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COMPARATIVE STUDY REGARDING THE USE OF HYDROGEN, NATURAL GAS AND BIOGAS FOR DUAL-FUEL OPERATION IN DIESEL ENGINES

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Abstract. *The use of fossil fuels has increasingly motivated researchers to lookup for more ecological alternatives. When it comes to mobility, the automotive sector already has economically applicable and environmentally sustainable alternatives for replacing fossil fuels, such as the replacement of a portion of diesel with biodiesel and gasoline with ethanol. Another option that can be highlighted is the Hydrotreated Vegetable Oil (HVO), already sold on a commercial scale in some European countries. Although these renewable options present benefits in terms of properties, performance and emission reductions, the competition of internal combustion engines with electric vehicles requires that researchers not only seek for alternatives to replace fossil fuels, but also develop combustion techniques capable of achieving near-zero pollutant emissions to compete with electric technology. In this sense, dual-fuel combustion emerges as an alternative capable of reducing emissions and improving the internal combustion engine's performance by using fuels with different reactivity. The use of dual-fuel technology, using renewable fuels, could be a way for alternative internal combustion engines to reach near-zero pollutant emissions to compete with electric vehicles, or at least to give survival to these engines that receive a lot of pressure to be discontinued in the future. A renewable fuel that deserves special mention is the green Hydrogen, which is produced by the electrolysis of water while using renewable energy, such as photovoltaics, wind and hydroelectric. Hydrogen has a remarkable calorific value (120 MJ/kg), and the result of its stoichiometric combustion produces only water. So, the use of green hydrogen has a great potential to reduce the carbon footprint in several sectors that make use of fossil fuels. In this sense, the use of hydrogen in internal combustion engines can emerge as a sustainable energy alternative, with much lower costs than fuel cells, a potential user of hydrogen for mobility in the future. In this sense, this work proposes the use of hydrogen in a compression ignition engine, as low-reactivity fuel, while using petrodiesel as high-reactivity fuel. This work also proposes the use of both natural gas and biogas as low-reactivity fuels, since these fuels are common and can provide a good comparison with hydrogen while operating in a dual-fuel compression ignition engine. Emissions, consumptions and efficiencies must be analyzed for each case, to verify the feasibility of the proposed study as an environmentally friendly alternative to the use of traditional single-fuel diesel.*

Keywords: diesel engine, dual-fuel, hydrogen, biogas, syngas

1. INTRODUCTION

The dependence on fossil fuels associated with an increase in energy demand heavily enhances greenhouse gas (GHG) emissions (Nanda et al., 2020). It is estimated that the transportation sector accounts for 27% of the total Greenhouse Gas Emissions in the USA, being the responsible for the largest share of GHG emissions in the country (EPA, 2020). Globally, it is estimated that the transportation sector accounts for 23% of the total GHG Emissions (IEA, 2020), while it is estimated that road transport accounts for 72% of this sector emissions (EEA, 2019). At the same time, the large emission of particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO) and SO_x (sulfur oxides) are typical vehicle pollutants that reduce the air quality index in many urban areas (Nanda et al., 2020).

While SO_x emissions can be greatly reduced with fuel desulfurization to meet the environmental regulations (Bonfá, 2011), the other common pollutants emitted by vehicles are intrinsically associated with the combustion of fossil fuels, thus the reduction in these pollutant emissions is dependent on the used fuel and technology. In this way, policies and regulations regarding the reduction of GHG are always being discussed, making the automobile and fuel industries to seek alternative environmentally friendly energy sources capable of not only reducing GHG emissions, but also supplying the increasing demand for fossil fuel and the rising crude oil price (Dimitriadis et al., 2018; Vignesh et al., 2021).

In this way, biofuels emerge as an alternative to replace fossil fuels since they contribute to a reduction in vehicle emissions (Liaquat et al., 2010), while also presenting a very small amount of sulfur, not favoring the SO_x emissions and generating carbon credits (Vásquez et al., 2017). Biodiesel, also known as FAME (fatty acid methyl ester) and bioethanol are two well-established alternatives currently applied in blends with the traditional fossil fuels diesel and gasoline (de Souza et al., 2022). Studies regarding alternative fuels to be used in internal combustion engines (ICE) can be found in literature: BTL (Rimkus et al., 2015), hydrotreated vegetable oil (HVO) (da Costa et al., 2022), waste pyrolysis oil (Pinto et al., 2019), Fischer-Tropsch (Cai et al., 2021), Farnesane (da Costa et al., 2021), and others, each one presenting their benefits and drawbacks.

