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MULTIPOINT ETHANOL INJECTION SYSTEM FOR DIESEL ENGINES

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Abstract. *This work presents an ethanol injection system for diesel engine air intake pipe in order to evaluate its effects on mechanical performance for different energy fraction rates. The equipment measures the machine speed, fuel consumption, calculates the replacement fraction and returns parameters such as start point and active injection time synchronized with diesel injection pulse. The system evaluation was performed on a test bench engine. The speed used in the tests was 1800 rpm and the evaluation loads were 60 Nm and 120 Nm. The tests allowed verify the injection point in the cylinders, substitution energy fraction, torque increasing, temperatures, fuel specific consumption and thermal efficiency.*

Keywords: *Electronic instrumentation, Electronic Injection, Mechanical Performance, Diesel Engines.*

1. INTRODUCTION

The massive use of non-renewable fuels is a threat to the planet earth, as a consequence there is a rise in average global temperature, increasing of acid rain incidence as well as frequent favoring of smogs in large urban centers (Imran et al, 2013; Kumar et al, 2013). In an attempt to reduce the negative impacts of the use of non-renewable fuels, the European Union, by means of Directive 2009 / EC, has been decided that until 2020 at least 10% of renewable fuels will be used in its land fleet, because the use of this type of fuel helps in reducing the emission of pollutants.

As in the European Union and other countries, Brazil has also adopted policies to reduce the use of fossil fuels by inserting 8% of biodiesel in commercial diesel since March 2017 and increasing the percentage to 10% in 2019 according to law 13,263/2016. The increasing insertion of biofuels into the country's energy matrix reduces dependence on oil-based fuel imports, as well as supporting agricultural producers thereby increasing their incomes (He, 2016; Mwangi et al, 2015).

The addition of oxygenated compounds to diesel engines combustion fuel, like ethanol, experiences an increasing of demand in Brazil. The use of ethanol in diesel engines allows increase the percentage of biofuel in the mixture, having a positive impact in the profile of gas emissions compared to mineral diesel.

Among the different ways of using ethanol, the fumigation technique requires few modifications of the engine, since the alcohol is introduced in the intake of air of the engine by a carburetor or system of electronic injectors of low pressure. In the case of electronic injection this has an embedded system that can control the rate of energy fraction replaced for each work situation. One advantage of this method in relation to the blended diesel method is that in fumigation it is

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possible to work with varied rates and well above 10% v / v substitution and with different alcoholic graduation of ethanol (95%, 98% , 99.3% purity), while in the blending method the blend is limited to 10% v / v using 99.3% pure ethanol because above the blend there is phase separation (Guarierio et al, 2009; Ferreira et al, 2014; Boretti, 2012).

Lu et al. (2008) studied the effect of ethanol being injected by the intake of engine air with several ethanol energy fractions and several equivalence ratios of the air / fuel mixture in a naturally aspirated single cylinder diesel engine. The results show a substantial decrease in NOx emissions with ethanol injection, however with increased emissions of total unburned hydrocarbons (THC) and carbon monoxide (CO) emissions. Tsang et al. (2010) tested the use of the ethanol spraying technique in a 4-cylinder direct injection engine, with reduction of NOx, opacity and mass of particulate matter, however with an increase in THC and NO2 emissions. Janousek (2010) sprayed via an intake duct, anhydrous ethanol and distilled water in different proportions in a 4-cylinder turbocharged 4.5L diesel engine. As a result it was obtained that the thermal efficiency of the machine operating with ethanol and distilled water was not significantly affected. The fumigation of ethanol / water helps to reduce NOx, but the levels of CO and HC, in the case of ethanol, were taken in comparison to pure Diesel.

This work describes the development of a system capable of managing the air collector (fumigation) ethanol injection. The system functionality was evaluated by checking the injection energy fraction, increasing of torque and power, exhaust gas temperature, specific fuel consumption and thermal efficiency.

