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COMPARATIVE STUDY OF ENERGY EFFICIENCY IN LOW-DISPLACEMENT ENGINES FUELED WITH METHANE-BASED GASES AND ETHANOL LIQUID AS FUEL

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Abstract. *In the pursuit of new fuels that would result in a reduction of carbon emissions to the atmosphere, the use of gases derived from the decomposition of organic matter presents itself as a promising alternative. Biogas is a renewable fuel produced through the anaerobic digestion process that produces a methane-rich gas, which can be purified and used as a vehicle fuel. Its use reduces greenhouse gas emissions, as the decomposition of organic waste emits greenhouse gases that are potentially worse than the products of combustion in automotive engines. Another advantage of biogas is its flexibility regarding vehicles. It can be used in natural gas-powered vehicles, such as those already on the market, or in vehicles converted to this type of fuel. Furthermore, biogas can be mixed with conventional natural gas, which increases the availability of this fuel and reduces dependence on fossil fuels. However, the use of this gas as a vehicle fuel faces some challenges: the lack of infrastructure for the production and distribution of this fuel, as well as the cost of the high-pressure purification and packaging process, which require advanced and expensive technologies. In this context, an experimental apparatus was set up, where a VW EA211 MPI engine adapted to run on both liquid and gaseous fuels was used. In the tests, natural gas with a known composition was used as a substitute for biogas. To collect comparative data on performance and energy efficiency under different operating conditions, programmable engine control units were used, and their control strategies and maps were developed and optimized. Engine parameters were measured using laboratory instruments, ensuring rigorous consumption data of air and fuel. Pressure and temperature data were also collected in real-time to map the best operating conditions under different load levels. As a result, curves and tables were obtained with the best engine settings for each type of fuel. Comparative energy efficiency between both fuels was equally presented, showing the limitations of use for each energy vector.*

Keywords: *Methanee-based fuel, landfill gas recovery, renewable fuel*

1. INTRODUCTION

In the pursuit of enhancing energy efficiency in internal combustion engines, the utilization of gaseous fuels emerges as a promising alternative. Certain combustible gases possess inherent characteristics that, when carefully harnessed, can optimize both mechanical and environmental performance outcomes. Within this context, comparing the results obtained by different fuels in the same engine proves invaluable for guiding the development of novel engine calibrations and propelling technological advancements.

Over time, the improvement of combustion processes has become imperative, aiming, among other objectives, to reduce harmful emissions and greenhouse gases originating from the exhaust system (Sinigaglia *et al.*, 2022) . However, the excessive consumption and high costs associated with liquid fossil fuels, coupled with the environmental impact of emissions, have prompted the exploration, experimentation, and implementation of alternative fuel sources such as natural gas and biomass-derived biofuels (Awad *et al.*, 2018).

By definition, Compressed Natural Gas (CNG) designates the gaseous fuel typically derived from natural gas or biogas, or a mixture of both, intended for vehicular use, with methane as the principal component, adhering to specifications established by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP) (ANP Resolution No. 16, June 18, 2008). Consequently, the use of CNG can offer a direct reduction in harmful emissions using essentially the same types of vehicles and powertrains currently in use (Alrazen and Ahmad, 2018).

According to Bae and Kim (2017), the abundance of natural gas is another compelling factor for its widespread application in internal combustion engines, given its sources include petroleum deposits, coal deposits, and gas reservoirs containing shale gas. This abundance can ensure reductions in extraction and production costs, as well as provide market stability. Additionally, another source of natural gas comes from synthesis gases, known as Syngas, derived from biomass, which, when subjected to gasification processes, generate second-generation biofuels such as synthetic natural gas (Molino *et al.*, 2018).

Presently, the global number of vehicles powered by CNG is rapidly increasing, primarily due to its lower cost compared to more conventional fuels like gasoline and diesel. In comparison, natural gas only requires processing from the production reservoir to the vehicle to be utilized as fuel, whereas petroleum-derived fuels necessitate separation from crude oil and undergo an extensive refining process (Alrazen and Ahmad, 2018).

The primary objective of the present work is the assembly of the experimental apparatus to enable the acquisition of sensor curves and the proper configuration of actuators. Initially, the programmable FuelTech ECU will be employed, followed by initial testing and ensuring the system's stability before securely transitioning to the Bosch Flex-ECU. The latter will involve testing new engine control strategies.

