COST-EFFECTIVE DUAL-FUEL COMBUSTION STRATEGY COMBINING LPG WITH PROTECTIVE INTAKE WATER INJECTION

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Abstract. This study presents the development and experimental evaluation of an innovative diesel-LPG dual-fuel combustion system designed to enhance mixture formation, improve thermal stability, and reduce diesel fuel consumption in compression-ignition engines. The proposed system integrates a dedicated gas–air mixer engineered to ensure a reliably turbulent flow regime downstream of the mixing section, thereby increasing mixture homogeneity across a wide range of operating conditions. Liquefied petroleum gas is used as the primary energy carrier, while a small pilot dose of diesel fuel provides stable ignition. To address the challenge of elevated combustion temperatures associated with high LPG substitution ratios, a low-rate intake water injection subsystem was incorporated. Introducing water into the already turbulent mixture results in improved evaporative cooling, reduced peak in-cylinder temperatures, and moderated heat-release rates, contributing to enhanced combustion stability and reduced thermal stress on engine components. Experimental investigations were conducted using an urban driving cycle to evaluate averaged in-cylinder pressure, temperature, and total fuel consumption under dual-fuel and conventional diesel operation. The results demonstrate that the combined use of controlled turbulence and water addition enables substantial diesel substitution while maintaining stable combustion and preventing excessive thermal loads. Moreover, the engine teardown after extended real-world operation exceeding 250,000 km revealed only minimal component wear, confirming the protective effect of water-assisted combustion in mitigating thermal fatigue and prolonging engine longevity. These findings underline the potential of integrating turbulence-enhanced mixing with water injection to improve efficiency, durability, and fuel flexibility in diesel-LPG dual-fuel applications.

Keywords: dual-fuel engine, diesel-LPG combustion, gas-air mixing, water injection, engine durability.

1. Introduction

Commercial road transport is a fundamental component of modern logistics systems and economic activity. Freight vehicles enable the efficient movement of goods between production sites, distribution centres, and consumers, thereby supporting global supply chains. However, the operation of commercial vehicles is associated with significant operating costs, among which fuel expenditures represent one of the largest cost categories for transport operators. As fuel prices fluctuate and regulatory pressures increase, reducing fuel consumption and overall driving costs has become a key priority for commercial vehicle fleets [1; 2].

At the same time, the environmental impact of diesel-powered transport has received increasing attention. Compression-ignition engines remain dominant in the heavy-duty transport sector due to their high efficiency and durability, yet they contribute substantially to atmospheric emissions of nitrogen oxides (NOx), particulate matter, and greenhouse gases. In response, both regulatory frameworks and industry initiatives have encouraged the development of alternative fuels and advanced combustion strategies aimed at reducing emissions while maintaining the efficiency and reliability of diesel engines [3; 4].

One widely investigated approach involves the use of gaseous fuels in dual-fuel compression-ignition engines. In such systems, a gaseous fuel – commonly natural gas or liquefied petroleum gas (LPG) – is supplied to the intake air, while a small pilot injection of diesel fuel is used to initiate combustion. This concept has been studied for several decades and has demonstrated potential for reducing diesel fuel consumption as well as particulate emissions [5; 6]. Experimental and numerical investigations have shown that dual-fuel combustion can achieve significant substitution ratios of diesel fuel while maintaining acceptable engine performance [7].

Liquefied petroleum gas represents a particularly attractive option for transport applications due to its wide availability, relatively low cost compared with diesel fuel, and well-developed distribution infrastructure. LPG also exhibits favourable combustion characteristics that can reduce soot formation compared with conventional diesel fuel [8]. For commercial transport fleets, these properties make LPG an appealing candidate for reducing total operating costs while maintaining compatibility with existing fuel supply systems.

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Despite these potential advantages, the introduction of gaseous fuels into internal combustion engines presents several technical and operational challenges. Previous studies have reported that gaseous fuel combustion can lead to increased combustion temperatures and altered lubrication conditions, which may influence long-term mechanical durability. In spark-ignition engines operating on gaseous fuels, accelerated wear has been observed in components such as valves and piston–cylinder assemblies under certain operating conditions [3; 9]. These observations highlight the importance of considering mechanical durability when implementing alternative fuel strategies.

In addition to durability considerations, the integration of alternative fuel systems into existing vehicles presents practical challenges. Many dual-fuel conversion technologies require significant modifications to engine control units, fuel injection systems, or other electronic components. Such modifications can increase system complexity and installation costs while also limiting compatibility with different vehicle platforms. Furthermore, extensive modifications to factory engine control systems may introduce reliability concerns and complicate maintenance procedures.

Recent research has therefore focused on improving the stability and efficiency of dual-fuel combustion through optimized mixture formation and combustion control strategies. Investigations have explored the effects of pilot injection timing, mixture preparation, and combustion regimes to improve engine efficiency and emission performance [10; 11]. Advanced combustion concepts and charge conditioning methods have also been proposed to mitigate undesirable combustion characteristics and reduce thermal loads [12].