2. MATERIALS AND METHODS

The prototype developed consists of an electronic system dedicated to the control of ethanol injection and a communication system between the digital scales, which are used to measure the consumption of the evaluated fuels and rotation measurement. A supervisor receives the information via RS-485 network and parameterizes the ethanol injector nozzles. Fig. 1 shows the developed system diagram coupled to the engine test bench.

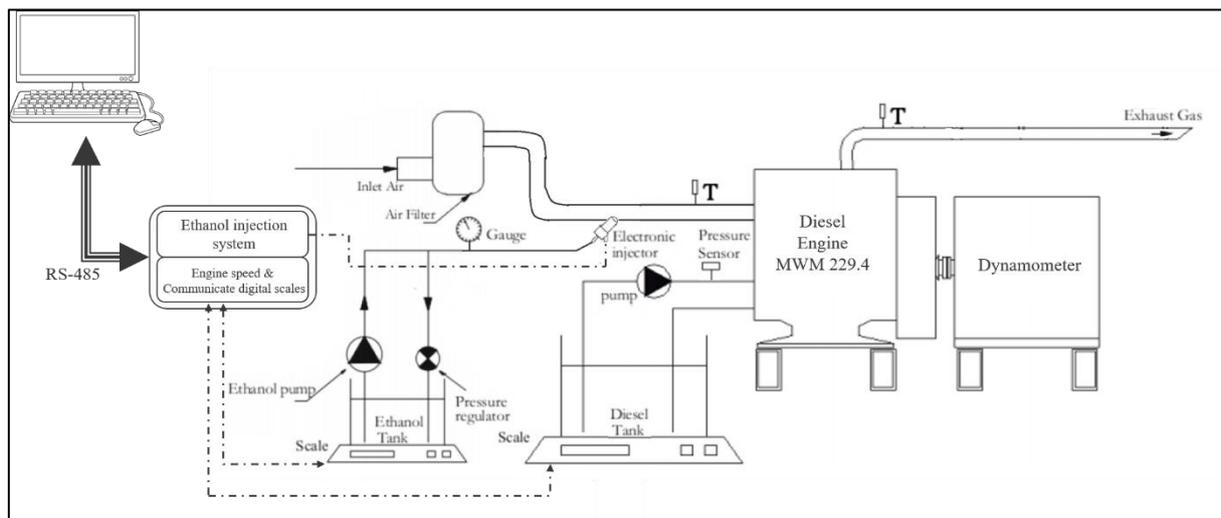


Figure 1: Injection system developed.

2.1 Electronic ethanol injection system

The electronic ethanol injection control system has two embedded subsystems. The first subsystem consists of an ATmega328P® microcontroller, with a 16MHz operating clock and 32kb programming memory, a TTL to RS-485 communication converter driver responsible for communication between this subsystem and the main supervisory system, a driver power ratio that adequately energizes the four injector nozzles and a pressure sensor with conditioning circuit that provides the diesel injection pulse that serves for the synchronization of the ethanol injection pulses. Figure 2 shows the electronic diagram projected and assembled of the diesel pressure sensor and its conditioning and Figure 3 shows the diagram of the power driver of the injector nozzles responsible for its activation.