Another alternative, which is able to reduce the dependence on diesel and gasoline while attenuating some of the harmful effects associated with these fuel emissions is Natural Gas (Hegab et al., 2017). Natural Gas (NG) is mainly composed of methane, which makes it able to present cleaner combustion, with lower emissions of HC, NO_x, CO₂, CO and almost zero smoke and PM (Korakianitis et al., 2011; Latache, 2021). Since NG has a very high octane number, this fuel is more suitable to be used in spark ignition (SI), allowing the engine to operate under high compression ratios than when operating with gasoline, resulting in higher thermal efficiencies (Cho & He, 2007).

An alternative technology, which allows the use of NG in compression ignition (CI) engine, is the dual-fuel mode. Dual-fuel CI engine operation is a hybrid of Diesel and Otto Cycles (Breeze, 2018). In this engine operation, a low-reactivity fuel (e.g. NG) is mixed with intake air, and this mixture is admitted to the cylinder during the intake stroke, just like in SI engines. Instead of having a spark plug to ignite this mixture, dual-fuel CI engines use a high-reactivity fuel (e.g. diesel), also known as pilot injection, to start the combustion, injecting this fuel when the piston is getting close to the top dead center (TDC), just as happens in CI engines (Breeze, 2018). This technology allows the use of a wide range of fuels in CI engines, providing a reduction in costs associated with the use of cheaper fuels and allowing the reduction in emissions associated with these fuels while maintaining the higher efficiency of CI engines in comparison with SI (Kassa & Hall, 2019; Klimstra, 2016). Figure 1 shows the concept of the dual-fuel engine.

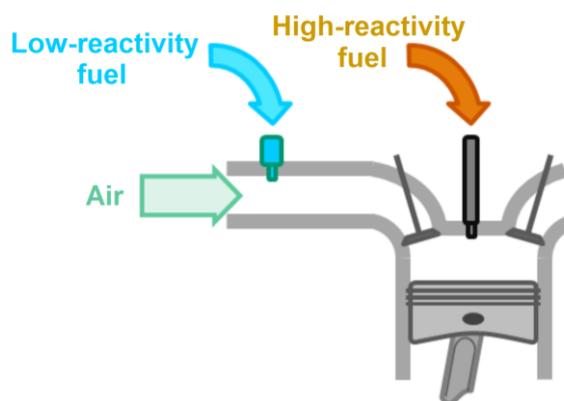


Figure 1: Dual-fuel concept

In this way, the use of biogas from landfills or biodigesters in dual-fuel engines comes as an excellent opportunity to supplement the use of diesel in CI engines with a renewable fuel (Prabhu et al., 2021). Mustafi et al. (2013) carried out a study regarding the use of NG and some biogases with different compositions; the authors found similar performance on the dual-fuel engine in comparison with single-fuel diesel operation. Besides presenting an increase in CO and HC emissions, the dual-fuel operation was able to achieve a reduction in NO_x while also presenting a considerable reduction in PM emissions. Lounici et al. (2014) observed in their study that dual-fuel operation with gas natural presented a higher

efficiency than the operation with single-diesel. The emission trend was: HC and CO presented increased emissions, while NO_x and PM emissions were reduced. Rimkus et al. (2020) also studied a dual-fuel diesel engine with biogas and natural gas. In their study, the authors observed a reduction in the engine efficiency, while the same trend was observed for emissions, with an increase in HC and CO and a reduction in NO_x and PM. The authors also observed a reduction in CO₂ emissions on NG while an increase was observed in biogas, due to the CO₂ content present in its composition. The authors highlight that a complete life cycle assessment would be necessary to take into account the carbon footprint associated with the use of biogas in dual-fuel engines, since even presenting an increased wheel-to-wheel emission, biogas can present a lower well-to-wheel one.

Moreover, the dual-fuel concept allows the use of Hydrogen in CI engines. Hydrogen is considered by many authors as the energy carrier of the future due to its better environmental characteristics, being a suitable option to replace fossil fuels both in the transportation sector and power production sector (OECD, 2005). It has an energy content of 120 MJ/kg, which is almost three times greater than conventional fossil fuels, making it the fuel with the highest energy content of all known fuels (Sankir & Sankir, 2017; Subramani et al., 2015). Hydrogen theoretical stoichiometric combustion produces only water, which makes it an excellent alternative to reduce GHG emissions (Chintala & Subramanian, 2017).

Once hydrogen has a very high self-ignition temperature it is suitable for SI engines, being able to operate without requiring major modifications (Stepień, 2021). However, SI engines have some limitations such as throttling losses, low thermal efficiency, low volumetric efficiency and are not the best solution at low engine speeds where high levels of torque are required (Chintala & Subramanian, 2017; Thiyagarajan et al., 2022). In this way, the use of hydrogen in CI engines operating in dual-fuel mode could be an interesting alternative to rely on the advantages associated with this fuel use, while improving significantly the thermal efficiency, and presenting lower costs than competing technologies.