Another line of research has examined methods for controlling combustion temperature and improving thermal management in internal combustion engines. Elevated in-cylinder temperatures can increase mechanical stress and contribute to long-term material degradation. Techniques such as water injection or other charge-conditioning strategies have been investigated as potential solutions for moderating combustion temperatures and influencing heat-release characteristics [13; 14]. Experimental studies have demonstrated that the addition of water to the intake charge can influence combustion dynamics and reduce peak temperatures under certain operating conditions.

Although extensive literature exists on gaseous fuel utilization and combustion control in internal combustion engines, several aspects remain insufficiently explored in the context of commercial vehicle applications. Many experimental investigations are conducted using heavily modified laboratory engines, which may limit the direct applicability of the results to real-world transport vehicles. In addition, relatively few studies address the economic aspects of dual-fuel operation in practical fleet environments. Long-term durability considerations and the interaction between alternative fuels and engine mechanical components also remain areas requiring further investigation.

These challenges highlight the need for practical dual-fuel solutions that can reduce fuel costs and environmental impact while preserving engine durability and compatibility with existing vehicle platforms.

2. Materials and methods

2.1. Temperature development during the diesel engine cycle and under diesel-LPG dual-fuel operation

The thermal state of the working medium in a diesel engine changes substantially throughout the engine cycle, and these temperature variations govern auto-ignition, heat-release characteristics, thermal efficiency, pollutant formation, and component durability. A defining feature of compression-ignition engines is their relatively high compression ratio, commonly ranging from approximately 12:1 to 24:1, which enables the in-cylinder air temperature to rise to a level sufficient for spontaneous ignition of the injected fuel near top dead centre [15]. As a first-order thermodynamic approximation, the temperature rise during compression may be expressed as

$$T_2 \approx T_1 r^{k-1}, \tag{1}$$

where T_1 – initial charge temperature, K;

T_2 – temperature at the end of compression, K;

r – compression ratio;

k – ratio of specific heats.

This relationship highlights the central role of compression ratio in establishing the thermal conditions required for diesel combustion.

During the intake stroke, the cylinder is filled primarily with fresh air, although the charge may also contain residual gases or recirculated exhaust gas depending on the engine configuration and operating strategy. At this stage, the gas temperature remains comparatively low and is typically close to the intake-charge temperature, with deviations caused by turbocharging, intercooling effectiveness, and residual-gas fraction. As compression proceeds, the trapped air is heated rapidly. Previous studies have shown that rapid auto-ignition in diesel-related combustion systems is generally associated with end-of-compression temperatures above approximately 800 K [16]. Under engine-relevant conditions, the bulk gas temperature near the end of compression is therefore commonly discussed in the approximate range of 700-1000 K, depending on the initial thermodynamic state, heat losses, and gas composition [16; 17].

Combustion starts when the injected liquid fuel atomizes, evaporates, mixes with the hot compressed air, and reaches conditions favourable for ignition. Following the ignition delay period, combustion typically develops through premixed and mixing-controlled phases. This stage produces the highest temperatures in the cylinder. Optical and laser-based diagnostics under diesel-engine conditions have reported characteristic flame temperatures of approximately 2300 ± 100 K (Förster et al., 2019). Other studies have likewise shown that local peak temperatures in conventional diesel combustion may exceed 2300 K, whereas strategies based on charge dilution and exhaust gas recirculation can lower combustion temperatures toward approximately 1800 K in low-temperature combustion concepts [18]. Consequently, peak in-cylinder gas temperatures corresponding to 1600 °C or more are entirely realistic in conventional diesel operation, provided that these values are interpreted as short-duration local gas temperatures rather than bulk metal temperatures.

After the main heat-release period, the burned gases expand during the power stroke, and their temperature decreases as internal energy is converted into mechanical work and partly transferred to the combustion-chamber walls. As a result, the gas temperature at the end of expansion is substantially lower than the transient combustion maximum. When the exhaust valve opens, the combustion products are discharged at the exhaust-gas temperature, which remains much lower than the in-cylinder flame temperature but is still strongly dependent on load and engine operating regime. Reported diesel exhaust-gas temperatures range from approximately 200 °C at very light load to about 600-700 °C at high load [19]. In engines equipped with selective catalytic reduction systems, exhaust temperature is especially important because meaningful NOx conversion generally requires temperatures on the order of 200 °C or above, while heavy-duty engines often operate in the approximate range of 250-350 °C over substantial parts of certification cycles [20].

A clear distinction must be made between gas temperature and solid-component temperature inside the cylinder. The very high temperatures discussed during combustion describe the working gases over short time scales and frequently in localized flame regions. By contrast, the piston crown, cylinder head, liner, and valves remain at considerably lower temperatures because of transient heat transfer, liquid cooling, oil cooling, and the cyclic nature of thermal loading [17]. Therefore, statements that diesel-engine cylinder temperatures can reach 1600 °C or more are physically correct only when referring to the combustion gases during peak heat release; such values should not be interpreted as steady-state temperatures of metallic engine components.

