# MULTIPOINT ELECTRONIC SYSTEM FOR ETHANOL INJECTION IN DIESEL ENGINES

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***Abstract.*** *This work shows a multipoint electronic management system equipped with two microcontrollers for ethanol injection by the air intake pipe of a diesel engine until 4 cylinders. The system was developed especially for the injection timing by monitoring the high pressure injection line of diesel oil. The temperature reduction provided by the ethanol vaporization was measured by two NTC sensors. The system also allows data transmission and remote parameterization of injection in real time via the PC serial port. A security protocol was used to adjust the moment and duration of the injection. The system was tested on a generator with mechanical indirect injection in 1750, 1800 and 1850 rpm in order to determine the frequency of injection, start of injection delays as well as the change in intake air temperature with ethanol injection. It was used an optical sensor to determine the engine top dead center. The maximum start of injection delay was less than 850 µs. It was found considerable reduction of the intake air temperature, especially at low speeds, indicating that ethanol can reduce the combustion temperature and thus contributing to NOx reduction in exhaust gas of diesel engines.*

***Keywords:*** *Diesel Engines, ethanol, electronic injection.*

## 1. INTRODUCTION

Interest in renewable energy has grown considerably in recent years primarily driven by factors such as the imminent exhaustion of natural reserves of fossil fuels, vulnerability in the supply of such concentrated energy sources in countries with economic and political instability and the increasingly stringent emissions regulations on combustion processes. Biodiesel fuel generates virtually no sulfur residues and has lower emissions of other pollutants due to the presence of the oxygen in its molecules (Sales, *et al.*, 2006); (Lin, *et al.*, 2007); (Hribernik *et al.*, 2007). However, biodiesel use leads to a consistent increase in the emissions of nitrogen oxides (NOx) (Sandum *et al.*, 2005). This can be an obstacle to the future growth of the market for biodiesel production and its application in engines. The modification of injection parameters and the addition of oxygenated compounds with high latent heat of vaporization are the generally proposed solutions to this problem.

The possibility of adding oxygenated compounds such as ethanol motivates the study of such compounds in Diesel engines. Ethanol can be produced from biomass, especially on a large scale in countries with a high agricultural potential, such as Brazil. Originally intended as an alternative for spark ignition engines, ethanol can be used in compression ignition engines, increasing the percentage of biofuel in the blend and improving the gas emissions profile when compared to petroleum diesel (Montero and Stoytchevap, 2011).

The use of ethanol in a Diesel engine is justifiable, however, it requires some dedicated solutions. The most common ways to introduce ethanol are through the use of ternary blends of diesel, biodiesel and ethanol and ethanol fumigation in the intake air. According to Ribeiro *et al.* (2007), oxygenated additives have been used to reduce the ignition temperature. However, the reduction of particulate emissions through the introduction of oxygenates depends on the molecular structure and oxygen content in the fuel. To reduce particulate emissions, the oxygenates can be added to Diesel fuel to produce a compound containing 10 to 25% oxygen by volume, which, however, will directly affect properties such as density, viscosity, volatility behavior at low temperatures, and the cetane number, however, this requires a limited amount of anhydrous ethanol (max. 10% v/v) due to its poor miscibility with diesel, unless solubility additives are used (Guariero *et al*., 2009).

In the fumigation technique, the ethanol is sprayed by an injector into the engine air pipe, at the intake stroke. The effect of the ethanol injection into the engine air intake has been studied with various energy fractions of ethanol and several equivalence ratios of fuel/air mixture. The results have shown a substantial reduction in NOx emissions by injecting ethanol, however, with an increase in total unburned hydrocarbons (THC) and carbon monoxide (CO) emissions Lu *et al*. (2008).

This paper describes the design, construction and testing of an electronic management system for ethanol injection in diesel engines using the fumigation technique in order to increase the percentage of renewable fuel in the mixture and to reduce NOx emissions by reducing the combustion temperature. The timing of the injection moment was obtained by monitoring the diesel injection pressure, simplifying the adaptation of such a system in diesel engines with mechanical injection.

## 2. MATERIALS AND METHODS

### 2.1. Electronic Instrumentation of the Testing Workbench

The electronic system allows the injection of ethanol in the air intake pipe in the speed range between 1700 and 1910 rpm. Synchrony detection was done by monitoring the injection pressure from the diesel injection line. The process flow of the management system is shown in Figure 1.

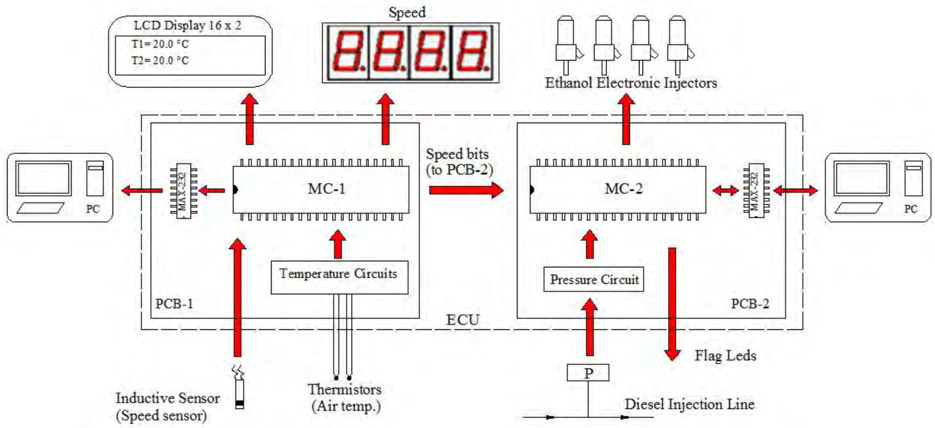


Figure 1. Lay-out of electronic management system.