Karagöz et al. (2016) carried out studies regarding the use of hydrogen in a dual-fuel CI engine and observed that the increase in hydrogen port-fueled reduced the CO and PM emissions, while HC emissions kept unchanged; the author observed an expressive increase in the NO_x emissions due to the higher hydrogen's adiabatic flame temperature. In a similar study, Rocha et al. (2017) observed an increase in the NO_x emissions under hydrogen-diesel dual-fuel operation, while reducing CO, HC and CO₂. Similarly, Dimitriou et al. (2018) observed a reduction in CO, CO₂, HC and PM emissions, while increasing the NO_x emissions in hydrogen-diesel dual-fuel operation. The authors also proposed an Exhaust Gas Recirculation (EGR) system to reduce NO_x emissions, and observed a great reduction in comparison with the scenario without EGR, while keeping unchanged the CO, CO₂ and HC emissions. The drawback of the EGR use was in PM emissions, which increased due to the reduction in the air content being admitted to the cylinder due to EGR.

In this way, this study investigates the use of natural gas, biogas and hydrogen in a diesel engine operating under dual-fuel mode. The aforementioned gaseous fuels were used as low-reactivity fuels, being port-injection to the engine, while diesel was used as high-reactivity fuel, being the responsible for starting the combustion. Performance and emissions analyses were carried out to compare each gaseous fuel operation and to highlight the advantages and drawbacks associated with each one use. Also, a comparison between single-fuel operation and dual-fuel operation was done.

2. MATERIALS AND METHODS

The tests were carried out in the Thermal Machines Laboratory (LMT), at the Federal University of Itajubá (UNIFEI). In the studies, a 4-stroke single-cylinder CI engine, model Buffalo BFDE 10.0, was used. Table 1 presents its specification. The engine is coupled to an oil hydraulic dynamometer, which is responsible for applying and controlling the load.

Table 1. Buffalo BFDE 10.0 specification

Model	Buffalo / BFDE 10.0
Type	4 stroke, compression ignition
Number of cylinders	1
Displaced volume	418 cm ³
Bore diameter	86 mm
Stroke	72 mm
Volumetric compression ratio	19.0:1
Number of valves	1 admission, 1 exhaust
Aspiration	Naturally aspirated
Cooling system	Air-cooled
Fuel injection	Direct injection, mechanical pump
Injection advance	22°±1° before TDC
Injection pressure	19.6 MPa
Maximum torque	27 Nm, at 2800 rpm
Maximum power	7.1 kW, at 3600 rpm

In order to make this engine able to operate under dual-fuel mode, an indirect fuel inject system was adopted, thus making the low-reactivity fuel being injected by Port Fuel Injection, while the high-reactivity (diesel S10) fuel injection was kept as a direct injection by a mechanical pump system.

Emission analyses were carried out using a PC-Multigás (bench NAPRO) analyzer, which was able to measure emissions of carbon monoxide (CO), carbon dioxide (CO₂), unburned hydrocarbons (HC) and nitrogen oxides (NO_x), while a Smoke Check 2000 opacimeter analyzer was used to measure smoke levels. Table 2 presents the specification of the emission analysis system.

Table 2. Gas emission measuring equipment specifications

Flue gas emission	
Model	PC-Multigás
CO	Non-dispersive infrared
CO ₂	
HC	
NO _x	Chemiluminescence
Smoke emission	
Model	Smoke Check 2000
PM	Opacimeter

A Bosch HFM 5 thermal flow sensor was used to measure air mass flow and an Aalborg DPC mass flow meter was used to determine the low-reactivity fuel mass flow. The high-reactivity fuel consumption was measured using the lambda factor (λ), measured by a Bosch LSU 4.2 broadband Lambda probe. Figure 1 presents a scheme of the test bench used in this study.