When diesel fuel is partially replaced by LPG in dual-fuel operation, the temperature development inside the cylinder may be altered further because the gaseous fuel fraction changes ignition delay, premixing intensity, and the overall heat-release pattern. In many reported cases, LPG addition increases the premixed fraction of combustion and accelerates the heat-release process, which may result in a higher rate of pressure rise, elevated local flame temperatures, and greater thermal loading of combustion-chamber components, especially at medium and high loads [21; 22]. Under such conditions, the piston crown, cylinder head, cylinder liner, and particularly the exhaust valves may be exposed to more severe thermal stress, which is unfavourable for long-term durability and may also increase the tendency toward abnormal combustion or knock in dual-fuel mode [23]. However, this effect should not be interpreted as a uniform temperature increase under all operating conditions, since the actual thermal response depends strongly on LPG substitution ratio, pilot-diesel quantity, injection timing, charge preparation, and engine load [21; 24]. A more precise interpretation is therefore that LPG substitution can increase local peak combustion temperatures and component thermal loading under unfavourable or highly reactive operating regimes.

A practical approach for controlling this temperature rise is water injection. Because of its high latent heat of vaporization, water reduces the charge and combustion temperature through evaporative cooling, thereby suppressing knock, decreasing NOx formation, and alleviating the thermal load imposed on metallic engine parts [24; 25]. In diesel-LPG dual-fuel engines, water injection has been shown to mitigate knock intensity and reduce NOx emissions significantly, which indicates that it is a promising thermal-management strategy when elevated in-cylinder temperatures become detrimental to the cylinder, piston, and valve materials [24].

Overall, the diesel cycle is characterized by relatively low intake temperatures, a strong temperature increases during compression, very high transient temperatures during combustion, and lower yet thermally significant temperatures during expansion and exhaust. Under diesel-LPG dual-fuel operation, these thermal processes may become more severe because of enhanced premixed combustion and higher local heat-release intensity. For this reason, control measures such as optimized pilot-fuel scheduling, charge dilution, and especially water injection is important for maintaining acceptable thermal loading and protecting critical metallic engine components while preserving the efficiency advantages of dual-fuel combustion.

2.2. Pressure development in the cylinder under conventional diesel and diesel-LPG dual-fuel operation

The evolution of in-cylinder pressure is one of the most important indicators of combustion quality in compression-ignition engines, because it directly reflects the interaction between compression, ignition delay, heat-release rate, and expansion work. In a conventional diesel engine, the cylinder pressure increases during the compression stroke as the trapped air is compressed toward top dead centre, after which the onset of combustion causes a further rapid pressure rise. The maximum cylinder pressure is typically reached shortly after top dead centre, when the combined effects of high compression pressure and early heat release are most pronounced. Experimental studies on diesel engines under representative operating conditions commonly report peak combustion pressures on the order of approximately 5.5-6.5 MPa for moderate-load operation, although the exact value depends strongly on engine geometry, boost level, load, injection strategy, and exhaust gas recirculation [21]. More highly loaded or intensified diesel combustion systems can operate at distinctly higher peak pressures, and modern research and calibration studies frequently treat peak cylinder pressure as a key limiting parameter for mechanical durability and combustion optimization [26-28].

In conventional diesel combustion, the pressure trace is governed not only by the absolute maximum pressure but also by the rate of pressure rise, since an excessively rapid pressure increase is associated with combustion harshness, elevated mechanical loading, and acoustic excitation. The pressure maximum is normally attained a few crank-angle degrees after top dead centre, when combustion of the premixed portion of the fuel has already started but the piston has not yet moved sufficiently downward to offset the pressure increase by expansion. Consequently, any factor that shortens ignition delay or advances the main heat-release phase toward top dead centre tends to increase peak pressure, whereas delayed combustion phasing generally reduces it [21]. This explains why pilot-fuel scheduling, injection timing, EGR, and boost pressure are all central tools for controlling the pressure history inside the cylinder [26; 29].

When diesel fuel is partially replaced by LPG in dual-fuel operation, the in-cylinder pressure development may change substantially because the premixed gaseous fuel fraction modifies ignition delay, mixture reactivity, and the distribution of heat release between premixed and mixing-controlled combustion. A number of studies report that LPG substitution can increase both the maximum rate of pressure rise and the peak cylinder pressure, especially when the gaseous substitution ratio is moderate to high and combustion remains stable. In one experimental study on a turbocharged and intercooled four-cylinder dual-fuel diesel engine, 30% LPG substitution increased peak cylinder pressure by about 6.95 bar relative to neat diesel operation, while also increasing the pressure-rise rate by 1.37 $\text{bar}\cdot\text{deg}^{-1}$ CA [22]. Other experimental and numerical work likewise reports that increasing the LPG mass fraction tends to increase cylinder pressure and temperature, although the magnitude of this effect depends on engine speed and operating point [30].