The electronic central unit (ECU) has two printed circuit boards (PCB), each one controlled by their respective microcontroller. PIC microcontrollers manufactured by Microchip®, model 18F4520, with maximum frequency of 40 MHz, equipped with 4 modules counter/timers, 13 analog inputs with 10-bit digital resolution, serial communication, and two levels of priority for internal and external interruptions were used.

The first printed circuit board (PCB-1) is responsible for measuring the engine speed, the sampling of this value on a seven-segment display of four digits, the measurement of the inlet air temperatures before and after ethanol injection and the indication of these values on an alphanumeric LCD display, as well as the transmission of measured data through the serial port of a personal computer (PC).

The second printed circuit board (PCB-2) is responsible for detecting the pulse from the diesel injection line and for determining the timing and duration required for the ethanol injection at the beginning of the engine intake stroke. For this, the engine speed is transmitted by an internal protocol from the PCB-1 responsible for this measurement.

Quartz crystals were used to generate a clock of 20.0 MHz for the microcontrollers. As shown in Figure 1, an inductive sensor sends pulses to the timer-1 (first bit of port C), in pin 15 of the microcontroller, which can be configured to operate as a counter or timer. In this work, this bit was set to count external pulses of 16 bits and to generate a signal (flag) for each signal sent by the inductive sensor. The timer-0 was configured as 16-bit timer programmed to burst every 3 seconds. Thus the PCB-1 microcontroller was programmed to have two interruption priority levels with the lowest priority reserved for the timer 1, responsible for counting events of speed sensor and the high priority for the timer 0, responsible for determining the sampling time.

The main program of the microcontroller was stopped every 3 seconds and the engine speed was calculated in rpm. The speed value was shown on a seven-segment display. In order to optimize the use of ports, a representation of each digit in the displays was adopted by scanning with a retention time of 2 micro-seconds. The seven bits of the port D (pins 19, 20, 21, 22, 27, 28, 29) were used as data bits of each digit. The switching of each digit was made by four transistors connected to bits 3, 4, 5 and 6 of port A (pins 5, 6, 7 and 8 of the microcontroller).

The amount of speed between 1700 and 1910 was discretized at regular intervals of 30 rpm and converted into an internal protocol for communication between two microcontrollers by bits 1, 2, 3 of port C (pins 16, 17 and 18) and then, brought up to the second printed circuit board (PCB-2). Table 1 shows the internal communication protocol below.

Table 1. Internal communication protocol for engine speed.

| Speed range | Portc.rc1 | Portc.rc2 | Portc.rc3 |
|---|---|---|---|
| rpm < 1700 or rpm ≥ 1910 | 0 | 0 | 0 |
| 1700 ≤ rpm < 1730 | 0 | 0 | 1 |
| 1730 ≤ rpm < 1760 | 0 | 1 | 0 |
| 1760 ≤ rpm < 1790 | 0 | 1 | 1 |
| 1790 ≤ rpm < 1820 | 1 | 0 | 0 |
| 1820 ≤ rpm < 1850 | 1 | 0 | 1 |
| 1850 ≤ rpm < 1880 | 1 | 1 | 0 |
| 1800 ≤ rpm < 1910 | 1 | 1 | 1 |

The first three bits of port A of the microcontroller (pins 2, 3 and 4) were used as analog inputs for temperature signals from the intake air (at the points of pre-injection and post-injection of ethanol) and the exhaust gas. These values were shown in an alphanumeric LCD display. The 8 bits of the port B (pins 33-40) were used to send the temperature data to the LCD display. In addition, the speed and temperatures values were sent to a microcomputer by a serial port through a buffer MAX-232. Figure 2 shows the details of the circuit developed for measuring the intake air temperatures, using NTC thermistors.

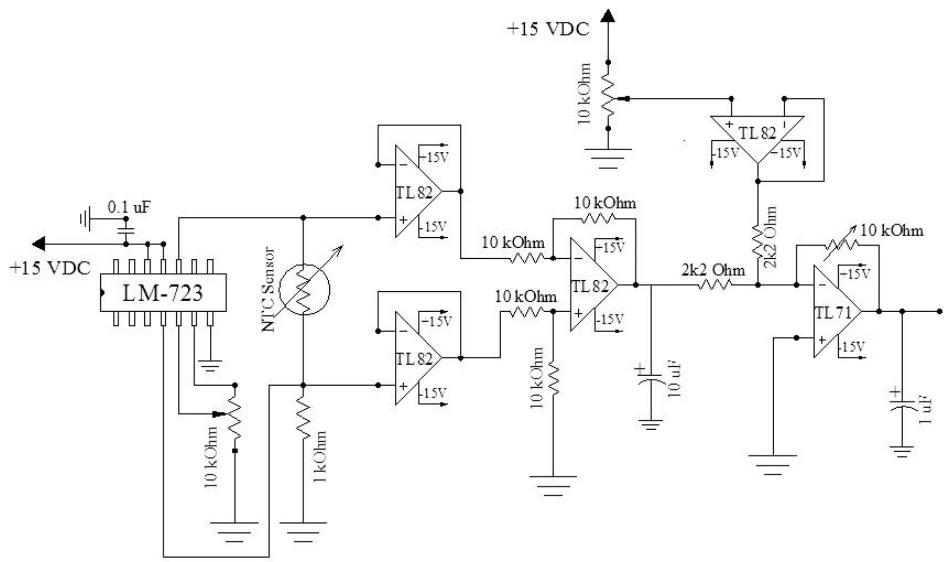


Figure 2. Details of the measurement circuit of the intake air temperatures in PCB-1.