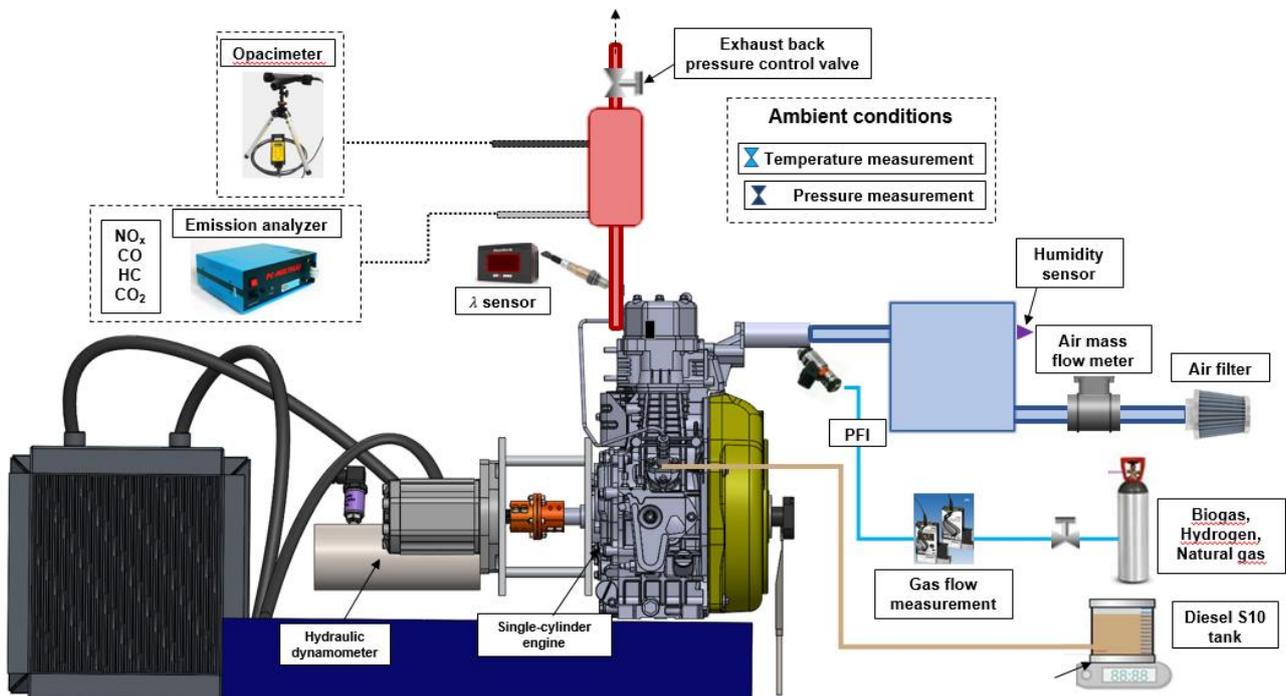


Figure 1: Test bench

2.1 Fuel characterization

Commercial Brazilian diesel, named diesel S10, was used as high-reactivity fuel. Diesel S10 consists of a mixture of 90% diesel and 10% biodiesel on a volume basis. This fuel is responsible for starting the combustion in the proposed dual-fuel operation, just as happens in conventional CI engines. Table 3 presents the main physicochemical properties of diesel S10.

Table 3. Diesel S10 specifications

Property	Diesel (da Costa et al., 2021)
<i>Composition</i>	
<i>C (% mass)</i>	85.33
<i>H (% mass)</i>	13.12
<i>O (% mass)</i>	1.55
<i>S (% mass)</i>	0.001
<i>H/C ratio</i>	1.84
<i>Stoichiometric air/fuel ratio (AF_{stoich})</i>	14.21
<i>LHV (MJ/kg)</i>	41.03
<i>Cetane number</i>	50.5
<i>Density at 20 °C (kg/m³)</i>	846.6
<i>Kinematic viscosity at 40 °C (mm²/s)</i>	2.88

The gaseous fuels used in the study were natural gas (NG), biogas and hydrogen. The gaseous fuel is port-injected to the engine, i.e., they are injected into the intake manifold, close to the engine's intake valve. Thus, the gaseous fuels are mixed with the intake air, entering the combustion chamber as a mixture during the admission stroke, just as happens in conventional SI engines. The combustion starts only at the point which the high-reactivity diesel fuel is injected. Table 4 presents the main properties of studied gaseous fuels.

Table 4. Natural gas, biogas and hydrogen specifications

Property	Natural Gas (da Costa et al., 2019)	Biogas (da Costa et al., 2020)	Hydrogen (Tutak et al., 2020)
<i>Composition (%vol)</i>	$CH_4 - 88.5\%$ $C_2H_6 - 6.2\%$ $C_3H_8 - 2.2\%$ $C_4H_{10} - 0.8\%$ $CO_2 - 1.8\%$ $N_2 - 0.5\%$	$CH_4 - 64.7\%$ $CO_2 - 34.3\%$	$H_2 - 100\%$
<i>Octane number</i>	120	130	>130
<i>Autoignition temperature [°C]</i>	~ 482 – 632 °C	650 °C	585
<i>Lower heating value (LHV) [MJ/kg]^l</i>	47.05	20.19	119.81
<i>Adiabatic flame temperature [°C]</i>	~ 1945 °C	~1872-1926 °C	2127
<i>Stoichiometric air-fuel ratio (AF_{stoich})</i>	16.08	6.94	34.3
<i>H/C ratio</i>	3.73	4	-

The measured lambda factor was used for the calculation of high-reactivity fuel consumption, according to Eq. (1).

$$\lambda = AF_{actual}/AF_{stoich} \quad (1)$$

where AF_{actual} is the air-fuel ratio on actual engine operation and AF_{stoich} is the air-fuel ratio of the stoichiometric combustion. Since the studied engine is working under dual-fuel operation, the air-fuel ratio must take into account both high-reactivity fuel and low-reactivity fuel. Thus, the stoichiometric air-fuel ratio can be calculated by Eq. (2) (Pedrozo, 2017).

$$AF_{stoich} = \frac{\dot{m}_{gas}}{\dot{m}_{gas} + \dot{m}_{diesel}} \cdot AF_{stoich_{gas}} + \frac{\dot{m}_{diesel}}{\dot{m}_{gas} + \dot{m}_{diesel}} \cdot AF_{stoich_{liq}} \quad (2)$$

where \dot{m} is the mass flow; subscript *gas* represents the gas fuels used and subscript *diesel* represents the diesel S10.