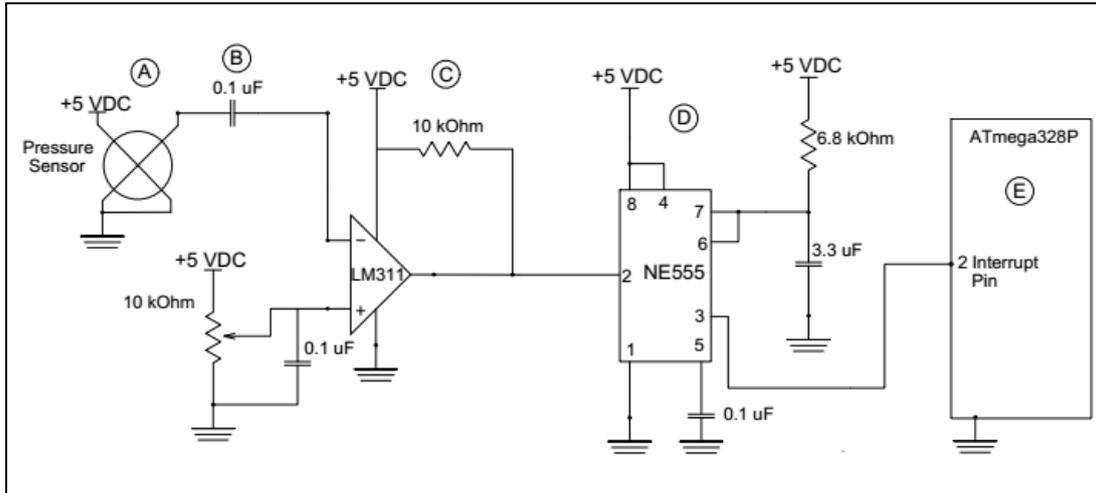


Figure 2 – Electronic diagram of the signal conditioning for the pressure sensor.

The conditioning circuit of Fig. 2 receives as input the electrical pressure signal (A) from the diesel injector nozzle of the first combustion chamber, as the diesel pressure oscillates around a nominal pressure, the electric output voltage of the sensor will have two components, a continuous voltage level, due to the nominal diesel pressure and other varied voltage due to pressure oscillation when the diesel injector nozzle injects fuel from the chamber. Since the continuous component of the electrical signal does not provide important information to the conditioning system, it needs to be filtered, so a capacitor (B) is used to filter this continuous wave composite. After this preconditioning, the signal passes through a voltage comparator (C) that transforms it into a binary signal, having a high value above the maximum pressure before the nozzle opening, in this way it is possible to determine the instant of injection of diesel with accuracy. The final stage of the circuit consists of a timer LM555 (D) configured as monostable which avoids the "bouncing effect" caused by the oscillations of the diesel line pressure signal, thus preventing loss of system timing or identification of false pulses by the microcontroller (E).

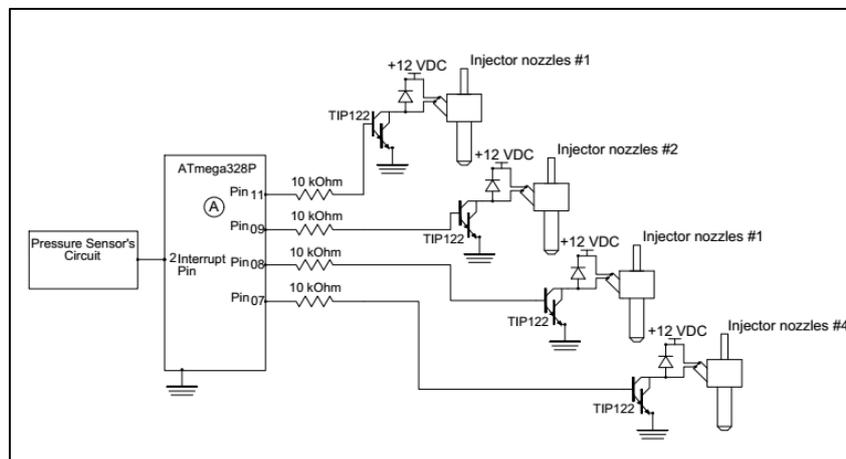


Figure 3. Power driver dedicated to electronic nozzles.

After detecting the synchronism pulse coming from the signal conditioning circuit of the diesel pressure sensor, the microcontroller (A), configured by the supervisory, sends the activation pulse of the ethanol injector nozzles that are installed in the diesel engine intake manifold, as the microcontroller ports do not have enough current a current driver (figure 3) that was made with TIP122 is required, antiparallel diodes were installed in the nozzle terminals to avoid the effect of the reverse current generated by the coil. The ethanol line feeding the injector flute is pressurized to 3.0 bar by means of a Gauss® brand GI3103-F fuel pump, inside the ethanol tank contains a heat exchanger with the function of maintaining its temperature stable.