It was necessary to build an electronic circuit that generates a constant low current (0.9 mA) in order not to induce undesirable effects of self-heating in the sensor. The circuit implemented and shown in Figure 2 is based on the LM-723 precision regulator mounted on a setting of constant current source. This constant current is applied to the series circuit made up of a fixed resistor (1.0 kΩ) and the sensor. The reference voltage of 0.9 V was adjusted in the multi-turn potentiometer (10 kOhm) in order to obtain a current of 0.9 mA, which also crosses the thermoresistive sensor. Then the voltage at the sensor terminals is insulated with a buffer stage and then it continues to a subtractor and inverter stage (third operational amplifier).

In order to maximize the circuit sensitivity in the temperature range, this output signal of this stage is then added to a positive voltage level which is properly buffered. Then an inverting amplification is performed with a gain in ratio of 2.72:1. Capacitive filters were used throughout the circuit in order to increase the noise immunity of the signal. Thus, it was possible to measure the temperatures with a sensitivity of up to 0.12 V/°C in the range of 15 to 30 °C.

At each interruption signal caused by the diesel pressure pulse, the microcontroller PCB-2 checks the engine speed, properly discretized (see Table 1) and available in bits 0, 1 and 2 of port A (pins 2, 3, and 4). Then the microcontroller determines a delay at the beginning of the injection, depending on the speed value. After that, it activates 4-bit of port C (pin 18), thereby polarizing the transistor that will trigger the electronic injectors by a configurable time. A reverse-polarized diode was used between the supply voltage (+12 VDC) and the transistor collector in order to protect it from over-current. Through a PC, a digital word with a security protocol is sent with the two most important parameters of ethanol injection. These are the delay related to the top dead center at the beginning of the engine intake stroke and the injection duration, both evaluated in microseconds.

This second print circuit board (PCB-2) also has two flag leds, one of them (green LED) is the indicator of the system operation status being commanded by port C bit 1 (pin 16) and the other (red LED) is the indicator of instability in the engine speed controlled by bit 2 of port C (pin 17). If the 3 input bits of rotation assessment (pins 2, 3 and 4) are simultaneously at a low level (see Table 1), the program will assume that the engine speed is out of the injection range (1700-1910 rpm) and will interrupt the ethanol supply to the engine.

PCB-2 also has a conditioning circuit for the pressure signal sent from diesel injection line in order to be a rectangular signal and therefore to interrupt the microcontroller in PCB-2. Figure 3 shows this circuit implemented in PCB-2.

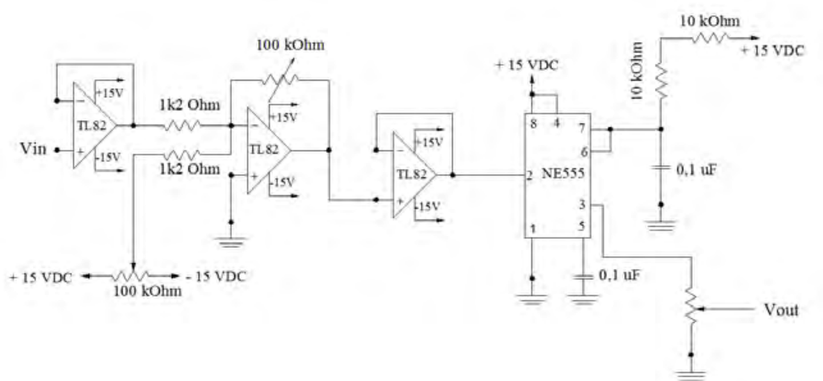


Figure 3. Signal conditioning circuit for diesel injection pulses.

The oil pressure pulses already properly adjusted to a rectangular wave shape are introduced in bit 0 of port C of the PCB-2 microcontroller (pin 15) which is the input for the timer-1, properly configured to operate as a 16-bit counter and to generate a signal (flag) of each oil pressure pulse. This microcontroller is configured again to operate with two levels of interruption priority with the lowest priority level reserved for the timer-1 and the highest priority interruption reserved for serial communication.

All circuits were conditioned in a plastic case. Figure 4 shows the front and back views of this case.


(a) (b)

Figure 4. Front (a) and back (b) views of ECU case.

### 2.2. Sensors and Calibration

#### 2.2.1. Engine Speed Sensor

For the speed engine measurement an inductive sensor model LM-12-3004-PA was used, manufactured by JNG sensors®. This sensor has a supply voltage of 12 VDC and digital output, with sensitive distance of 4 mm. The sensor was mounted at the engine base in an orthogonal position to the coupling, where two metallic diametrically opposed plates were fixed. The implemented tachometer was calibrated in order to verify the indication errors. For this a photo-reflexive portable digital tachometer was used, model TC-5035, manufactured by ICEL®, with digital resolution of 0.1 rpm. The calibration in the range between 1400 and 1700 rpm occurred at regular intervals of 100 rpm, while in the range 1700 to 1950 rpm, it occurred at regular intervals of 50 rpm. Table 2 shows the results obtained.