From a physical standpoint, this increase in pressure is associated with the larger premixed combustible fraction formed before ignition in diesel-LPG operation. Once ignition is initiated by the pilot diesel spray, a larger amount of already prepared combustible mixture may burn over a relatively short crank-angle interval, producing a steeper pressure rise and a higher local pressure peak than in conventional diesel diffusion-dominated combustion. Under unfavourable conditions, this can intensify combustion noise and increase the tendency toward knock-like behaviour in dual-fuel mode, which is undesirable from the standpoint of engine durability and mechanical loading of the piston, connecting rod, cylinder head, and bearings [21; 22]. However, the response is not universal at all operating points: review literature emphasizes that the pressure trace in diesel-LPG engines depends strongly on the LPG substitution ratio, pilot-diesel quantity, injection timing, intake-charge conditions, and load, so that pressure increases observed in one regime should not be generalized without qualification to the entire operating map [30].

Accordingly, the most accurate interpretation is that diesel-LPG dual-fuel combustion often raises peak cylinder pressure and pressure-rise rate under combustion-favourable or highly reactive conditions, but the extent of this increase must be managed carefully through combustion control. In practical applications, this is commonly achieved by optimizing pilot-fuel quantity and injection timing, and, where necessary, by using dilution strategies such as EGR or other charge-conditioning methods to moderate the premixed heat-release intensity [21; 22]. Thus, compared with conventional diesel operation, the main pressure-related challenge of diesel-LPG dual-fuel combustion is not simply a higher absolute pressure level, but rather the increased sensitivity of the pressure history to combustion phasing and the greater risk of abrupt pressure development if the gaseous substitution level is pushed beyond the stable operating window [21; 22; 30].

2.3. System description and flow-conditioning concept

The proposed system consists of a liquid petroleum gas tank, a water tank, a mixer equipped with an ultrasonic water evaporator, and a delivery line to the intake manifold, from which the prepared mixture is supplied further to the engine. In this arrangement, gas is fed from the storage tank to the mixer, while water is introduced from a separate tank into the same unit. The ultrasonic evaporator promotes atomization of the water into fine aerosol with a relatively narrow droplet-size distribution, which is advantageous for forming a more homogeneous gas-water mixture before entry into the intake system. Ultrasonic atomization references commonly report narrow droplet-size distributions with median droplet diameters on the order of tens of micrometre, depending on the operating frequency.

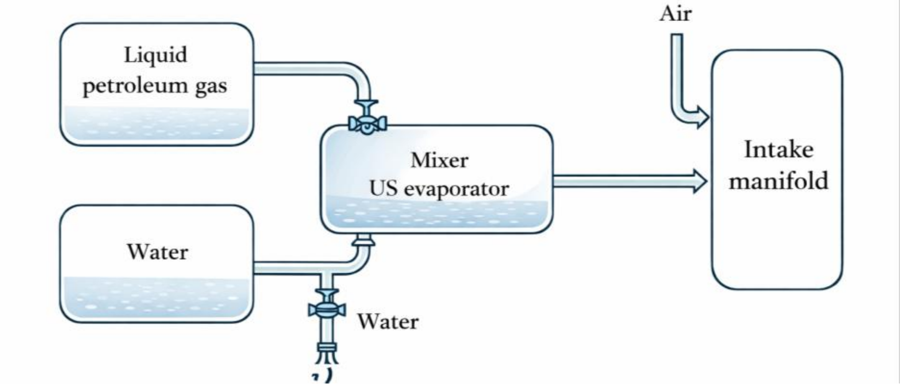

Fig. 1. **Dual fuel supply system.** In addition to the standard diesel fuel injection system, a mixture of water and gas is supplied. Diesel fuel injection directly into the combustion chamber is not marked

After primary preparation in the mixer (Fig. 1), the gas-water mixture is directed to the intake manifold and then into the engine. A key design feature of the system is the relatively small-diameter hose used between the mixer and the intake manifold. The hose diameter is selected such that the Reynolds number of the internal flow remains well above 6,000, thereby ensuring a fully turbulent flow regime. For internal flow in pipes and ducts, Reynolds number is commonly expressed as a function of fluid density, velocity, hydraulic diameter, and viscosity, and flow is generally classified as turbulent when *Re* > 4,000. Therefore, maintaining *Re* > 6,000 provides a clear margin above the transition range and ensures strongly developed turbulent mixing conditions.

This flow regime is important not only for transport, but also for secondary hydrodynamic homogenization of the mixture. Turbulent motion intensifies momentum and mass transfer within the line, enhances interaction between the LPG gaseous phase and the atomized water droplets, and reduces local concentration non-uniformities before the mixture reaches the intake manifold. Reviews of intake-pipe and intake-manifold flow behaviour emphasize that the flow structure in the intake system plays a major role in mixture formation and in the quality of charge preparation delivered to the engine.

