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Comparative Analysis of Efficiency and Economic Performance of a Dual-Fuel Diesel Engine Fueled with Compressed Natural Gas and Hydrogen

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***Abstract*—This study presents a comparative experimental analysis of the thermodynamic and economic performance of a compression ignition engine operating in conventional diesel mode and in dual-fuel mode with compressed natural gas and hydrogen. The investigation evaluates the influence of gaseous fuel addition on fuel consumption, brake specific fuel consumption, thermal efficiency, and cost of energy production under identical operating conditions. Experimental tests were conducted on a single-cylinder diesel engine at constant engine speed of 2000 min^{-1} and variable load, using both fixed (K = 20%) and maximum gas substitution ratios. The performance of the engine was assessed based on measured fuel consumption parameters and calculated efficiency indicators. An economic evaluation was also performed using representative fuel prices. The results show that conventional diesel operation achieves the highest thermal efficiency, reaching approximately 29.5% at medium load, compared to about 28 – 29% for hydrogen and 26 – 27% for compressed natural gas. From an economic perspective, compressed natural gas provides the lowest cost of energy production, reaching values as low as approximately 0.50 €/kWh, followed by diesel at around 0.65 – 0.70 €/kWh, while hydrogen results in the highest cost, exceeding 1.0 €/kWh at low loads due to its higher fuel price. The results highlight a clear trade-off between efficiency and cost. While diesel operation remains the most efficient, and compressed natural gas is the most economically favorable option, hydrogen demonstrates improved performance compared to methane and offers significant environmental benefits.**

Keywords— compressed natural gas, dual-fuel engine, hydrogen, thermal efficiency.

I. INTRODUCTION

Internal combustion engines (ICEs) continue to play a dominant role in transportation, agriculture, and distributed power generation systems due to their robustness, high energy density, and operational flexibility. Among the various types of ICEs, compression ignition (CI) engines are particularly valued for their superior thermal efficiency and durability. However, the increasing demand for reduced environmental impact and improved energy efficiency has led to intensified research efforts toward the utilization of alternative fuels and advanced combustion strategies [1] –[5].

One of the most promising approaches to achieving these objectives is the implementation of dual-fuel combustion, commonly referred to as the gas–diesel cycle. In this mode of operation, a gaseous fuel is introduced into the intake air, forming a premixed charge that is ignited by a pilot injection of diesel fuel. This method allows partial substitution of conventional diesel fuel while maintaining stable combustion and engine operability. The dual-fuel concept provides an opportunity to simultaneously influence combustion characteristics, fuel economy, and exhaust emissions, depending on the type and proportion of the gaseous fuel used [6], [7].

Compressed natural gas (CNG), with methane as its primary component, is one of the most widely investigated gaseous fuels for dual-fuel applications. Its relatively low cost, widespread availability, and established infrastructure make it an attractive option for practical implementation. Studies have shown that the use of CNG in dual-fuel CI engines can lead to a reduction in carbon dioxide and

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particulate emissions due to its lower carbon-to-hydrogen ratio compared to diesel fuel [8] - [10]. Furthermore, at higher engine loads, improved combustion conditions contribute to enhanced thermal efficiency and reduced specific fuel consumption.

Despite these advantages, several limitations of CNG-diesel operation have been identified. At low and medium loads, the slower flame propagation speed of methane and the reduced in-cylinder temperature can lead to incomplete combustion, resulting in increased emissions of carbon monoxide (*CO*) and unburned hydrocarbons (*HC*)

Additionally, the displacement of intake air by gaseous fuel may reduce the available oxygen for combustion, further contributing to inefficiencies under certain operating conditions [11], [12]. These challenges highlight the importance of optimizing operating parameters such as load, gas substitution ratio, and injection strategy.

Hydrogen (H_2) has attracted considerable attention as a next-generation alternative fuel due to its unique physicochemical properties. It is a carbon-free fuel with a significantly higher lower heating value (LHV) compared to hydrocarbon fuels, wide flammability limits, and high flame speed. These properties enable rapid and more complete combustion, which can improve thermal efficiency and reduce carbon-based emissions. Moreover, hydrogen's high diffusivity promotes better mixing with air, leading to a more homogeneous charge and enhanced combustion stability, particularly at lean conditions.