Table 2. Tachometer calibration results.

| Speed (rpm) | Indicated value (rpm) | Standard value (rpm) | Percentage Error (%) |
|---|---|---|---|
| 1400 | 1400 | 1401.7 ± 0.5 | 0.12 |
| 1500 | 1500 | 1495.0 ± 0.5 | 0.33 |
| 1600 | 1600 | 1598.2 ± 0.5 | 0.11 |
| 1700 | 1700 | 1698.4 ± 0.5 | 0.09 |
| 1750 | 1750 | 1750.0 ± 0.5 | 0.00 |
| 1800 | 1800 | 1805.2 ± 0.5 | 0.28 |
| 1850 | 1850 | 1850.2 ± 0.5 | 0.01 |
| 1900 | 1900 | 1902.0 ± 0.5 | 0.11 |
| 1950 | 1950 | 1953.0 ± 0.5 | 0.15 |

As seen in Table 2, the tachometer maximum relative error was 0.33%, occurring at 1500 rpm, thus making the use of correction factors for rotation evaluation unnecessary during the ethanol injection because the tests occurred at such a frequency that the intake engine cycle was sufficiently long, thus avoiding any synchrony problem.

### 2.2.2. Diesel Injection Pressure Sensor

For the monitoring of the diesel oil pressure in the line of the injection pump, a low-cost pressure sensor was used, model 3PP6-12, Mobil line, manufactured by Ideal Sensors®. This sensor has a measurement range of 0 to 30 MPa, with a supply voltage of 5.0 VDC and output voltage proportional to the pressure in the range 0.5 to 4.5 VDC. This sensor was statically calibrated with the use of nitrogen between 0 and 30MPa, at regular intervals of 5 MPa. A Bourdon pressure gauge with an accuracy of 1% was used as the standard system. The results are shown in Figure 5, with a proper calibration line.

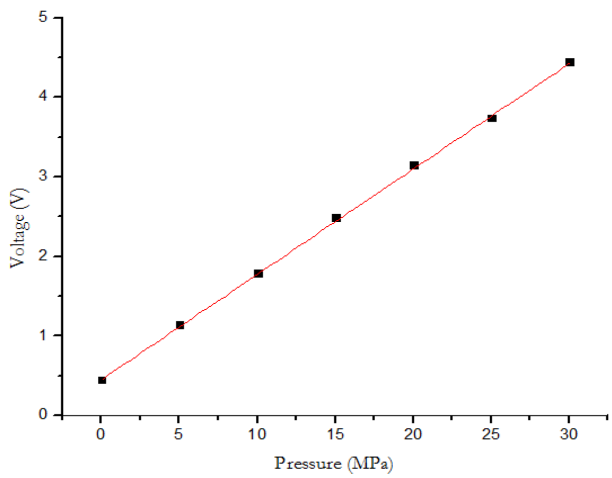


Figure 5. Diesel pressure sensor calibration.

As seen in Figure 8, the pressure sensor presents a linear relationship between output voltage and the measured pressure. It was possible to obtain the described ratio between the output voltage in Volts and the pressure in MPa, as described in eq. (1) with a correlation factor ($R^2$) of 0.9985.

$$Voltage\,(V) = 0.1324.P(MPa) + 0.4818 \quad (1)$$

The input signal from the diesel pump pressure sensor has a continuous voltage level of approximately 0.5 volts and a peak voltage of about 2.25 V, as shown in Figure 6. The waveforms presented below were collected by a digital oscilloscope, model 1062C, manufactured by Rigol ®.

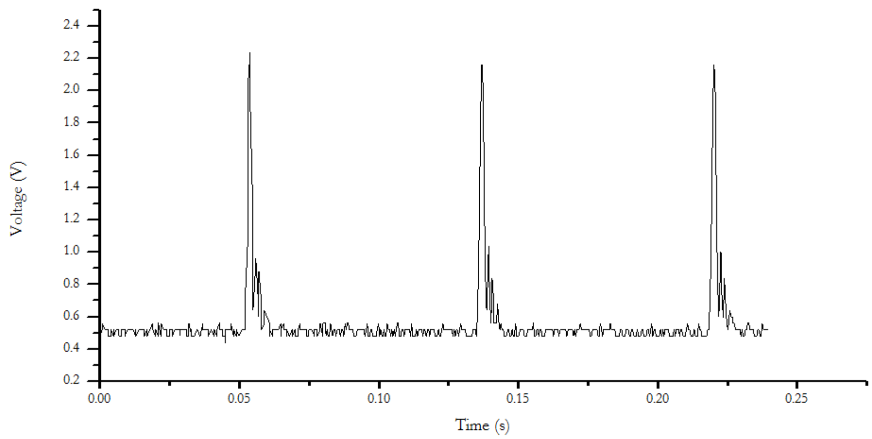


Figure 6. Signal of diesel injection pressure sensor.

As described in the electronic circuit in Figure 3, this input signal was properly insulated by a buffer stage, then the signal has a level reduction of 0.5 V and after that an amplification and inversion stage is carried out. Thus the signal at the output of the second operational amplifier is as shown in Figure 7. The signal at this point presents a level of approximately 14.0 V and at the time of injection the signal decreases to approximately 0 V.