Regarding the tested fuels, the initial goal is to establish a control sequence for ethanol, facilitating the configuration for operation with Compressed Natural Gas (CNG). Subsequently, control maps will be configured based on the methane concentration present in the biogas to be used as fuel.

2. METHODS

For the experiments, a Volkswagen engine, model EA211 1.0 L, naturally aspirated, with 3 cylinders and 12 valves, was prepared. According to information provided in the user manual by WOLSCHICK (2014), this engine features Multipoint Fuel Injection (MPI), variable intake camshaft timing, and indirect fuel injection, allowing precise delivery of nearly equal amounts of fuel to each cylinder at the required timing.

The tests were conducted with the engine fueled by both Compressed Natural Gas (CNG) and ethanol for comparative purposes. The Fuel Tech model FT 550 was employed as the ignition and electronic injection control system, as well as for acquiring engine operating parameters. This Engine Control Unit (ECU) is equipped with integrated components such as GearController, accelerometer, gyroscope, and electronic throttle control (FUELTECH, 2022).

The connection between the ECU and the engine is established through a wiring harness, enabling precise recognition of the engine parameters through sensors and promoting accurate control and performance optimization. The following sensors are integrated into the engine system: - Knock sensor: Detects potential combustion knock within the combustion chamber. - Manifold Absolute Pressure (MAP) sensor: Connected to the air intake system, it measures temperature and absolute pressure in the intake manifold. - Lambda probe: Monitors the concentration of oxygen in the air-fuel mixture. - Engine temperature sensor: Collects data on the engine's temperature, ensuring safe operation. - Phase sensor: Verifies the position of the camshaft. - Throttle position sensor: Determines the percentage of opening of the throttle valve based on accelerator input. Each of these sensors was individually characterized and collaborates with the ECU strategy to provide essential data for precise engine control through its actuators, also controlled by the FT550, aiming at optimizing the overall performance of the system.

The programmable ECU was configured according to the following specifications:

Engine Type: Piston; Number of Cylinders: 3; Maximum RPM: 8000; Starter Motor RPM: 400; Main Map and Rapid Injection: TPS (Throttle Position Sensor); Rotation Sensor Type: Hall; Toothed Wheel: 60-2 (located on the crankshaft); First Tooth Alignment: 81.9 degrees, 14 teeth + 2.1 degrees; Number of Teeth on the Wheel: 60; Number of Missing Teeth: 2; Fault Duration Time: 1.75; Installed Position of Phase Sensor: 93.0; Tooth Tolerance: 40%; Sequential Ignition, Coil with Integrated Module; Sequential Injection Mode, Bank Outputs A: 3; Total Flow Rate of the Bank: 20.0 lb/h; Injector Dead Time: 1.00 ms; Predefined Electronic Throttle, Continental, Model 04C.133.062.F/A2C8272570, 45mm Up MPI 1.0L, KP of 464, KI of 52, and KD of 143, Normal Speed, Linear Mode, 2 References, and 99% Opening Limit; Idle Actuator: Throttle, with 260 steps, frequency 100 Hz; Dwell: MAP by voltage; Internal MAP, 125 Hz, quality factor 1.00.

Data acquisition is facilitated through the Fuel Tech data management software. Engine maps are generated from accelerator pedal input data, intake manifold pressure and temperature, engine coolant temperature, lambda value, engine rpm, injection timing, and ignition timing, recorded over a specified time interval. Comprehensive analysis of engine performance data and operational parameters enables engine optimization.

Performance data is acquired by the Dynomax – Pro software, which, via a data acquisition (DAQ) system connected to sensors on the engine and an active brake for up to 200hp, measures performance data with an accuracy of less than 5%. The Dynomite AC Absorber measurement system adheres to the ROAD VEHICLES - MOTOR TEST CODE - EFFECTIVE NET POWER (ABNT NBR ISO 1585) standard.

2.1 Gas Engine and Gas Subsystem

Considering that the combustion engine used is factory-configured to utilize only gasoline and ethanol as fuels, the adaptation of both the fuel injection system and the ignition system is necessary, along with other parameters required for the efficient use of the previously mentioned natural gas (CNG). This adaptation, along with its associated instruments, is referred to as the "Gas Kit" in this work.