Experimental studies have demonstrated that hydrogen enrichment in dual-fuel CI engines can lead to reduced brake specific fuel consumption and improved overall engine efficiency [13], [14]. Additionally, significant reductions in exhaust gas opacity and carbon dioxide emissions have been reported due to the absence of carbon in hydrogen fuel. However, the use of hydrogen is also associated with certain challenges. The higher combustion temperatures and faster heat release rates may result in increased nitrogen oxide (NO_x) emissions, particularly at higher engine loads. Furthermore, hydrogen's low density can reduce volumetric efficiency, affecting the overall air–fuel mixture formation [15], [16].

The dual-fuel concept has also been explored with other gaseous fuels, such as liquefied petroleum gas (LPG), which has demonstrated similar trends in enhancing combustion intensity and increasing in-cylinder pressure . These findings confirm that the introduction of a gaseous fuel into the diesel combustion process fundamentally alters the thermodynamic and kinetic characteristics of the cycle, providing opportunities for performance optimization.

Although a substantial body of research exists on dual-fuel engines, most studies focus primarily on emission characteristics or performance parameters independently. Comparative analyses between different gaseous fuels are often limited to specific aspects, such as emissions behavior, without a comprehensive evaluation of efficiency and economic performance under identical operating conditions. This creates a gap in the current literature, particularly in understanding the trade-offs between thermodynamic benefits and economic feasibility.

In practical applications, the economic aspect of fuel utilization is of critical importance. While methane is relatively inexpensive and supported by established infrastructure, hydrogen remains significantly more costly due to production, storage, and distribution challenges. Therefore, evaluating the cost of energy production in addition to engine efficiency is essential for determining the real-world applicability of dual-fuel strategies.

Based on the above considerations, the primary objective of the present study is to perform a comparative experimental assessment of the influence of compressed natural gas and hydrogen addition on the performance and economic characteristics of a compression ignition engine operating in dual-fuel mode under conventional diesel engine settings. The investigation is conducted at identical operating conditions and constant gas substitution ratios, allowing direct comparison of the effects of the two gaseous fuels on fuel consumption, thermal efficiency, and cost of energy production.

The study is focused on practical dual-fuel implementation scenarios, where existing diesel engines operate without substantial modification of their original design and calibration parameters. Such an approach reflects many currently applied dual-fuel systems used in practice, where gaseous fuels are introduced into conventionally calibrated diesel engines in order to simplify implementation and reduce conversion complexity.

It should be emphasized that the present work does not aim to optimize the combustion process separately for each gaseous fuel. Parameters such as injection timing, compression ratio, and fuel delivery strategy are intentionally maintained close to the standard diesel configuration in order to evaluate the direct influence of fuel substitution under comparable baseline conditions. Future investigations will focus on dedicated optimization of dual-fuel combustion parameters for hydrogen and methane operation.

II. MATERIALS AND METHODS

For the experimental investigation, a single-cylinder compression ignition engine type *DV550* was used. The engine is characterized by a cylinder bore of D = 91.5 mm, a piston stroke of S = 85 mm, and a compression ratio of ε = 17.5. The engine operates with direct fuel injection and has a rated brake power output of *8* kW at a rotational speed of n = 3000 min^{-1}. The injection timing angle was kept as its default setting of 20° before top dead canter for all of the operation modes.

The test engine is coupled to a direct current electric dynamometer (*SAK 28*), which enables precise control of the engine load and measurement of brake performance parameters. The dynamometer is capable of absorbing power up to 28 kW at engine speeds reaching 6000 min^{-1}, thus ensuring stable operation over a wide range of test conditions.

The experimental setup is designed to allow operation in dual-fuel mode, where gaseous fuel (compressed natural gas or hydrogen) is introduced into the intake manifold. The gas is supplied in a pulsed manner through solenoid-controlled valves. The *CNG* injection pressure was in range between 0.85 to 0.9 bar while the H_2 pressure was in the range 0.3 to 0.59 bar The injection duration and, consequently, the mass flow rate of the gaseous fuel are regulated by a dedicated electronic control unit (*ECU*). The control system was specifically developed at the Department of Combustion Engines, Automobile Engineering and Transport, Technical University of Sofia, and allows flexible adjustment of the gas supply parameters.