Accordingly, the system may be interpreted as operating in two sequential mixing stages. The first stage is the primary mixing process inside the mixer, where petroleum gas and ultrasonically atomized water are brought together. The second stage is the secondary mixing process in the delivery hose, where the deliberately turbulent flow provides additional homogenization prior to the intake manifold. This combined approach is expected to improve the mixture uniformity, stabilize the composition of the supplied charge, and support more even distribution of the prepared gas-water mixture before its entry into the engine.

3. Results and discussion

A key contribution of this work is the integration of water addition into the combustion process as a protective thermal-management mechanism during dual-fuel operation. Modern experimental and numerical investigations demonstrate that water addition increases the effective heat capacity of the working mixture and absorbs heat during vaporization, thereby moderating the heat-release rate and reducing peak in-cylinder temperatures [25; 31]. Lower combustion temperatures are strongly correlated with reductions in NOx formation, as nitrogen oxide generation is highly temperature dependent in diesel combustion processes. Experimental studies have shown that the addition of atomized water into the intake or combustion chamber can reduce in-cylinder temperatures by several tens of degrees Celsius while simultaneously improving emission characteristics [31; 32].

Recent research further indicates that water addition may also influence combustion kinetics and heat-release dynamics in beneficial ways. Simulation and experimental studies conducted on dual-fuel engines have shown that moderate water addition can improve combustion completeness, stabilize combustion phasing, and reduce soot formation under certain operating conditions [33]. In addition, studies investigating water port injection demonstrate that water vaporization during the compression and early combustion stages can reduce local hot spots and suppress abnormal combustion phenomena such as knock or excessive pressure rise rates [34; 35].

Another important aspect of water-assisted combustion is its potential influence on the engine durability. Elevated combustion temperatures and rapid heat-release rates can accelerate mechanical degradation of engine components, including pistons, cylinder liners, and valves. Thermal fatigue and excessive thermal loading are recognized contributors to long-term engine wear. By reducing peak combustion temperatures and moderating pressure rise rates, water addition can decrease thermal stresses acting on combustion chamber components. Several recent studies have therefore identified water injection as a promising strategy for improving the long-term reliability of engines operating on alternative fuels or high-reactivity fuel mixtures [31; 32].

Furthermore, water addition can influence mixture thermodynamics and combustion chemistry through both dilution and thermal effects. The presence of water increases the specific heat capacity of the in-cylinder mixture and reduces adiabatic flame temperatures, which contributes to smoother heat-release characteristics. Computational and experimental studies have demonstrated that these mechanisms can lower nitrogen oxide formation and reduce particulate emissions while maintaining acceptable combustion efficiency [36; 37].

3.1. Experimental temperature observations in the combustion chamber at idle operation

Preliminary experimental measurements were carried out to compare the combustion-chamber temperature behaviour of the engine at idle under two operating modes: conventional diesel operation and diesel-LPG dual-fuel operation with water addition. Temperature was measured using a k-type thermocouple connected to a driver AD8495, and the signal was recorded by a Raspberry Pi Pico W microcontroller at a sampling frequency of 1 kHz. The thermocouple was mounted in the housing (Fig. 2) of the diesel engine glow-plug holder and installed in the corresponding location in the cylinder head, so that temperature could be measured directly near the approximate centre of the combustion chamber. This configuration was used for continuous acquisition of the combustion-chamber temperature signal during engine operation. However, despite the small size of the thermocouple and the relatively high sampling frequency, the sensor still possesses finite thermal inertia; therefore, the recorded temperature traces should be interpreted as comparative and illustrative signals rather than exact instantaneous gas-temperature histories.

Fig. 2. **Modified glow-plug holder with an installed thermocouple for direct temperature measurement inside the combustion chamber**

The obtained temperature profiles (Figs. 3 and 4) exhibited a similar overall trend in both operating modes, although the diesel-LPG-water mode showed a slightly higher peak temperature. For the diesel-only case, the test conditions were 800 rpm, idle operation, and diesel fuel only, with a measurement accuracy of ± 2%. For the dual-fuel case, the engine was also operated at 800 rpm under idle conditions with diesel + LPG + water fuelling. Under these idle conditions, the dual-fuel mixture consisted of approximately 40% diesel and 60% LPG, as adjusted by the control application, while water consumption was approximately 0.8 g/min and increased with increasing the engine speed. The diesel/LPG ratio was not constant but varied with the engine speed and load under the control of the ArtuPower module controller. The maximum recorded temperature in the diesel-LPG-water mode was approximately 1620 °C, compared with approximately 1590 °C in the diesel-only mode. Thus, even at idle, the measurements indicate a modest increase in the observed combustion-chamber temperature when gaseous fuel was introduced.