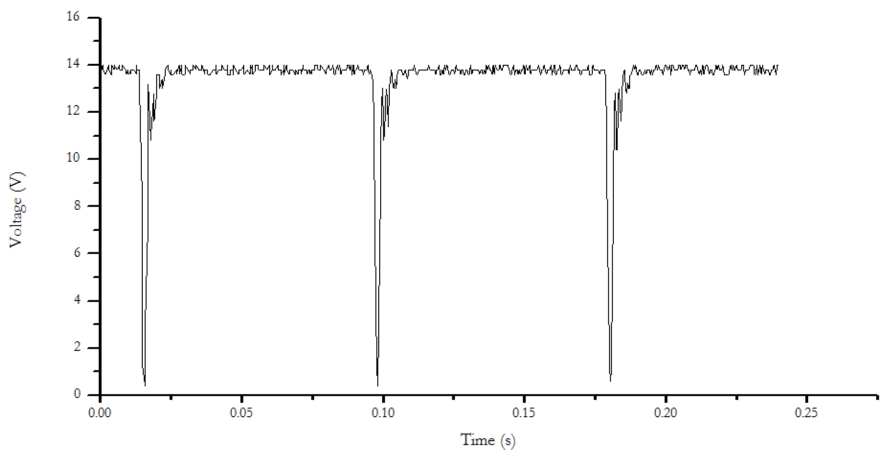


Figure 7. Pressure signal after inverting and amplifier second stage.

These output pulses from the second amplifier are again isolated (buffered) with a voltage follower stage, and then introduced into the input pin of the NE-555 timer integrated circuit, implemented in a monostable configuration oscillator (see Figure 3). In this configuration, the NE-555 timer can be triggered when the signal input (pin 2) decreases to 0 V. The active cycle time was determined by an association of two 10 kOhm resistors mounted in series with a ceramic capacitor of 0.1 µF (see Figure 3). Thus, the active cycle time was set to 2.0 ms. As the IC NE 555 was fed with a voltage of 15 VDC, the output signal is reduced by a multi-turn potentiometer and adjusted for maximum 5.0 VDC, in order to be detected as logic high ("1") by PIC 18F-4520 microcontroller. After being conditioned for diesel injection pump pressure, the input and output signals are shown simultaneously in Figure 8.

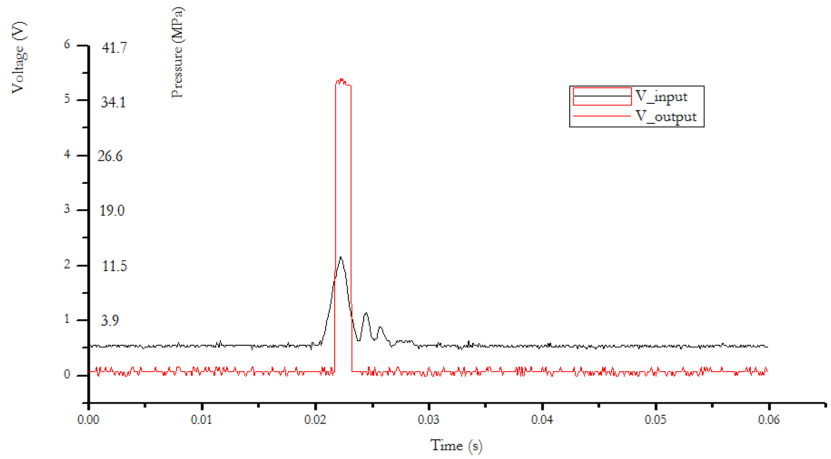


Figure 8. Comparation between input and output signals of the pressure circuit.

As shown in Figure 8, the output voltage of the pressure sensor provides an output voltage of approximately 2.25 V, at the instant peak pressure, which according to equation (1), corresponds to an injection pressure of approximately 13.4 MPa. It is possible to note that the rising edge of the output signal occurs with a certain delay, compared to the input signal. This delay was less than 500μs in the tests.

### 2.2.3. Intake Air and Exhaust Gas Temperature Measurement

For the intake air temperature measurement, two NTC thermistors were used, provided by Digikey, model AL03006-1248-73-G1 with a nominal resistance of 2.0 kOhms to 25 °C. The sensors have a glass cover and are cylindrical shape with a diameter of 1.6 mm and a length of 4.0 mm.

The calibration curve of the thermistors was obtained within a range of 5.0 °C to 80.0 °C in a thermostatic bath. A digital thermometer model Penta Five manufactured by Full Gauge with a resolution of 0.1 °C was used as a standard thermometer. The results for the thermistor-1 calibration and its fitted curve are shown in Figure 9.