The determination of gaseous fuel consumption is based on measurements of volumetric flow, pressure, and temperature. A diaphragm-type gas flow meter (*G4*) is used in combination with a pressure gauge and a type *K* thermocouple to determine the operating conditions of the supplied gas. The temperature range of *CNG* gas fuel and H_2 is in the range of 18 – 21.5 ºC and 26.5 – 28 ºC correspondingly. The measured volumetric flow is converted into mass flow using the corresponding thermodynamic relations. The maximum relative uncertainty associated with the determination of the hourly gaseous fuel consumption is estimated to be 8.2%.

The consumption of the liquid diesel fuel is determined using a custom-developed volumetric flow measurement system. The method is based on recording the time required for the engine to consume a predefined volume of fuel, allowing the calculation of the corresponding mass flow rate. The measured time was in the between 23 and 67 sec. This approach provides reliable measurement of fuel consumption under steady-state operating conditions. The maximum relative uncertainty of the diesel fuel consumption measurement is evaluated at 6.9%.

A schematic representation of the experimental setup, including the fuel supply systems, measurement instrumentation, and dynamometer arrangement, is presented in Fig. 1.

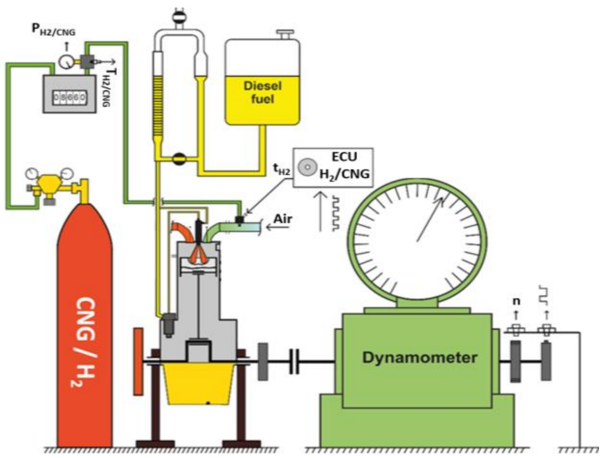

Fig. 1. Test setup

The quantity of gaseous fuel supplied to the engine is characterized by the coefficient *K*. This parameter defines the mass share of the gaseous fuel relative to the total fuel consumption and can be expressed as:

$$K = \frac{B_{gas}}{B_h} 100,\% \quad (1)$$

where B_{gas} is the hourly consumption of gaseous fuel, kg/h, and B_h represents the total (combined) hourly fuel consumption, kg/h.

The total fuel consumption is determined as the sum of the gaseous and liquid fuel components:

$$B_h = B_{gas} + B_D, \text{ kg/h} \quad (2)$$

where B_D is the hourly diesel fuel consumption, kg/h.

The hourly fuel consumption used to calculate the brake specific fuel consumption – b_e:

$$b_e = \frac{B_h}{N_e}, \text{ kg/kWh} \quad (3)$$

where N_e is the engine brake power, kW.

The engine thermal efficiency (η_e) is calculated based on the following equation:

$$\eta_e = \frac{3{,}6 * 10^3}{\left[\left(LHV_D\left(1-\frac{K}{100}\right)+LHV_{gas}\frac{K}{100}\right).b_e\right]}.100, \% \quad (4)$$

where LHV_D and LHV_{gas} are the low heat values of the diesel fuel (~42.5 MJ/kg) and gas fuel (~120 MJ/kg for H_2 and ~49.1 MJ/kg for *CNG*) respectively.

In addition to the thermodynamic evaluation, an economic analysis was performed in order to assess the cost effectiveness of the dual-fuel operation. The economic performance of the engine was evaluated based on the cost of produced energy, expressed in €/kWh.

The cost of energy production - C_{kWh} was calculated using the specific fuel consumption and the corresponding fuel prices according to the following relationship:

$$C_{kWh} = b_e\left[\left(1 - \frac{K}{100}\right)P_D + \frac{K}{100}P_{gas}\right] \quad (5)$$

where P_D and P_{gas} are the corresponding fuel price, of the diesel and gas fuels €/kg.

The fuel prices used in the analysis were selected based on representative market values and are assumed constant for the purpose of comparison. This approach enables a consistent evaluation of the economic impact of methane and hydrogen addition under identical operating conditions.

The experimental results used for comparing the effects of *CNG* and H_2 on engine thermal efficiency and economic analysis were obtained at constant values of the coefficient *K* (*K* = 20% and *K* = max) and variable engine loads (load characteristics), while maintaining a constant engine speed of n = 2000 min^{-1}. The engine load point used for the test are expressed by brake mean effective pressure equal to: 0.22 MPa (30% load), 0.31 MPa (47% load), 0.375 MPa (57% load) and 0.436 MPa (67% load). These results are based on previously determined regulating characteristics.