The Gas Kit for the adaptation of the combustion engine includes several essential instruments. These instruments include a Pressure Regulator Valve to reduce the CNG pressure in the cylinders to a suitable level for the intake manifold. A Cylinder Valve allows the passage of CNG into the system. The system also includes a CNG Cylinder with a capacity of 15 m3 for storing the compressed gas. High-pressure tubes enable the flow of CNG at high pressure to the Pressure Regulator Valve. Low-pressure hoses carry the CNG at a lower pressure to the intake manifold. CNG Injectors are connected to the original intake system of the engine to deliver the gas. A TMAP Sensor is installed in the intake manifold to collect pressure and temperature data. The system is controlled by an Autogas ECU STAG 200 Gofast, a versatile electronic control unit capable of working with sequential, semi-sequential, and direct CNG injection modes. The Gas Kit also includes a switching valve for fuel selection, wiring harness for instrument installation and connections, and a pressure gauge to monitor the CNG pressure in the low-pressure hoses.

2.2 Experimental Procedure

Following the assembly of the measurement system, the engine underwent performance tests under partial loads to assess the setup and responses of sensors and actuators. The laboratory's safety system and measurement infrastructure were also enhanced and adapted for the use of gaseous fuels. The entire assembly adhered to the ABNT NBR ISO 1585 standard, although the engine was tested only under partial loads—this standard specifically addresses tests under full load conditions.

Testing routines were established, fixing the throttle position and engine rotation. Under these conditions, measurements presented in the following chapter were taken. Liquid fuel consumption was measured using gravimetric difference, employing a Toledo model 9094C/5 scale with Inmetro Class III resolution (±2g). The flow of gaseous fuel was determined through data provided by the FuelTech program, cross-verified by airflow measurements and exhaust gas lambda measurements. Airflow was measured using an orifice plate installed in a pulsation-damping box.

Thermocouples were installed in the exhaust duct and the liquid fuel reservoir (ethanol) for calculating correction factors. A mini weather station recorded environmental data such as absolute pressure, ambient temperature, and air humidity. All these data were processed in the Dynomax-pro program, which corrected the measured performance values.

3. RESULTS

Starting the tests with the engine fueled by ethanol, the results were obtained, and the main findings are presented in Table 1. The fuel mass was measured by gravimetric difference using a balance, while the air flow was obtained through an orifice plate installed in a pulsation damper box. Subsequently, the testing apparatus was switched to CNG (Compressed Natural Gas) fueling. In this case, the fuel quantity was calculated based on the air flow data and measurements from the lambda probe. The results are presented in Table 2, and Figure 1 provides a comparison of the specific fuel consumption's for each test.

A better overall efficiency was observed when the engine was fueled by CNG, achieving an average of 15%, compared to 14% obtained with ethanol. This improved efficiency is attributed to the lower specific fuel consumption Eq. 1 achieved with the use of CNG, averaging at 0.81 kg/kWh, compared to an average of 1.03 kg/kWh obtained with ethanol.

$$\eta_e = \frac{1}{bsfc \cdot LHV} \tag{1}$$

Table 1. Results obtained with EA211 MPI engine fueled with ethanol at partial loads.

Engine RPM	Fuel flow (kg/s)	Air flow (kg/s)	AF ratio	Lambda	bsfc Ethanol (kg/kW.h)	Efficiency Ethanol (%)
1130	0.0002	0.002	9.1	1.01	1.38	10%
2000	0.0004	0.004	9.0	0.99	0.98	15%
3000	0.0008	0.007	9.0	1.00	0.99	15%
4000	0.0010	0.009	8.5	0.94	0.70	20%
5000	0.0013	0.011	8.8	0.98	0.89	16%
6000	0.0019	0.016	8.6	0.96	1.30	11%

The bsfc stands for Brake Specific Fuel Consumption. It is a measure of the fuel efficiency of an internal combustion engine. Specifically, *bsfc* quantifies the amount of fuel consumed by an engine per unit of power produced, it can be calculated by Eq. 2 and their unit is kg/kWh. The injection time can be estimated using Eq. 3, and the results were verified with the data retrieved from the FuelTech log, showing close agreement.

$$bsfc = \frac{\dot{m}_f}{\dot{W}_e} \tag{2}$$

$$t_i = \frac{\rho_0 \left(\frac{p_1}{p_0}\right) \left(\frac{T_o}{T_1}\right) V_d e_V}{f n_i \left(A/F\right)} \tag{3}$$

Table 2. Results obtained with EA211 MPI engine fueled with CNG (Compressed Natural Gas) at partial loads.