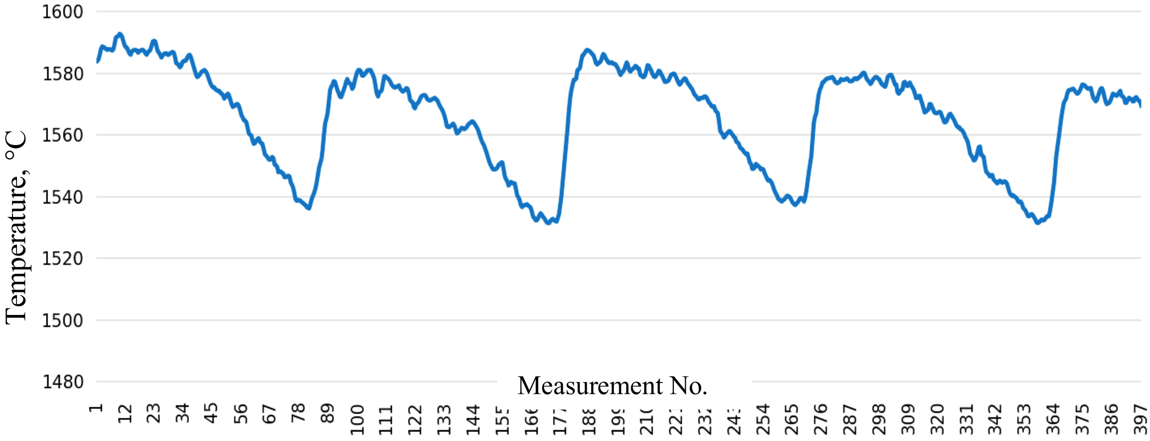

Fig. 3. **Diesel fuel temperature in the cylinder combustion chamber during operation**

Although the absolute values should be treated with caution because of thermocouple response limitations, the comparative trend is consistent with the thermodynamic interpretation developed in the present study. The addition of LPG promotes a more reactive premixed combustible fraction and can intensify heat release, which tends to increase local combustion temperature. At the same time, the presence of water is expected to suppress excessive temperature rise by evaporative cooling, by increasing the heat capacity of the working mixture, and by reducing local hot spots. The fact that only a small temperature increase was observed under dual-fuel operation is therefore physically meaningful: it suggests that LPG contribution tends to elevate combustion temperature, while the simultaneously introduced water moderates this effect and prevents a more pronounced thermal rise.

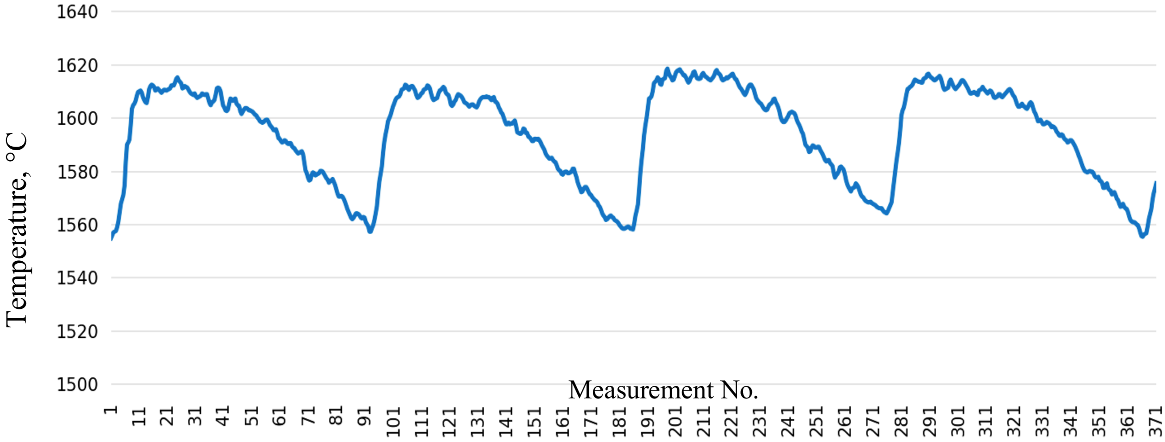

Fig. 4. **Temperature in the cylinder combustion chamber during engine operation**

From this standpoint, the experimental observations may be regarded as supportive evidence for the proposed interpretation of the dual-fuel combustion process. The measured temperature difference is not large, yet it follows the expected direction and therefore qualitatively confirms that LPG addition tends to increase the thermal intensity of combustion, whereas water acts as a damping factor. Consequently, the measurements support the hypothesis that the combined diesel-LPG-water strategy modifies combustion in a controlled manner, allowing a slight increase in combustion intensity without an excessive rise in the chamber temperature.

Because the measurements were conducted at idle and with a thermocouple subject to unavoidable dynamic lag, these results should be treated primarily as qualitative validation rather than as a basis for precise quantitative analysis of peak in-cylinder gas temperature. More detailed future measurements using faster-response diagnostics and a wider range of operating loads would be beneficial for confirming the magnitude of the thermal effect under practical engine conditions.