The regulating characteristics are defined under conditions of constant engine load, expressed by constant brake mean effective pressure (p_e = const), and variable values of the coefficient K (K = var). Additional details regarding the experimental methodology and the procedure for obtaining these characteristics are provided in [6], [17].

The maximum admissible share of gaseous fuel supplied to the engine (K = max) is determined based on the onset of limiting operating conditions. These include either a critical rate of in-cylinder pressure rise or the occurrence of misfire, which may result from an excessively small pilot diesel quantity with insufficient energy to initiate reliable combustion of the gas–air mixture.

In the present study, a value of K = 20% was selected as a representative operating point, ensuring stable engine operation and allowing a consistent comparison between the different gaseous fuels.

III. Results and Discussion

The experimental results obtained from the investigation of the dual-fuel diesel engine operation with methane (*CNG*) and hydrogen (*H₂*) are presented in Fig. 2 to Fig. 5. The analysis focuses on the influence of the gaseous fuel type and substitution ratio on fuel consumption, brake specific fuel consumption, thermal efficiency, and cost of energy production.

A. Hourly Fuel Consumption

At K = 20% (Fig. 2a), the total hourly fuel consumption exhibits a similar increasing trend with load for all investigated fuel modes. The introduction of gaseous fuels leads to variations in total consumption depending on their physicochemical properties. Hydrogen-assisted operation generally results in lower total fuel consumption compared to *CNG*, particularly at lower loads, which can be attributed to its higher energy content and faster combustion characteristics.

However, when compared to conventional diesel operation, the differences are less pronounced and vary with load. Diesel operation demonstrates competitive fuel consumption, especially at higher loads, where combustion conditions are more favorable. In contrast, *CNG* operation tends to exhibit slightly higher consumption values across the load range, particularly at low loads, due to slower flame propagation and incomplete combustion.

At K = max (Fig. 2b), the reduction in total fuel consumption with hydrogen becomes more noticeable, especially at low and medium loads. Nevertheless, the comparison with diesel operation indicates that the benefits of gaseous fuel substitution are strongly dependent on operating conditions and substitution ratio, rather than representing a uniform improvement.

The increase in total fuel consumption observed during dual-fuel operation can be explained by several factors associated with the combustion process in gas–diesel mode. The introduction of gaseous fuel into the intake manifold displaces part of the intake air, which may reduce volumetric efficiency and affect the air–fuel ratio inside the cylinder. In addition, the combustion process becomes strongly dependent on the interaction between the diesel pilot injection and the premixed gaseous fuel–air mixture.

For methane operation, the relatively low flame propagation speed and lower reactivity of the fuel may lead to incomplete combustion, particularly at low loads and high gas substitution ratios. In the case of hydrogen, combustion is more intensive due to its high flame speed and wide flammability limits; however, the non-optimized combustion phasing and standard diesel engine calibration may still prevent full utilization of the fuel energy. As a result, the dual-fuel process may lead to increased overall fuel consumption and reduced thermal efficiency compared to optimized conventional diesel operation.

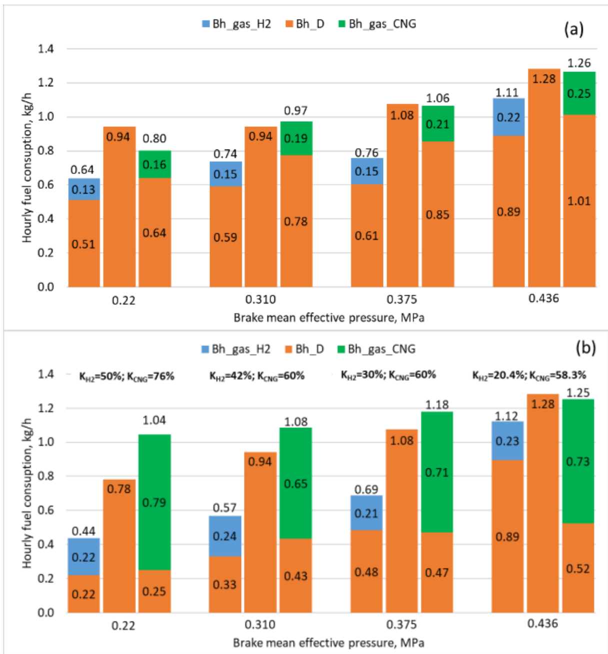

Fig. 2. Variation of total hourly fuel consumption as a function of brake mean effective pressure at (a) constant gas substitution ratio (K = 20%) and (b) maximum admissible substitution (K = max).)