Engine RPM	Fuel flow (kg/s)	Air flow (kg/s)	AF ratio	Lambda	bsfc GNV (kg/kWh)	Efficiency GNV (%)
1130	0.00023	0.00309	13.56	0.79	1.64	6%
2000	0.00026	0.00411	15.79	0.92	0.62	17%
3000	0.00066	0.01048	15.79	0.92	0.80	13%
4000	0.00071	0.01142	16.13	0.94	0.49	21%
5000	0.00080	0.01293	16.13	0.94	0.55	19%
6000	0.00110	0.01769	16.13	0.94	0.76	14%

where ρ_0 is density of air, p_1 and p_0 the intake and ambient pressure, T_1 and T_0 the intake and temperature, V_d displacement volume, e_v volumetric efficiency, f fuel flow of injectors, and A/F the air fuel ratio.

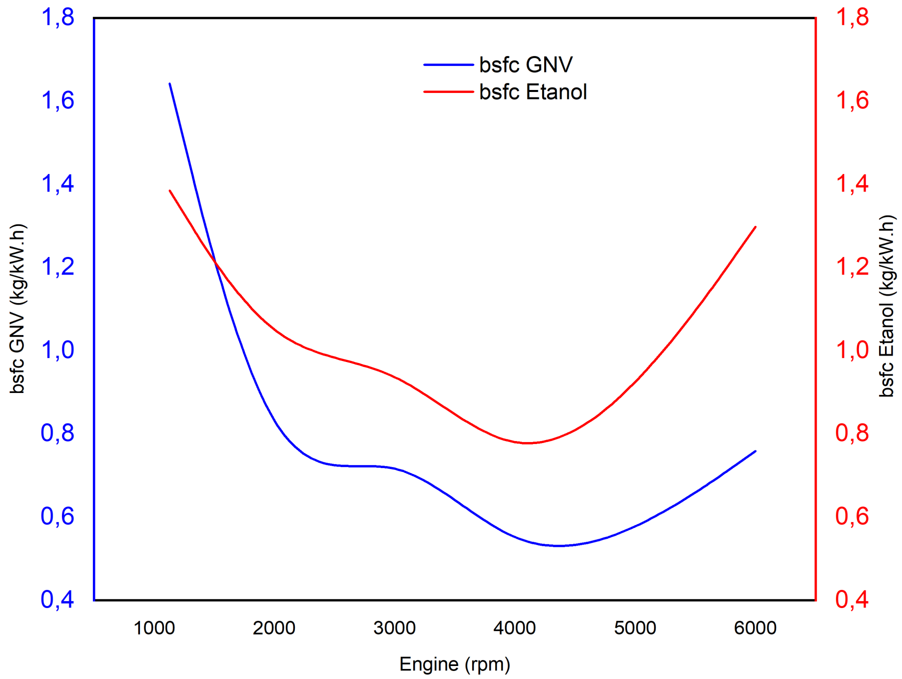

Figure 1. Comparative results of specific fuel consumption of the EA211 MPI engine fueled with ethanol and CNG.

Compressed Natural Gas (CNG) is primarily sourced from underground natural gas reservoirs. It predominantly consists of methane, although it can also contain varying amounts of other hydrocarbons and impurities. The methane content in CNG typically falls within the range of 85% to 98%.

Biomethane, as the name suggests, is produced through the natural decomposition of organic materials, including agricultural waste, sewage, or landfill waste. The methane content in biomethane can vary depending on the specific feedstock and the production process employed. Generally, biomethane exhibits methane levels comparable to or even higher than conventional natural gas. The methane content in biomethane typically ranges from 90% to over 99% after undergoing upgrading processes that eliminate impurities and enhance the methane concentration. These purification steps aim to achieve a methane content comparable to or even surpassing that of conventional natural gas.

The graphs in Figure 2 depict the 3D curves of injection timing and ignition advance for the utilized engine. It is important to note that the engine tests were conducted under partial load conditions, without reaching full load. When operating with CNG, the original maps were adjusted using a dedicated control module. As part of the project, the development of specific control strategies programmed in the Flex-ECU Bosch using ETAS ACET software and controlled by ETAS INCA is underway. It is expected that these new strategies and dedicated maps will yield even better results than those observed in the experiments.