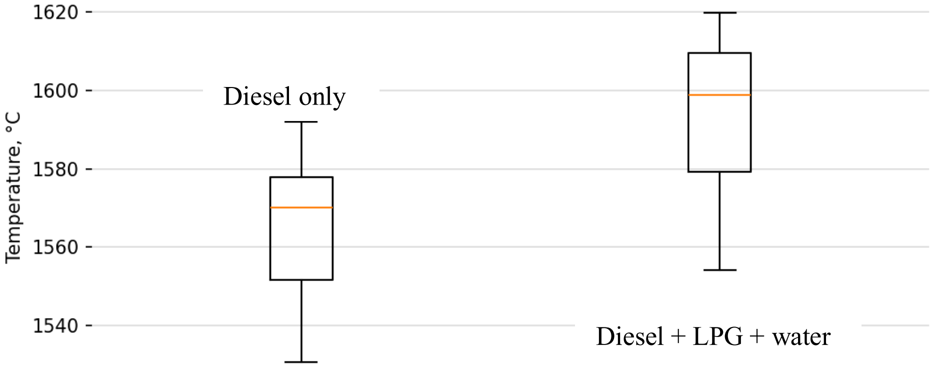

Fig. 5. **Temperature distribution and variability**

Fig. 5 presents a box plot comparison of the combustion-chamber temperature distributions obtained under diesel-only operation and under diesel + LPG + water operation. The diagram indicates that the dual-fuel mode is characterized by a higher median temperature level than the diesel-only case, which is consistent with the previously observed increase in peak combustion-chamber temperature when gaseous fuel is introduced. At the same time, the spread of the temperature values in the dual-fuel mode is slightly wider, suggesting somewhat greater variability of the thermal process. Overall, the box plot supports the interpretation that the addition of LPG increases combustion intensity, whereas the simultaneous introduction of water moderates this effect and maintains the temperature distribution within a controlled range.

3.2. Engine wear assessment

The present study provides a practical experimental contribution by evaluating a dual-fuel diesel-LPG system with controlled water addition during extended real-world vehicle operation. The proposed system is a mechanically non-invasive add-on that preserves the original diesel injection system and control software while enabling partial diesel substitution with LPG. This approach allows implementation without major engine modification and enables direct comparison between conventional diesel and dual-fuel operation on the same engine platform. Its reversible design also improves practical applicability, particularly for commercial transport, where reliability, maintainability, and low installation complexity are essential.

Unlike many experimental studies limited to short laboratory tests, the present work includes long-term operational evaluation exceeding 250,000 km, followed by engine disassembly and inspection (Fig. 6). The results provide rare empirical evidence regarding the mechanical durability of water-assisted dual-fuel combustion under realistic operating conditions.

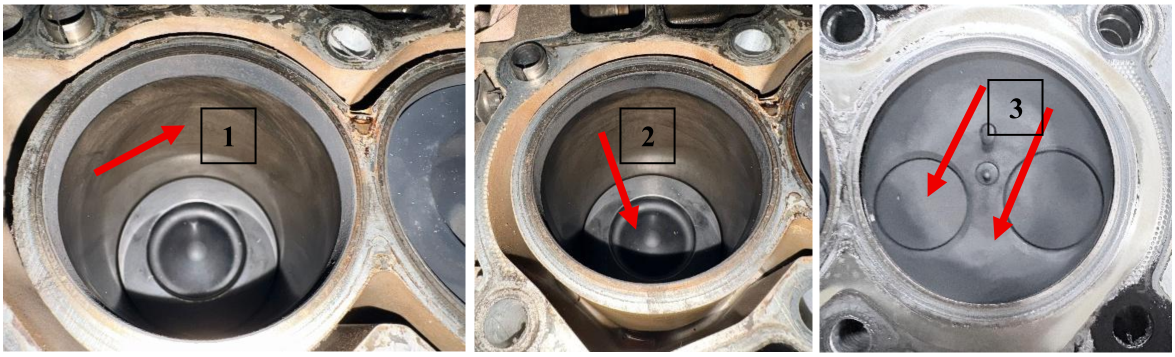

Fig. 6. **Parts of the disassembled engine mechanism – cylinders, pistons, valves; the technical condition of the engine does not indicate significant wear after 250,000 km of mileage:** 1 – no vertical wear streaks are observed in the cylinders; 2 – no damage is observed in the vicinity of the piston combustion chamber; 3 – clean, unburned surfaces on the cylinder head and valves

By combining economically motivated diesel substitution with water-assisted thermal management and a reversible system architecture, this work contributes to the development of practical dual-fuel technologies capable of reducing fuel costs, lowering emissions, and preserving engine longevity in commercial transport applications.