The other embedded subsystem is composed of an ATmega2560P microcontroller, two serial ports (RS-232) are used for communication with the digital scales that measure the fuel consumption of commercial diesel and ethanol, a digital interruption port for measurement of the motor shaft rotation and a TTL to RS-485 communication converter driver

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responsible for communication between this system and the main supervisory program. The diagram in Fig. 4 shows the flowchart of this embedded system.

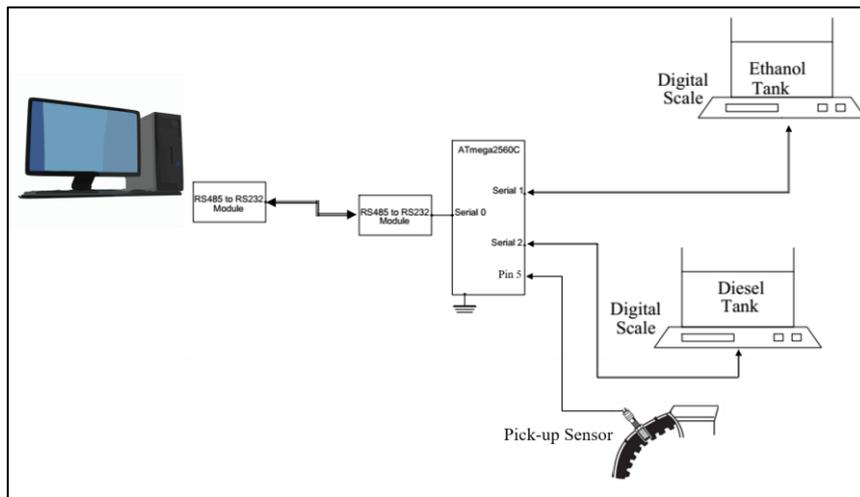


Figure 4. Flowchart of the communication of the scales and rotation meter with the supervisor.

2.2 Injection system supervisory management

The supervisory program has been developed using the software Wonderware InduSoft® Web Studio V8.0 educational version, the supervisory in addition to measuring the consumption of diesel fuel and ethanol by the gravimetric method it is possible to still change the parameters of ethanol injection, for example the instant initial injection, which may be in the admission, compression, explosion or escape phase. Another important parameter is the amount of ethanol injected and the injection strategy adopted, being able to be monopoint per cycle or multipoint per cycle, that is, the operator can inject once in the intake duct per cycle per camera or several times in the duct during the period of the Diesel pulse. Fig. 5a shows the main monitor screen and Fig. 5b shows the configuration screen of the ethanol injection by the four electro-nozzles.