B. Brake Specific Fuel Consumption

At K = 20% (Fig. 3a), the lowest brake specific fuel consumption values are observed during conventional diesel operation across the entire load range. The introduction of gaseous fuels leads to an increase in b_e, reflecting less efficient overall energy conversion in dual-fuel mode.

Among the investigated gaseous fuels, hydrogen demonstrates lower B_e values compared to *CNG*, indicating more favorable combustion characteristics and improved utilization of the supplied energy relative to methane. However, despite this improvement, hydrogen-assisted operation does not reach the efficiency level of pure diesel combustion. For example, at p_e = 0.375 MPa, the b_e value for hydrogen remains higher than that of diesel, while still being significantly lower than that of *CNG*.

At *K* = max (Fig. 3b), the differences between the fuels become more pronounced. *CNG* exhibits the highest b_e values, particularly at low loads, where incomplete combustion effects are dominant. Hydrogen operation shows improved performance compared to *CNG*, with reduced specific consumption, but still remains less efficient than diesel operation. This behavior confirms that while hydrogen enhances combustion relative to methane, the dual-fuel process inherently introduces limitations compared to conventional diesel combustion.

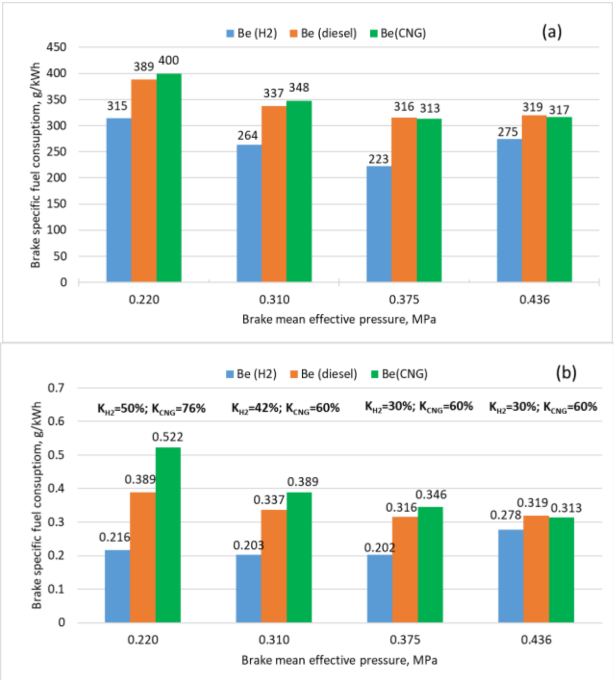

Fig. 3. Brake specific fuel consumption versus brake mean effective pressure for diesel, *CNG*, and hydrogen dual-fuel operation at (a) *K* = 20% and (b) *K* = max.)

C. Thermal Efficiency

The thermal efficiency calculations are based on the total supplied fuel energy, including both the diesel pilot fuel and the gaseous fuel contribution. The variation of η_e is presented in Fig. 4.

At *K* = 20% (Fig. 4a), conventional diesel operation demonstrates the highest thermal efficiency across most of the investigated load range. The introduction of gaseous fuels results in a reduction in efficiency, which is more pronounced in the case of CNG. Hydrogen-assisted operation shows improved efficiency compared to *CNG*, particularly at medium and high loads, due to its favorable combustion properties such as high flame speed and wide flammability limits.

However, despite these advantages, hydrogen does not exceed the efficiency of diesel operation. This can be explained by the inherent characteristics of dual-fuel combustion, including reduced volumetric efficiency and less optimal ignition conditions compared to direct diesel injection.

At *K* = max (Fig. 4b), the efficiency differences between the fuels become more evident. *CNG* exhibits a significant decrease in efficiency at low loads, indicating poor combustion stability. Hydrogen maintains intermediate efficiency values, consistently higher than those of *CNG* but still below diesel operation. At higher loads, the gap between the fuels decreases, suggesting improved combustion conditions for all modes.