Better results can be achieved through modifications in the engine geometries, such as increasing the compression ratio and valve opening times, which would require the replacement of the valve train components. New configurations of

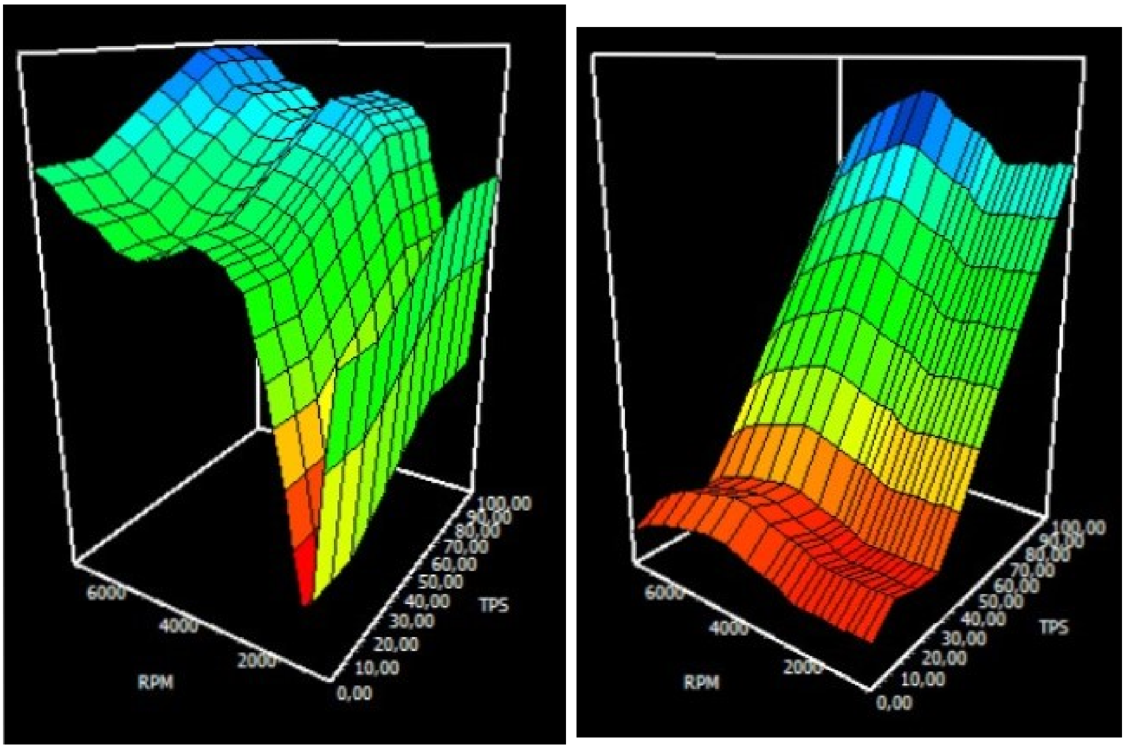

Figure 2. 3D representation of the ignition advance (left) and injection timing (right) maps used in the FuelTech 550.

the Variable Valve Timing (VVT) system can maximize the efficiency of the engine when operating with biomethane in an Otto cycle. Since the tests were conducted under low-load conditions, the overall efficiency results were affected. New tests under full load conditions will be performed aiming to achieve efficiencies in the range of 30% when the engine is fueled with both fuels.

4. CONCLUSION

In summary, this study examined the performance of an engine powered by ethanol and Compressed Natural Gas (CNG), comparing their overall efficiency and specific fuel consumption under partial load conditions. The experimental setup operated effectively, and the findings indicated that the CNG-fueled engine outperformed, exhibiting an average overall efficiency of 15%, as opposed to the 14% recorded with ethanol. This improved efficiency was attributed to the lower specific fuel consumption of CNG, averaging at 0.81 kg/kWh, in contrast to the average of 1.03 kg/kWh observed with ethanol.

Compressed Natural Gas (CNG) is predominantly derived from subterranean natural gas reservoirs and primarily consists of methane, with methane content ranging from 85% to 98%. Biomethane, which shares a similar composition to conventional natural gas, is produced through the natural decomposition of organic materials and undergoes purification processes.

These findings underscore the potential of CNG, as well as biomethane, as more efficient fuel alternatives for engines due to their lower specific fuel consumption when compared to ethanol. Furthermore, the utilization of biomethane as a renewable source of methane exhibits promise in achieving comparable or even superior performance to conventional natural gas. Further research and development efforts in these domains can contribute to the advancement of sustainable and efficient energy solutions across various applications.

5. ACKNOWLEDGEMENTS

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