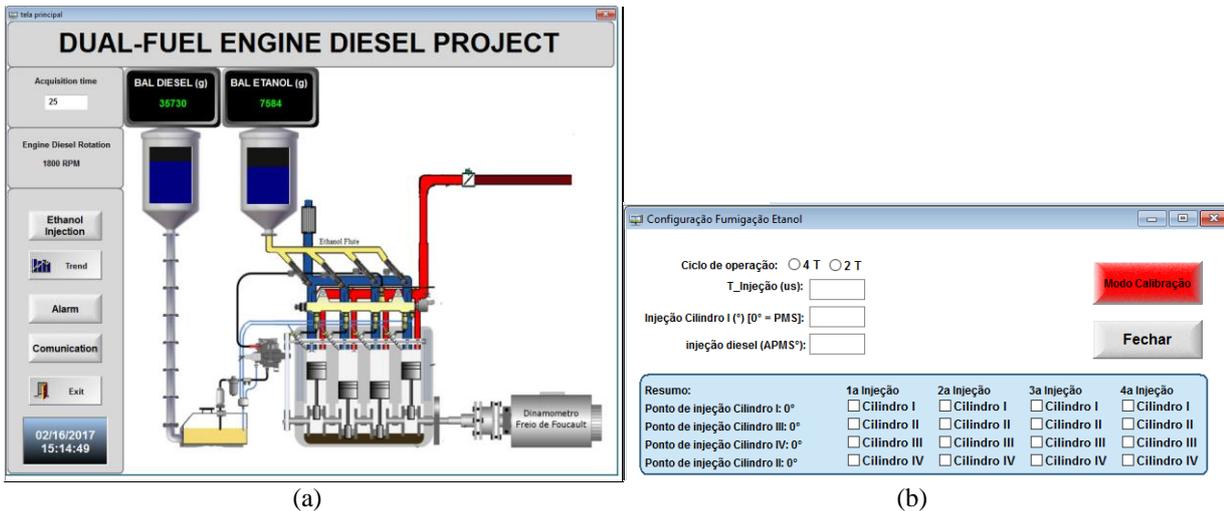


Figure 5. (a) Supervisory of the system developed for the management of ethanol and (b) detail of the configuration screen of the ethanol injection.

2.3 Test bench for motor and fuels used

2.3.1 Dynamometric test bench

The experimental evaluations of the multipoint ethanol injection system were performed on a dynamometric bench composed by a 4 cylinder diesel cycle engine, manufactured by MWM of Brazil of direct injection and maximum power

of 76 CV coupled to a dynamometer of the type Foucault brake with maximum braking power of 400 hp, a cardan shaft of automobile use was used to couple both parts. The detailed characteristics of the motor and dynamometer are described in Tab. 1 and Tab. 2.

Table 1. Engine Features Used.

Feature	Engine
Maximum power (kW)	54 (NBR-1585)
Rotation (rpm)	900-2600
Compression ratio	17,0:1
Number of Cylinders	4
Injection	Direct mechanical
Injection pressure (MPa)	23
Displacement (L)	3,922
Type of building	four Time
Ignition order	1-3-4-2

Table 2. Dynamometer Feature.

Feature	Dynamometer
Type	Foucault break
Maximum power (CV)	400
Maximum rotation (rpm)	4.500
Rotation and torque control	By dedicated software

The system assembly diagram is shown in figure 5, with the positioning of the diesel oil pressure sensor in the high-pressure line of the injection pump, as well as the two temperature sensors used to investigate the reduction of the air temperature of admission. An electric injection pump and a pressure regulator adjusted to 0.25MPa were used for the ethanol feed. A Bourdon gauge measured this pressure during the tests.

2.3.2 Fuels used

Class S-10 commercial diesel (D92B8) and the hydrous ethanol (95% of purity) was purchased from Petrobras's local supply station in the city of Cruz das Almas-BA. Tab. 3 shows the main characteristics of the raw materials used for fuel composition.

Table 3. Some properties of the raw materials for fuels.

Properties	Commercial Diesel	Ethanol
Chemical formula	$C_{9,84}H_{17,95}$	C_2H_6O
Molecular weight (kg.kmol ⁻¹)	136.3	30.1
Density	0.853	0.790
Latent Heat of Vaporization (kJ.kg ⁻¹)	270	840
Cetane number	48	6
Lower Calorific Power (kJ.kg ⁻¹)	42820	28300

Four different combinations of fuels were tested for each load applied to the motor shaft. The tests were started with commercial diesel fuel without the addition of ethanol via fumigation and then 3 ethanol-containing compositions (D92B8E10, D92B8E15, D92B8E20) added by the engine inlet pipe were tested by time and time of the four injector injectors.

The calculation of the energy fraction replaced by ethanol (PI), as described in Lu et al. (2008), for each fuel combination was determined applying eq. (1).

$$PI(\%) = \left(\frac{m_e \cdot LHV_e}{m_e \cdot LHV_e + m_{d_b} \cdot LHV_{d_b}} \right) \cdot 100 \quad (1)$$

Where:

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m_e is the mass of ethanol injected during each cycle, in kg;
 $m_{d,b}$ is the mass of the binary mixture consumed in each cycle, in kg;
 LHV_e is the lower calorific value of ethanol;
 $LHV_{d,b}$ is the lower calorific value of commercial diesel.

2.4 Test methodology

The system validation was performed on a diesel engine (Maxxforce 229.4 MWM®) coupled to a dynamometer responsible for controlling torque in the engine. The experimental schedule is presented in Tab. 4.