Overall, the results indicate that while hydrogen improves efficiency relative to methane, conventional diesel operation remains the most efficient mode under the investigated conditions.

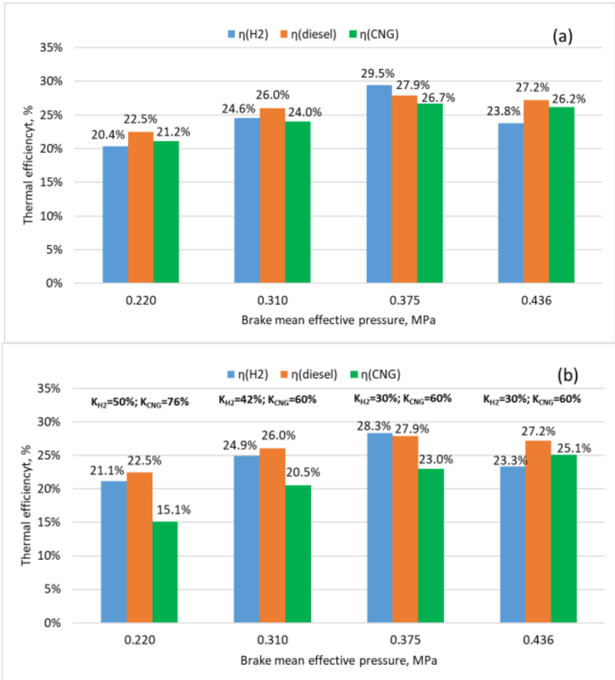

Fig. 4. Brake thermal efficiency (based on the total supplied fuel energy, including both the diesel pilot fuel and the gaseous fuel contribution) as a function of engine load for different fuel configurations at (a) constant substitution ratio (*K* = 20%) and (b) maximum substitution level (*K* = max).)

D. Cost of Energy Production

The economic analysis results are presented in Fig. 5, showing the cost of energy production (€/kWh).

At *K* = 20% (Fig. 5a), *CNG* provides the lowest cost of energy across all operating points, followed by diesel, while hydrogen remains significantly more expensive. For example, at p_e = 0.375 MPa, the cost is approximately 0.61 €/kWh for *CNG*, 0.68 €/kWh for diesel, and 0.74 €/kWh for hydrogen.

This trend is consistent across all loads and reflects the relatively high market price of hydrogen compared to conventional fuels.

At *K* = max (Fig. 5b), the cost difference becomes even more pronounced. Despite the improved efficiency, hydrogen operation results in the highest cost of energy, reaching values above 1.0 €/kWh at low loads. In contrast, *CNG* achieves the lowest cost (as low as 0.50 €/kWh), making it the most economically favorable option.

Considering the current fuel prices used in the present study, hydrogen operation remains economically less favorable compared to CNG-assisted dual-fuel combustion. However, the economic competitiveness of hydrogen is strongly dependent on future reductions in production, storage, and distribution costs. Based on the obtained results, hydrogen could become economically comparable to CNG if its market price decreases substantially below the currently assumed value of approximately 8 €/kg. Such a scenario is considered realistic in the context of ongoing development of green hydrogen technologies and expansion of hydrogen infrastructure.

In addition, it should be noted that many currently implemented dual-fuel retrofit systems in practical applications operate without dedicated optimization of engine calibration parameters for gaseous fuels. Despite this limitation, such systems remain attractive due to their relatively simple implementation and reduced conversion costs.

It should also be noted that the investigated dual-fuel operation modes were implemented using the standard diesel engine calibration settings, without dedicated optimization for each gaseous fuel. Under such conditions, increases in total fuel consumption and reductions in thermal efficiency may occur due to several factors, including reduced volumetric efficiency, altered ignition characteristics, non-optimal combustion phasing, and incomplete oxidation of the premixed gaseous fuel-air mixture. These effects are particularly pronounced at low loads and high gas substitution ratios.

Despite these limitations, the applied methodology reflects many practically implemented retrofit dual-fuel systems currently used in stationary and transport applications, where preservation of the original diesel engine configuration is preferred due to lower cost and reduced system complexity.