Both gas fuel mass flow and lambda factor can be measured by appropriated equipment and stoichiometric air-fuel ratio can be calculated for each fuel. Thus, the high-reactivity mass flow is determined by using Eqs. (1) and (2).

2.2 Experimental analysis

Tests were carried out under fixed engine rotation of 1800 rpm and fixed brake torque of 10 Nm. Diesel S10 was used as high-reactivity fuel, while natural gas, biogas and hydrogen were used as low-reactivity fuel. The tests were carried

out in the aforementioned conditions while changing the port-injected gaseous fuel mass flow for each dual-fuel studied case. Once the mass flow of the gaseous fuel was increased, the energy content admitted into the cylinder during the admission stroke will increase, while the diesel fuel injection reduces. In this way, the energy content (EC) associated with the gaseous fuel port injected replacing conventional diesel can be calculated by Eq. (4):

$$EC = \frac{\dot{m}_{gas} \cdot LHV_{gas}}{\dot{m}_{diesel} \cdot LHV_{diesel} + \dot{m}_{gas} \cdot LHV_{gas}} \quad (4)$$

where LHV is the low heating value of each fuel.

In this way, for each different diesel-gas fuel combination, tests were carried out to determine the performance and emissions of the diesel engine under dual-fuel mode.

2.3 Emission analysis

PC-Multigás gas analyzer measures the emission concentrations of CO (%), CO₂ (%), NO_x (ppm) and HC (ppm). Following the procedures determined by the global standard ISO 8178-1 (ABNT, 2012), the emission concentrations were used to calculate the brake-specific emissions (g/kWh). Similarly, the PM emissions obtained from the Smoke Check 2000 were calculated following the methodology proposed by (Lakshminarayanan & Aswin, 2016) and the brake-specific emission of PM were calculated.

Once the brake-specific (BS) emissions of these pollutants were determined, according to ISO 8178-1, the combustion efficiency can be calculated by Eq. (5) (Pedrozo, 2017).

$$\eta_{comb} = \left\{ 1 - P_B \left[\frac{(BSCO \cdot LHV_{CO}) + (BSHC \cdot LHV_{HC}) + (BSPM \cdot LHV_{PM})}{(\dot{m}_{diesel} \cdot LHV_{diesel}) + (\dot{m}_{gas} \cdot LHV_{gas})} \right] \right\} \quad (5)$$

where P_B is the brake power (MW), BS is the brake-specific emission (g/kWh) of the correspondent pollutant, and the subscripts CO, HC and PM are used to represent the emission pollutant itself. In the study, the LHV_{HC} was considered to be the LHV of a hypothetical mixture of diesel fuel and the gas fuel used in each test dual-fuel, calculated by Eq. (6), or the diesel LHV on the single-fuel operation. LHV_{CO} and LHV_{PM} were assumed to be 10.1 MJ/kg and 32.8 MJ/kg, respectively (Heywood, 2018).

$$LHV_{HC} = \frac{\dot{m}_{gas} \cdot LHV_{gas}}{EC \cdot (\dot{m}_{gas} + \dot{m}_{diesel})} \quad (6)$$

2.4 Efficiency analysis

Brake thermal efficiency (BTE) can be calculated by Eq (7).

$$BTE = \frac{3.6 \cdot P_B}{(\dot{m}_{diesel} \cdot LHV_{diesel}) + (\dot{m}_{gas} \cdot LHV_{gas})} \quad (7)$$

3. RESULTS

Brake-specific CO emissions are presented in Figure 2. CO emissions are usually a result of incomplete combustion of carbon-based fuels (Pinto et al., 2019). As can be observed in this figure, a slight increase in this pollutant emission is observed both for NG and biogas, while hydrogen operation presented a CO reduction. The increased CO emissions for NG and biogas can be attributed to a reduction in the oxygen content being admitted to the cylinder during the intake stroke and to a poor combustion under dual-fuel operation (Deheri et al., 2020; Rimkus et al., 2020), while the reduction caused by the hydrogen addition would be already expected since this fuel is carbon-free, therefore not favoring this pollutant emission (Dimitriou et al., 2018). Also, hydrogen combustion increases in-cylinder temperature, thus accelerating the CO oxidation process (Nag et al., 2019).