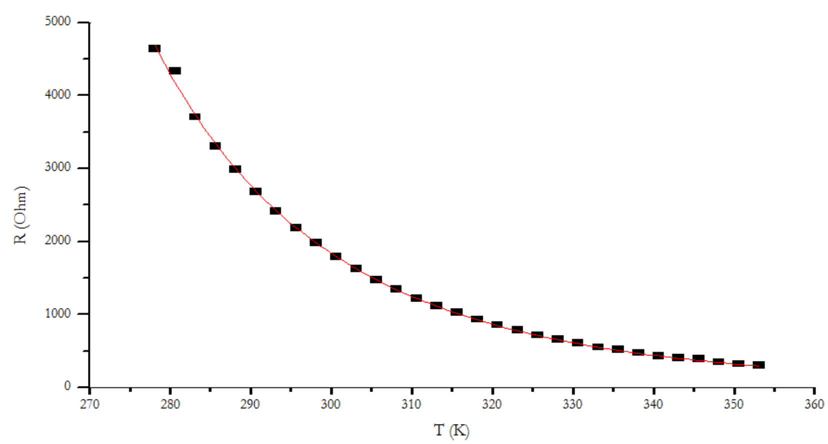


Figure 9. Resistance x Temperature curve for thermistor-1.

The traditional relationship between resistance and temperature, shaped in a decaying exponential function [11] was used to find the fitted curve for thermistor-1, since the temperature range in this paper is less than 30 °C. Equation (2) can be obtained with a correlation factor ($R^2$) from 0.9993.

$$R(Ohm) = 1999.e^{\left[-\frac{3542.5.(T-298)}{(T.298)}\right]} \tag{2}$$

The results for the thermistor-2 calibration, and its fitted curve are shown in Figure 10.

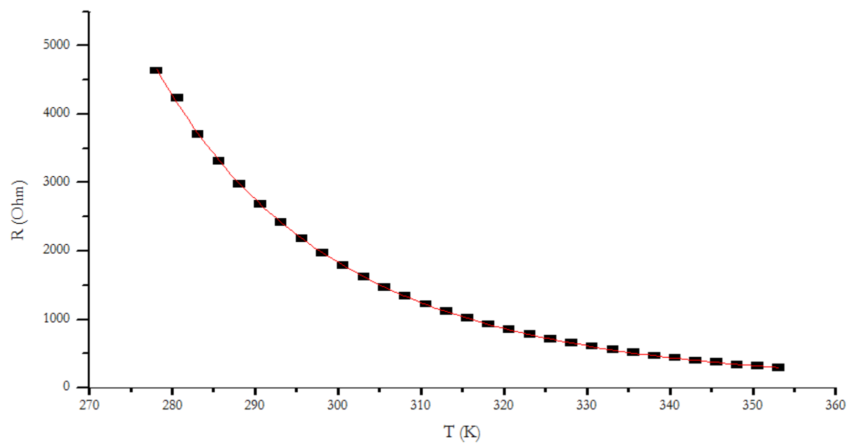


Figure 10. Resistance x Temperature curve for thermistor-2.

The adjusted curve for the thermistor-2 with a correlation factor ($R^2$) of 0.9994 is shown in Eq. (3).

$$R(Ohm) = 1998.e^{\left[\frac{3549.0.(T-298)}{(T.298)}\right]} \tag{3}$$

The relationship between the hot junction temperature and the output voltage of the amplifier used (AD595C) reported by the manufacturer in the range of 0 to 600 °C was used to determine the expression of converting the output voltage of the amplifier temperature with an accuracy of 1%, as described in Eq. (4).

$$Vout\ \ AD595\ (V) = 10.23.\,T\,(^{\circ}C) - 18.59 \tag{4}$$

### 2.2.4. Testing Engine and Assembly Details

The tests were conducted in a three-phase generator manufactured by Kohlbach®, powered by a single cylinder 4-stroke Diesel engine, manufactured by Agrale® with indirect injection and maximum power of 10 HP. The generator fed a panel of resistive loads. The engine and generator properties are described in Table (3) and (4), respectively.

Table 3. Engine Properties.

| Property | Engine |
|---|---|
| Maximum Power (kW) | 7.6 (NBR-1585) |
| Speed (rpm) | 1800-2500 |
| Number of cylinders | 1 |
| Injection type | Indirect |
| Injection Pressure (MPa) | 15 |
| Sweep volume ($cm^3$) | 567 |

Table 4. Electric Generator Properties.

| Property | Generator |
|---|---|
| Maximum Power (kVA) | 6.0 |
| Speed (rpm) | 1800 |
| Voltage | 3~/ 220V/ 60Hz |

The details of the diesel supply and the ethanol injection systems are shown in Figure 14. In order to check the injection delay, a reflective-type optical sensor was used, model 45FSL-2LHE, PNP type, manufactured by Allen Bradley®, with wavelength of 660 nm, response time of 30 μs and supply voltage of 12VDC. This sensor was fixed on the engine housing. A reflective tape was attached to the flywheel so that when the piston was at the top dead center, the tape was positioned in front of the optical sensor. In Figure 11 it is possible to see the positioning of the diesel pressure sensor in the supply line of the high pressure injection pump. For the ethanol feeding an electric injection pump and a pressure regulator adjusted to 0.25 MPa, were used. A Bourdon type gauge measured this pressure during the tests.

The advance angle of diesel injection, which corresponds to the crankshaft angle between the injection time, and the top dead center (TDC), was measured initially by a goniometer, and its value (26°23') stored in the program memory of the PCB-2 microcontroller.