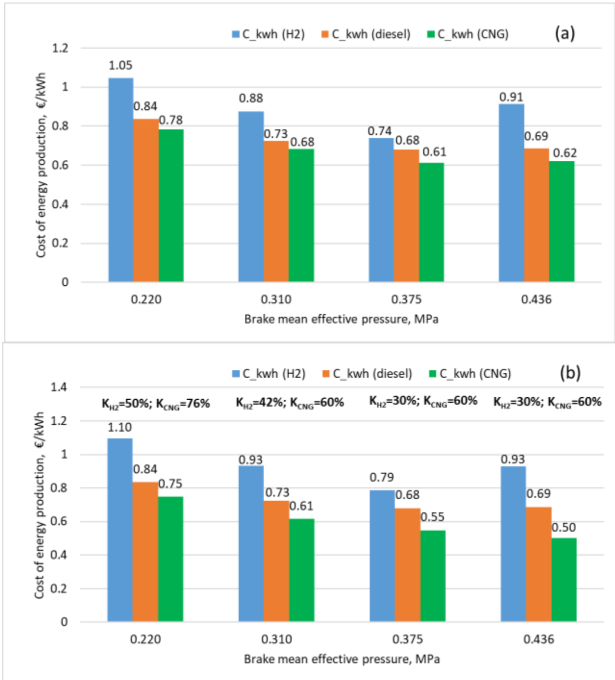

Fig. 5. Cost of energy production (€/kWh) as a function of brake mean effective pressure for diesel, CNG, and hydrogen operation at (a) K = 20% and (b) K = max.)

IV. Conclusions

A comparative experimental study of a compression ignition engine operating in conventional diesel mode and in dual-fuel mode with methane (*CNG*) and hydrogen (H_2) was conducted. The analysis covered fuel consumption, brake specific fuel consumption, thermal efficiency, and cost of energy production under identical operating conditions.

The results show that conventional diesel operation remains the most efficient mode in terms of thermal efficiency across the investigated load range. The introduction of gaseous fuels leads to a slight reduction in efficiency, which is more pronounced in the case of methane. Hydrogen-assisted operation demonstrates better efficiency compared to *CNG*; however, it does not surpass the efficiency of pure diesel operation. This behavior can be explained by changes in mixture formation and combustion characteristics in dual-fuel mode, including reduced volumetric efficiency and altered ignition conditions.

A similar trend is observed for brake specific fuel consumption. The lowest values are achieved in diesel-only operation, while the addition of gaseous fuels results in an increase in specific fuel consumption. Among the dual-fuel modes, hydrogen shows lower b_e values compared to *CNG*, indicating more efficient combustion relative to methane, although still inferior to conventional diesel operation.

In terms of hourly fuel consumption, hydrogen operation demonstrates lower total fuel consumption compared to both diesel and *CNG* dual-fuel modes under certain operating conditions, particularly at lower loads. This effect is associated with the high energy content of hydrogen and its favorable combustion kinetics. *CNG* operation generally results in higher fuel consumption, especially at low loads, due to slower combustion and incomplete oxidation of the fuel–air mixture.

From an economic perspective, conventional diesel operation and CNG dual-fuel mode offer more favorable results compared to hydrogen. The cost of energy production for hydrogen remains the highest among the investigated fuels, primarily due to its elevated market price. In contrast, *CNG* provides the lowest cost per unit of produced energy, making it the most economically viable option under current conditions. Diesel operation shows intermediate cost values, depending on the load.

It should be emphasized that the economic evaluation is based on a hydrogen price of approximately 8 €/kg. Although hydrogen is currently not a cost-competitive fuel, significant reductions in its price are expected in the future as production technologies and infrastructure develop. Under such conditions, hydrogen could become a promising alternative, combining acceptable efficiency with substantial environmental advantages.

In addition to the economic considerations, hydrogen offers important ecological benefits due to its carbon-free nature, which reduce the majority of harmful emissions. These characteristics position hydrogen as a perspective long-term solution for sustainable engine operation.

Overall, the results indicate that while conventional diesel operation remains superior in terms of efficiency, and *CNG* represents the most economically attractive alternative, hydrogen shows potential as a cleaner fuel with improved performance compared to methane. Its wider application will strongly depend on future reductions in fuel cost and further optimization of dual-fuel combustion strategies.

Future research will focus on optimization of the dual-fuel combustion process for the individual gaseous fuels. Particular attention will be given to parameters such as diesel pilot injection timing, compression ratio, gaseous fuel injection strategy, and combustion phasing in order to improve thermal efficiency and overall engine performance under hydrogen- and methane-assisted operation.

Acknowledgments

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