Figure 3 presents the HC emissions (g/kWh). As observed for CO, HC emissions are a result of incomplete combustion of hydrocarbons, thus a similar trend is expected for CO and HC and this can be observed by this figure. As can be seen, for hydrogen dual-fuel operation, HC emissions remain the same as those observed by single-fuel operation. Once again, this trend can be justified by the fact that hydrogen is a hydrocarbon-free fuel, thus not favoring this pollutant emission (Chintala & Subramanian, 2017). On the other hand, an increase in HC emissions was observed for both NG and biogas, due to a deterioration in the combustion process (Deheri et al., 2020; Rimkus et al., 2020).

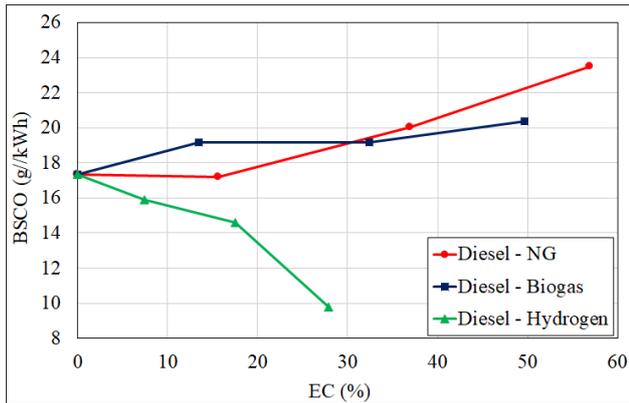


Figure 2: Brake-specific CO emissions

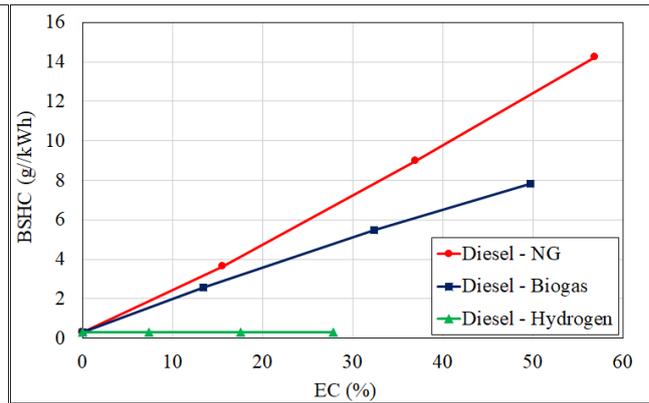


Figure 3: Brake-specific HC emissions

Figure 4 presents the NO_x emissions (g/kWh) for each dual-fuel scenario studied. A strong rise in NO_x emissions can be observed when the engine operates with hydrogen as port-fuel, which is a result of an increase in the combustion temperature due to the combustion characteristics of hydrogen. Vijayaragavan et al. (2021) highlight that NO_x emission is the major problem in hydrogen use due to its high adiabatic temperature, high LHV and high flame speed. Hydrogen enrichment enhances the completeness of the combustion, resulting in higher in-cylinder peak pressure and higher in-cylinder peak temperature, resulting in an increase in NO_x emissions due to the Zeldovich mechanism. Thus, high combustion temperature due to H_2 enrichment is the main reason behind NO_x formation (Saravanan et al., 2008).

On the other hand, a small increase in NO_x emission was observed for NG operation while a reduction in this pollutant emission was observed in biogas operation. The reduction in NO_x emissions during biogas operation is a result of CO_2 content in the biogas, acting as a diluent and since it has a high molar specific heat capacity, it helps to decrease the in-cylinder temperature, thus not favoring the thermal NO_x formation (Mustafi et al., 2013).

Brake-specific PM emissions are presented in Figure 5. As can be observed, the use of NG, biogas and hydrogen strongly reduces PM emissions. In general, PM emissions are associated with a heterogeneous air-fuel mixture and its formation generally occurs in regions with insufficient air/oxygen for oxidation (Thiyagarajan et al., 2022). A considerable reduction in PM emissions was observed for all gases studied under dual-fuel mode, as shown in Figure 5. This emission reduction is a result of the quantity of diesel injected being minimized in dual-fuel operation, which reduces fuel-rich zones from liquid hydrocarbon fuel (Mustafi et al., 2013), while also reducing the presence of aromatics, cyclic molecules and unsaturated hydrocarbon that are found in diesel composition but are absent in NG, biogas and hydrogen, thus resulting in a reduction on the tendency of PM formation (Tree & Svensson, 2007). The reduction in carbon content, which is the main component of soot, and the high temperatures associated with hydrogen combustion, which enhances the soot oxidation, are the main reason that makes the diesel-hydrogen combination present lower PM emissions than NG and biogas (Chintala & Subramanian, 2017).