3.3. Cost-effectiveness of the dual-fuel strategy

The proposed dual-fuel concept is economically attractive because part of the diesel fuel is replaced by LPG, which is generally a lower-cost fuel in practical operation. In the present vehicle-level example, a 2018 Jaguar F-PACE equipped with a 2.0 L common-rail diesel engine and operated with the developed dual-fuel system consumed 3.6 L of diesel and 3.2 L of LPG per 100 km over an 800 km route. This corresponds to a total fuel use of 28.8 L of diesel and 25.6 L of LPG over the test distance. For comparison, operation in conventional diesel mode is taken as 8.0 L per 100 km, which corresponds to 64.0 L of diesel over the same 800 km distance.

From an economic standpoint, the dual-fuel strategy becomes beneficial when the reduction in diesel consumption compensates for the additional LPG consumption. Expressed per 100 km, the fuel cost of the dual-fuel mode can be written as

$$C_{DF} = 3.6C_d + 3.2C_{LPG}, \tag{2}$$

where C_d – diesel price per litre;
C_{LPG} – LPG price per litre.

Under diesel-only operation, the corresponding fuel cost is

$$C_D = 8.0C_d. \tag{3}$$

Accordingly, the dual-fuel mode is economically favourable when

$$3.6C_d + 3.2C_{LPG} < 8.0C_d, \tag{4}$$

which gives

$$C_{LPG} < 1.375C_d. \tag{5}$$

This result indicates that the dual-fuel system remains cost-effective as long as the LPG price doess not exceed approximately 137% of the diesel price. Since LPG is typically cheaper than diesel in most practical fuel markets, this condition is readily satisfied, which confirms the economic potential of the proposed approach.

In addition to direct fuel-cost savings, the concept also has value from the standpoint of engine protection. As discussed in the previous sections, diesel-LPG combustion may increase local temperature and pressure peaks, thereby increasing thermal and mechanical loading of critical engine components. The addition of intake water provides a practical means of moderating combustion severity and reducing these adverse effects. Therefore, the combined LPG and water-injection strategy should be regarded not only as a fuel-cost reduction measure, but also as a protective dual-fuel combustion concept capable of improving economic performance while helping to preserve engine durability.

3.4. Thermodynamic interpretation of the efficiency gain in diesel-LPG-water operation

The observed improvement in practical fuel economy may be attributed to an increase in effective conversion efficiency, rather than to any direct energetic contribution of water itself. In dual-fuel operation, the gaseous nature of LPG promotes more homogeneous premixing with the intake air than liquid diesel alone, which improves charge preparation and reduces locally over-rich or poorly mixed regions inside the cylinder; this more homogeneous combustible charge can intensify the premixed combustion phase and improve the utilization of the released chemical energy under suitable operating conditions [21; 38]. At the same time, water addition can make the combustion process thermally more uniform by suppressing local hot spots, moderating the heat-release rate, and reducing knock tendency and excessive peak firing conditions through charge cooling and the high latent heat of vaporization of water [39; 40]. Beyond simple temperature reduction, water injection has also been reported to reduce heat losses to the walls and exhaust gases in controlled engine studies, which provides a thermodynamic pathway by which a larger fraction of the fuel chemical energy may be converted into useful work rather than being rejected as loss [41]. Additional favourable effects may include smoother pressure development, lower soot-prone locally rich regions, improved combustion phasing and, when knock suppression permits more favourable calibration, measurable gains in brake thermal efficiency [21; 24; 25; 42]. Consequently, even when the total chemical energy input of the diesel-LPG mixture is lower than that of diesel-only operation, the engine may still deliver comparable useful work because the combustion process becomes more homogeneous, more controllable, and thermodynamically more effective, particularly when water addition helps maintain stable and less aggressive heat release [21, 24; 41].

Conclusions

1. A diesel-LPG dual-fuel supply system with protective intake water injection was developed and implemented for a common-rail diesel engine.
2. The proposed system enabled two-stage mixture preparation, combining primary mixing in the mixer with additional turbulent homogenization in the delivery line before entry into the intake manifold.
3. LPG addition improved mixture formation and increased combustion intensity, while water addition moderated this effect by suppressing local temperature peaks and reducing excessive thermal loading of engine components.
4. Idle temperature measurements showed a slightly higher peak temperature in dual-fuel operation with LPG and water than in diesel-only mode, which qualitatively confirms the expected increase in combustion temperature caused by LPG together with the damping effect of water.
5. The observed reduction in total fuel-energy input indicates that the improved practical fuel economy is most likely associated with better mixture preparation, more uniform combustion, and higher effective conversion efficiency rather than any direct energetic contribution of water.

6. Overall, the developed diesel-LPG-water concept can be regarded as a technically feasible and economically promising strategy for partial diesel substitution while maintaining controlled combustion and protecting critical engine components.

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The proposed solution is protected by an international patent application published under the Patent Cooperation Treaty (PCT), WO 2021/073783 A1.

Author contributions:

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