The following methodology was adopted during the tests: initially the motor was powered up at low speed and without load, after that, the speed and load were adjusted to a given target point, the tests were started only when the exhaust gas temperature reached its nominal value, 160 °C for 60 Nm of load and 215 °C for 120 Nm of load. For each ethanol injection cycle, the torque gain was evaluated for 5 minutes, then the diesel injection was decreased to reaches the target load (60 Nm or 120 Nm), for exhaust gas temperature stabilization, before start measuring, the operator should wait for 10 minutes.

Table 4. - Test cycles of the ethanol injection system.

Speed [RPM]	Load target[Nm]	Energy fractions [%]		
1800	60	7.3	13.2	19.9
1800	120	9.2	15.5	21.9

In all test cycles was recorded diesel and ethanol 95% consumption, the temperatures for the diesel, ethanol, for the intake air and the ambient air, as well as torque and motor speed. The power on axis, the specific consumption, the thermal efficiency and ethanol fraction for each fuel were computed.

3. RESULTS AND DISCUSSION

The following are the results of the performance of the embedded electronic injection system, fuel consumption of the intake air temperature reduction, specific fuel consumption, torque gain, energy efficiency. The uncertainties of the following measurements were evaluated for a maximum error of 5%.

3.1 Evaluation of the ethanol injection electronic system

The ethanol injections were programmed to inject at 23°C after the injection of the diesel in the combustion chamber, this instant represents the top dead center of the piston, the first test was between the pulse of diesel emitted by the pressure sensor 3PP6-12 and the digital activation pulse of the electro-injectors control, the calibration procedure of the pressure sensor and its response curve can be seen in (Pinheiro et al, 2014). Fig. 6 (a) shows the pressure pulse (in black) generated by the sensor in the diesel high pressure line and the synchronization pulse (in red) of the embedded system. Fig. 6 (b) shows the digital activation signal of the injector nozzle control routine and the negative pulse needed to actuate the nozzle.

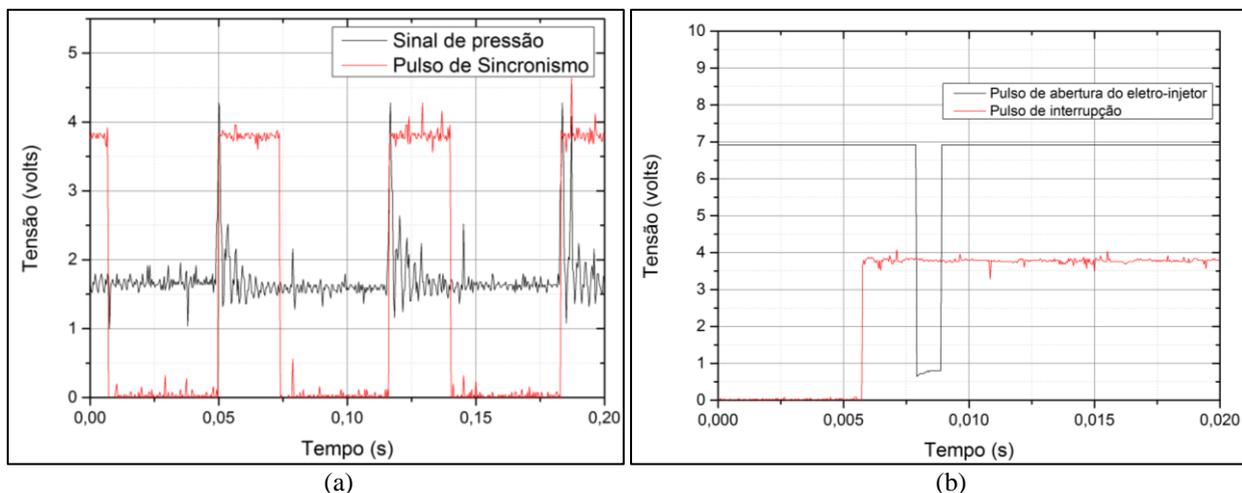


Figure 6. (a) Diesel pressure pulse and synchronism pulse. (b) Interruption pulse and active nozzle pulse.