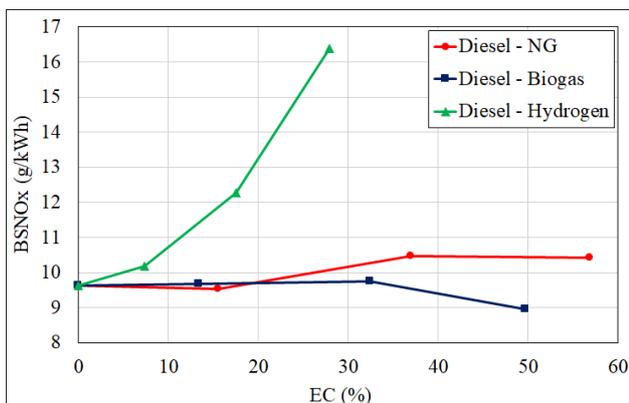


Figure 4: Brake-specific NO_x emissions

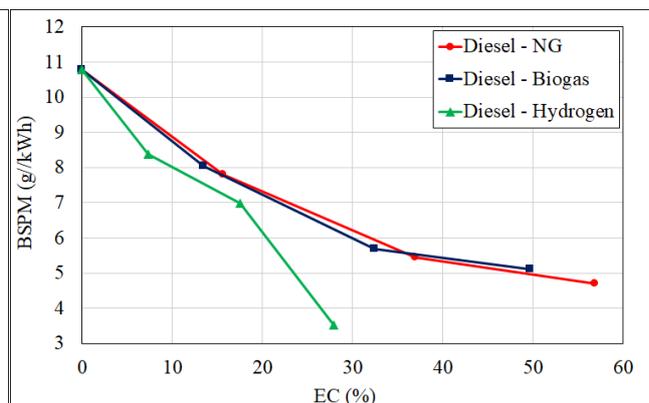


Figure 5: Brake-specific PM emissions

Figure 6 presents the brake-specific emissions of CO_2 . Both NG and hydrogen reduce CO_2 emissions while biogas operation presents an opposite trend. As would be expected, the use of a carbon-free fuel like hydrogen does not result in CO_2 during combustion, and this pollutant emission is decreased. Since the dual-fuel operation with hydrogen presented lower CO and HC emissions than with biogas and NG, it is expected that the carbon content is being oxidized more effectively on hydrogen operation, thus the reduction in CO_2 emissions is not so expressive until 15% hydrogen EC

(Rocha et al., 2017). However, for higher EC, it can be seen that there is a tendency to present a more expressive reduction in CO₂ emissions with the increase in hydrogen content. Moreover, as can be seen in BTE results, the diesel-hydrogen operation was the one with the worst efficiency, which means that more diesel is being injected to supply the same brake power, thus not favoring a greater reduction in CO₂ emissions.

The reduced CO₂ emissions in NG operation are a result of a lower carbon-to-hydrogen ratio (C/H) associated with this fuel (mainly composed of CH₄), which confirms that the dual-fuel operation with diesel and NG is an effective alternative to reduce GHG with an already available technology (Hegab et al., 2017). On the other hand, biogas presents an increased BSCO₂, which can be justified by the high CO₂ volumetric fraction (see Table 4) that composes this fuel and does not take part in combustion. However, Rimkus et al. (2020) highlight that, once biogas is a renewable fuel, its complete life cycle could present significantly reduced CO₂ emission in comparison to the fossil fuels operation.

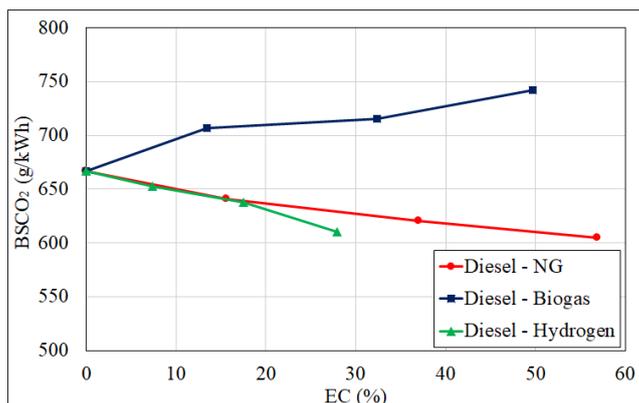


Figure 6: Brake-specific CO₂ emissions

Figure 7 presents the combustion efficiency for each dual-fuel combination analyzed. This parameter represents the conversion rate of the fuel chemical energy into thermal energy (da Costa et al., 2021). As can be seen by Eq. (5), this parameter can be calculated by the not fully oxidized combustion products in the exhaust. A reduction in efficiency of NG operation was observed, while biogas combustion efficiency was kept practically unchanged. The reduction in PM emissions for both NG and biogas helps to increase combustion efficiency, but the increase in CO and HC results in a reduction of this parameter. In this way, the reduction of PM was able to balance the increase in CO and HC for biogas emission, but the NG operation presented fewer fully oxidized pollutants. For hydrogen, the reduction in CO, HC and PM enhances the combustion efficiency, as can be seen in Fig. (7). However, it should be highlighted that any “unburnt H₂” cannot be measured by the PC-Multigás gas analyzer and, besides H₂ emission not being harmful, if any H₂ leaves the combustion chamber unburned, means that the combustion is not that efficient as shown in Fig. (7).

