HfC-coated piston, and a B-20 blend with an uncoated piston. The conclusons are as follows.

- Diesel consistently demonstrated superior performance with the lowest BSFC, reaching 0.2 kg/kWh at a brake power of 7 kW. In terms of emissions, it recorded the lowest values with CO being 30 ppm, HC at 14 ppm, NO_x at 105 ppm, and smoke at 55 ppm at this same brake power.
- The B-20 blend in the HfC-coated piston closely trailed diesel, suggesting that the HfC coating significantly optimizes biodiesel combustion. Its performance peaked at a BSFC of 0.25 kg/kWh, while emissions at the 7 kW brake power were CO at 34 ppm, HC at 18 ppm, NO_x at 110 ppm, and smoke at 60 ppm.
- The B-20 with the uncoated piston consistently lagged in performance and emission standards, recording a BSFC of 0.28 kg/kWh at 7 kW. Its emissions included CO at 37 ppm, HC at 20 ppm, NO_x at 114 ppm, and smoke at 65 ppm.

In conclusion, while diesel remains the benchmark for engine performance and emissions, advanced engine modifications like the HfC coating can significantly enhance the performance of alternative fuels, narrowing the gap between them and traditional fuels.

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