An average of three data collections were performed on both the diesel pressure signal pair and the synchronizing pulse as well as the synchronizing signal and the energizing pulse of the injector nozzle. The maximum delays generated by the system were also measured. The controller behaved as expected having a delay of $10 \pm 2 \mu\text{s}$ between the diesel pressure pulse and the digital synchronizing pulse, relative to the synchronizing pulse and the start of the opening pulse of the injector nozzle the measured delay was around $250 \pm 25 \mu\text{s}$, which represents an error of 2.6°CA . Finally, for the active injection time, the maximum error was $15 \pm 5 \mu\text{s}$. It is important to note that at no time was observed a loss of synchronism pulse of the system, or the non-activation of the injector nozzle system, which gives the electronic system enough robustness for the final application.

3.2 Evaluation of engine performance due to ethanol injection

The evaluation of the performance of the engine due to the injection of ethanol through fumigation occurred by the analysis of observed torque gain, power gain, specific fuel consumption and thermal efficiency. Figure 7 and Table 5 present the results obtained for the torque of 60 Nm in the rotation of 1800 RPM. There were no significant gains in the mechanical performance of the engine; there was practically no change in engine power, with an average gain of 4% under the conditions of higher ethanol injection (from 15% to 20% of substitution). The measured torque. The temperature variation before and after the injection was 5°C in the condition of 20% replacement. The thermal efficiency of the engine, calculated by equation 2, was lower with the low torque than with the high torque, comparing similar levels of substituted ethanol, see Fig. 7 and Fig. 8. At low torque, the motor cannot have a higher conversion rate of potential fuel energy even with the addition of ethanol.

$$\eta = \frac{P_{eixo}}{LHV_d * Consumo_d + LHV_{et} * Consumo_{et}} * 100 \quad (2)$$

Where: P_{eixo} the output power calculated on the motor axis in kW, LHV_d the lower calorific value of commercial diesel in kJ/Kg, LHV_{et} the lower calorific value of ethanol 95% in kJ/Kg, $Consumo_d$ e $Consumo_{et}$ consumption of diesel fuel and ethanol in Kg/s.

Other researchers observe these results as Zang (2010) who conducted an experiment with fumigated alcohol injection in the proportions of 10%, 20% and 30% of substitution and reported that for low loads there is a decrease in the thermal efficiency of the machine. One of the explanations for this fact is that in this situation, the alcohol is not suitably mixed into the intake air, either by the engine low temperature or by low airflow. In Abu-Qudais et al. (2000), Heisey et al. (1981) similar results are also reported.

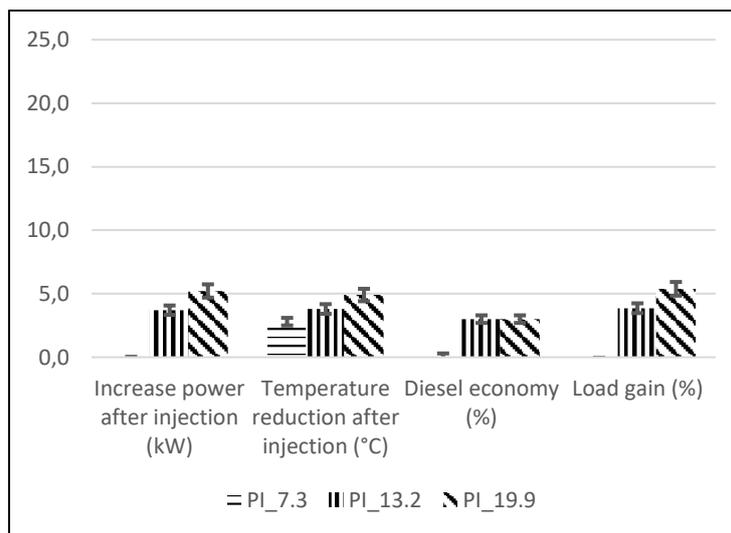


Figure 7. Result of Torque Gain, Economy of Diesel and Temperatures in 60Nm.