Figure 8 presents the brake-thermal efficiency. As can be seen, there is a reduction in BTE for any gas replacing diesel, which is due to the fact that this engine is not optimized to operate in dual-fuel mode. Since the studied engine has fixed mechanical injection (see Table 1), it has to operate under specific pre-determined conditions, which does not necessarily favor the dual-fuel operation. While NG and biogas present a relatively smooth reduction in BTE, hydrogen operation presented a sharp one, which can be due to its higher flame speed, thus starting the combustion at a point that will not result in the maximum power output. In this way, optimization studies are necessary to enhance the dual-fuel operation.

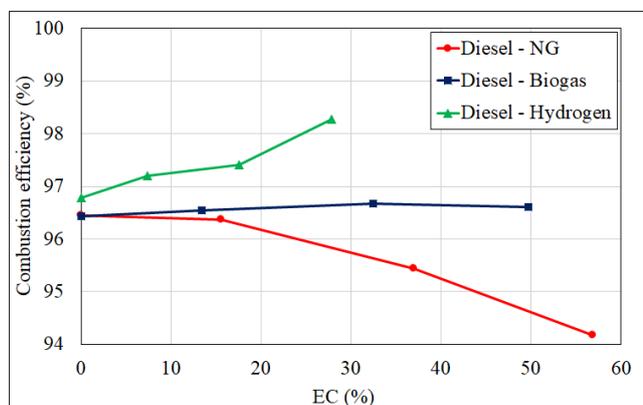


Figure 7: Combustion efficiency

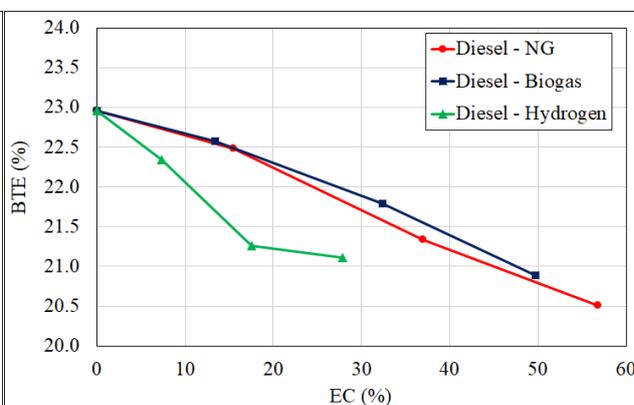


Figure 8: BTE

4. CONCLUSIONS

The use of natural gas, biogas and hydrogen in a single cylinder CI engine under dual-fuel mode was investigated. These fuels were used as low-reactivity fuels, while fossil diesel was used as high-reactivity fuel to start the combustion (pilot fuel). All fuel combinations were able to satisfactorily run the CI engine, but resulting in a reduction in efficiency for all scenarios.

A considerable reduction in PM emission was observed for all gaseous fuel operations, due to their better physicochemical characteristics. Hydrogen operation presented a reduction in CO and HC emission, while a significant increase in NO_x was observed. An opposite trend was observed for both NG and biogas, so that an increased CO and HC emission and a reduced NO_x emission were reported.

In terms of CO₂ emissions, NG and hydrogen presented a reduced emission of this pollutant. On the other hand, biogas presented an increased tank-to-wheel CO₂ emission due to the fact that this fuel already presents this GHG pollutant in its composition. Besides that, once biogas is a renewable fuel, the well-to-wheel CO₂ emissions associated with this fuel use is probably lower than the one associated with both NG and diesel.

In this way, besides some drawbacks found by each gaseous fuel use, it can be seen that they are good alternatives to supply the increasing demand for fossil fuels while also presenting some advantages. NG is a cheap and well-established fuel that helps to reduce emissions. Biogas is a renewable fuel, usually produced from waste, and its use in CI engines not only provides an alternative energy source but also presents reduced GHG emissions during its life cycle. Hydrogen is one of the most prominent energy carriers for the future, being carbon-free when produced by clean energy sources, and which can highly reduce GHG emissions. Thus, studies regarding each fuel operation in dual-fuel engines as well as optimization techniques can provide knowledge to a short-term usage of NG and future use of green hydrogen, and also can allow the use of organic waste as a fuel alternative, while allowing a reduction in GHG emissions.

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