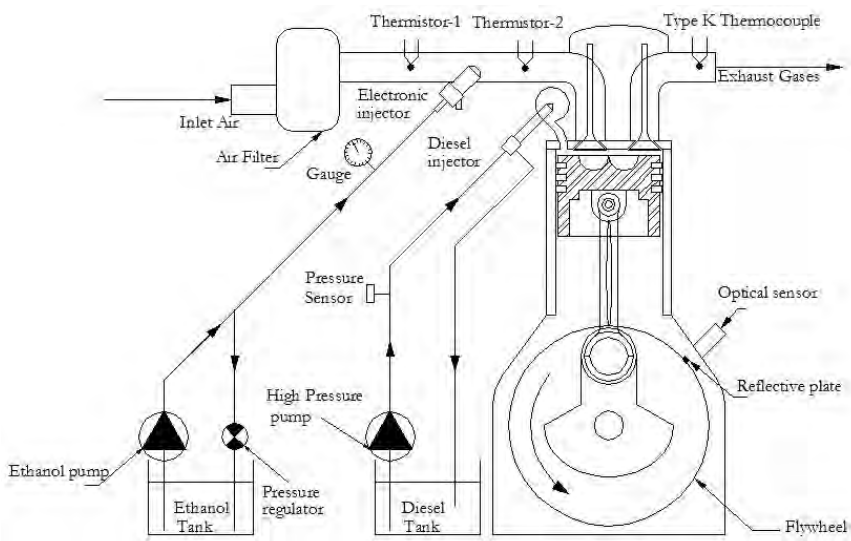


Figure 11. Details of dual fuel injection engine.

## 3. RESULTS

Initially, the system was tested in order to verify the synchrony of pressure pulses of the diesel injection pump and the ethanol injection delay in three different speeds: 1700, 1750 and 1850 rpm, given that the electric generator operates in a nominal speed of 1800 rpm. In all tests, the injection was programmed by a PC serial port to start exactly at TDC time with a fixed duration of 2.0 ms.

After that, the reduction in the temperature of the intake air and exhaust gases with a high content of ethanol were evaluated. In these tests the injection was scheduled to occur 5º after the top dead center. During the tests, the electric generator operated at a constant load of 1.6 kW. A low pressure eletronic injector manufactured by Honda®, KVB-T01 model, with a 12VDC supply voltage was used.

In the main tank of the engine a binary mixture (D70B30) composed of 70% v/v mineral diesel and 30% v/v soybean biodiesel was used. The ethyl alcohol used had a purity of 99.3%. The tests took place at an ambient temperature of 30 ± 2 ºC and relative humidity of 55 ± 2%.

### 3.1. Diesel Pressure Pulse Synchrony

The synchrony between the diesel pressure pulses in digital format and the top dead center (TDC) signal were verified. Figure 11 shows these results for an approximate speed of 1800 rpm.

As shown in Figure 12, the pulses of diesel oil pressure are shown in rectangular waveform and frequency which corresponds to half the frequency of the top dead center signal (TDC), which was expected for a 4-stroke engine. It is notable that the pressure event of diesel oil occurs in advance, compared to the TDC signal, considering that there is a diesel injection advance (26°23') which corresponds to approximately 2.0 ms, if the speed is 1800 rpm.

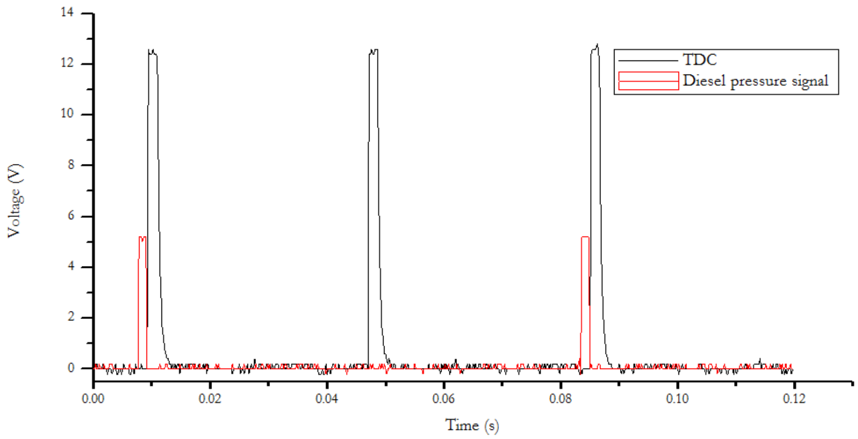


Figure 12. TDC signals and diesel pressure pulses in digital format.

**3.2. Injection Synchrony Tests**

The frequency and waveforms were evaluated for 1750, 1800 and 1850 rpm. Figure 13 shows the supply signal of the electronic injector and the TDC signal for these speeds.

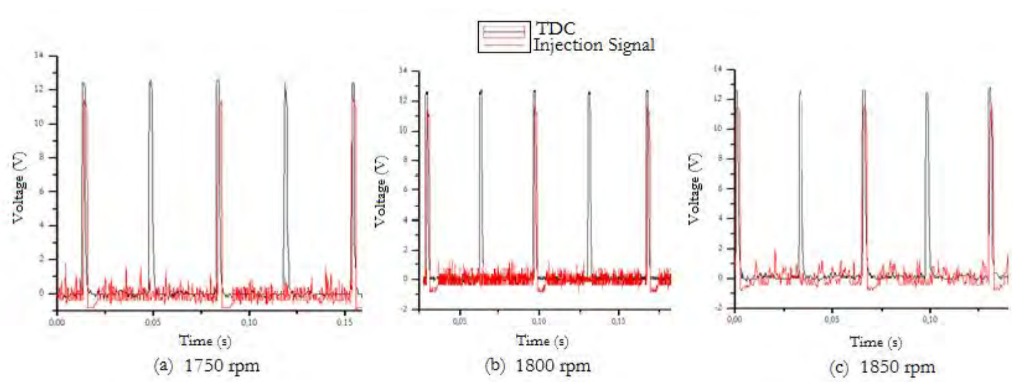


Figure 13. TDC and injection signals for 1750, 1800 and 1850 rpm.