Table 5. Mechanical performance rating of the engine for 60Nm.

Fraction ethanol fuel (%)		Specific consumption (g/kWh)		Thermal efficiency (%)	
PI_0	0	BSFC_0	267.5	ET_0	30.8
PI_7.3	7.3	BSFC_7.3	300.2	ET_9.2	29.1
PI_13.2	13.2	BSFC_13.2	324.0	ET_15.5	28.1

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PI_19.9	19.9	BSFC_19.9	337.3	ET_21.9	25.9
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The results obtained for the diesel engine in rotation of 1800RPM and 120Nm load are shown in Fig. 8 and Tab. 5. As found in the literature, the higher the load the smaller the specific fuel consumption, improving its thermal conversion efficiency.

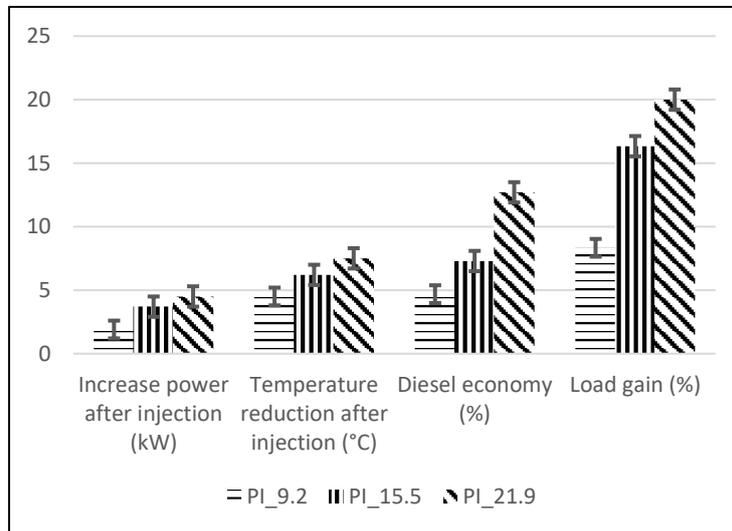


Figure 8. Result of Torque Gain, Economy of Diesel and Temperatures in 120Nm.

Table 5. Mechanical performance rating of the engine for 120Nm.

Fraction ethanol fuel (%)		Specific consumption (g/kWh)		Thermal efficiency (%)	
PI_0	0	BSFC_0	190.6	ET_0	40.3
PI_9.2	9.2	BSFC_9.2	210.4	ET_9.2	40.0
PI_15.5	15.5	BSFC_15.5	227.1	ET_15.5	39.5
PI_21.9	21.9	BSFC_21.9	239.0	ET_21.9	38.8

Comparing the results of Tables 4 and 5, it is evident that the specific fuel consumption increases with the increase of the ethanol content for both the 60Nm and the 120Nm loads. The explanation for this fact is that in order to maintain the same output power, it is necessary to increase the amount of ethanol injected, since it may have a lower calorific value, so the total fuel consumption tends to be higher than that provided without the addition of ethanol. The experiments indicate this same trend as found in Ajav E. A, et al (1998), Janousek (2010) and Cheung C. S, et al (2008).

4. CONCLUSIONS

The controller was implemented with minimal motor adaptations. The dedicated microcontroller for ethanol injections enables configuring the system in different controls strategies (mono-point or multi-point). The use of a second microcontroller for communication with the supervisor system prevents main controller overload. The results showed reduction in the intake air temperature in all tests and in the exhaustion for mid loads. For all loads there was an increase in the specific consumption and a decrease in the thermal efficiency of the tested machine with the increase of the energy fraction of ethanol, but for the load of 120 Nm the rate of variation was the smallest. Although not presented in this paper, several authors also cite the importance of using ethanol in diesel engines as a valuable alternative to reduce Nitrogen Oxides (NOx) emissions when using biodiesel, even in low concentrations, as fuel in the ignition engines by compression.

5. ACKNOWLEDGEMENTS

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