As shown in Figure 13, the supply pulse of the ethanol injection is rectangular and the frequency corresponding to half the signal frequency of the top dead center. The signals are then sampled with a lower sampling time in order to measure their injection delays using a digital oscilloscope, model 1062C, manufactured by Rigol ®, as illustrated in Figure 14.

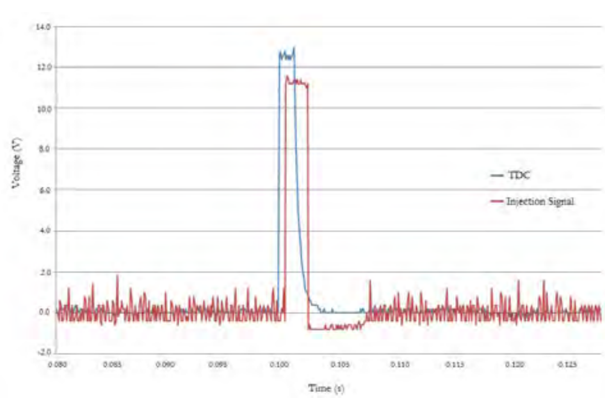


Figure 14. Delay measuring between TDC and electronic injection signals for 1800 rpm.

The results for the injection delays for three rotations were collected at 5 cycles and are shown in Table 5.

Table 5. Results for injection delay in 1750, 1800 and 1850 rpm.

| Cycles | Start of Injection Delay (μs) | | |
|---|---|---|---|
| | 1750 rpm | 1800 rpm | 1850 rpm |
| 1 | 800 | 700 | 400 |
| 2 | 900 | 650 | 450 |
| 3 | 800 | 750 | 500 |
| 4 | 900 | 700 | 400 |
| 5 | 800 | 700 | 400 |
| Average Value | 840 ± 152 | 700 ± 95 | 430 ± 120 |

### 3.3. **Results for Intake Air Temperatures**

The variation in combustion conditions was evaluated for increasing levels of ethanol. The variation in the ethanol content was obtained by increasing the duty cycle time of the electronic injector. Table 6 shows the volumetric proportions of ethanol for each composition tested as well as the corresponding active cycle time.

Table 6 –Injection Duration and Ethanol Volumetric Fraction.

| Fuel | Injection Duration (μs) | Ethanol Volumetric Fraction (%) |
|---|---|---|
| D70B30 | 0.0 | 0.0 |
| D70B30-E5 | 850 | 5.1 |
| D70B30-E9 | 1000 | 9.2 |
| D70B30-E15 | 1500 | 15.2 |

The intake air temperatures at the point of pre-and post-injection temperatures are shown in Table 7. As can be seen, the use of ethanol resulted in a significant reduction in the temperature of intake air caused by the high latent heat of ethanol (840 $kJ.kg^{-1}$) compared to mineral diesel fuel (270 $kJ.kg^{-1}$) and biodiesel (200$kJ.kg^{-1}$).

Table 7. Results for intake air temperatures.

| Fuel | Upstream Air Temperature (ºC) | Downstream Air Temperature (ºC) |
|---|---|---|
| D70B30 | 29.5 ± 0.2 | 29.5 ± 0.2 |
| D70B30-E5 | 29.5 ± 0.3 | 19.2 ± 0.3 |
| D70B30-E9 | 30.8 ± 0.2 | 15.0 ± 0.2 |
| D70B30-E15 | 30.7 ± 0.2 | 14.2 ± 0.2 |

## 4. CONCLUSIONS

Ethanol use can be a valuable alternative to reduce emission of nitrogen oxides (NOx) as well as reduce the use of fossil resources by decreasing the consumption of diesel fuel in Diesel engines.

This paper presented an electronic injection system that can be implemented with minimal changes in engine construction, considering that the detection of the synchrony of the oil pressure pulse means that the implementation of a specific sensor on the camshaft is not necessary.

The low cost pressure sensor was adequate in detecting the pulses of the diesel injection line, however, the measured pressure values differed slightly from the injection pressure values informed by the engine manufacturer. The circuit for conditioning this signal did not provide any significant delay (less than 500 μs).

The use of two microcontrollers provided greater flexibility in injection control because one of them is only for the detection function of the synchrony pulse and injection control, ensuring their use in real-time at even higher speeds.

The analog circuit for temperature measurement showed good sensitivity for investigating the influence of ethanol at the time of injection. The results for the air temperatures at the upstream and downstream points of the cooling air injection were up to 16.0 ºC. The high latent heat of vaporization of ethanol can justify this reduction, which can significantly change the characteristics of the combustion. Injection delays evaluated for 3 different speeds were within the expected value (less than 850 μs) which does not significantly affect operation, even in engines with higher revolutions.

The developed system may be adapted for other stationary engines with few adaptations. However, all the sensors used must be carefully considered in each case because modern Diesel engines are faster and they present higher injection pressures than the engine studied here.

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