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CONVERSION OF A DIESEL ENGINE TO OPERATE WITH HCCI OF WET ETHANOL IN ONE OF THE CYLINDERS

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Abstract. *The Homogeneous Charge Compression Ignition (HCCI) is an alternative combustion concept which provides high efficiency and low emission levels. Due to these advantages, HCCI has been object of several studies. HCCI shows also great potential when using renewable fuels such as ethanol, which offers the benefit of being a renewable fuel with high knock resistance. This paper presents the construction process of a computational model of an HCCI engine, validated with experimental tests that provided results of heat release, energy efficiency and a thorough combustion analysis. For this analysis, a GT-Power TPA (three pressure analysis) template has been used to post-processing data from the experiments. A three-cylinder four-stroke engine originally fueled with diesel was used. The diesel injection system in one of the cylinders was replaced by an ethanol electronic fuel injection. Inlet heat for achieving HCCI was provided by complete exhaust recycling from one of the diesel cylinders. Stable HCCI combustion was achieved on the ethanol cylinder, with very low cycle-to-cycle combustion variation and similar indicated efficiency as of the original diesel engine.*

Keywords: *Engine, HCCI, Renewable source, Hydrous ethanol, EGR.*

1. INTRODUCTION

In a report released in 2007 for the IPCC (2014) (Intergovernmental Panel on Climate Change), it was stated that from 1970 to 2004 there was an increase in 70% of greenhouse gases, mostly caused by fossil fuel combustion. The rising energy demand in the last decades and the conclusion that oil reserves will still last a long time lead to increased concern regarding climate change. The WWF (2014) (World Wildlife Fund) says the climate changes arising by the high level of carbon emissions could increase the likelihood of dramatic events such as storms, heat waves and floods. In this world scenario, the use of renewable sources are a necessity for economic development (Bronzatti and Iarozinski, 2008), and biofuels are seen as the most promising hope for reducing emissions and bring economic benefits to the rural sector. Meanwhile, Brazil and USA are together responsible for 90% of ethanol production in the world (Rosegrant, *et al*., 2008). The geographic location of Brazil favors the production of sugar cane, and that enabled the country to pioneer the use of ethanol for mobility (Feijó and Alvim, 2010).

Governmental actions such as the PROALCOOL program (National Program of Alcohol), implemented in 1975, enabled 11% reduction in CO_2 emissions (Tolmasquim, *et al*., 2007) since then. The law of biodiesel which came into effect in January 2005, in the *Plano Nacional de Agroenergia* (National Agro-Energy Plan, 2006), together with the Program of Incentives for Innovation and Densification of the Productive Chain of Motor Vehicles (INOVAR-Auto), and other recent regulations promote the use of biofuels. Hence, the use of ethanol can be regarded as inevitable, due to its good technical and environmental performance, the increasing price of gasoline and CO_2 emissions mitigation policies (Vianna, *et al*., 2009).

One of the main advantages of ethanol is the high knock resistance that makes possible higher compression ratios without knock occurrence. Although with 37% lower calorific value than gasoline (Ministry of Mines and Energy, 2014), the specific fuel consumption of ethanol is only 20% higher (Sousa and Vianna, 1998). When used in internal combustion engines, its higher latent heat of vaporization cools the inlet air allowing a greater amount of mass inducted and higher volumetric effciency. It also has higher laminar flame speed and wider flammable limits, being able to operate with very lean or diluted mixtures.

In view of the promising future of ethanol and its advantages, it is necessary to further investigate its performance with regards to emissions and economy. The high ethanol price is a challenge for small producers. It is only profitable when its price is up to 70% of gasoline (Lima, 2011). The closer to its azeotropic blend (95.6% ethanol in water), the greater the energy demand in production. The production cost increases linearly to distillate from 0% up to 80% of ethanol in water. After that point the cost increases exponentially (Mack, *et al*., 2009; Martinez-Frias, *et al*., 2007). Thus, higher water content results in direct savings (Saxena, *et al*., 2012). According to Humphrey and Selbert (1992) the separation processes such as distillation, extraction and absorption are responsible for 43% of energy demand for chemical processing industries. In recent studies, a 1.9L turbocharged direct injection 4-cylinder HCCI engine (Homogeneous charge compression ignition), running with hydrated ethanol (40% water content), had a stable operation. Emissions wise, it was found that the higher the water content, the higher hydrocarbon and CO emissions. On the other hand, NO_x emissions reduced to very low levels (Mack, *et al*., 2009). Musin *et al*. (2013), studied the combustion performance in a SI engine. It was found that there was an increase in specific consumption and reduction in the indicated efficiency when water content varied from 20% to 40%. Even though, HC and CO emission increased and NO_x emission reduced by 80%.

The influence of water injection in the intake manifold was studied by Cristensen and Johansson (1999), in an engine running in HCCI mode. Controlling intake air temperature made possible to control ignition timing. The range of operation without knock was increased with lower cylinder temperatures. HC and CO emissions increased while NO_x had a significantly reduction.

Tests in a diesel engine carried out by Idaho University in partnership with RAI (Automotive Resources, Inc.) evaluated the use of catalytic igniters to burn high water content ethanol. A new PFI injection system was developed to run is SI mode with 30% of water in ethanol. Reduction in HC and NO_x emissions were found due to lower temperatures.

Saxena *et al*. (2014) studied the operation of a generator set with HCCI combustion using hydrous ethanol. Blends of up to 30% water in ethanol were tested for a fixed engine speed of 1800 RPM, reaching optimum combustion phasing with the 50% mass fraction burned point happening close to 8° ATDC.

Thus, this study aims at evaluating the potential of HCCI combustion for using low grade ethanol fuel, i.e., hydrous ethanol with high water content. The engine used was a 3-cylinder generator set with 2.942 L, compression ratio of 16.6:1, originally running on Diesel. This engine had one of the cylinders converted to ethanol with a throttle body and a Megasquirt electronic controlled port-fuel injection. New intake and exhaust runners were fabricated and installed. The middle cylinder (number 2) was used as the intake air heater and EGR generator for inducing ethanol HCCI on cylinder one.

Table 1. Engine parameters before and after modifications

	Original	**Modified**	
Engine Brand/Model	MWM D229-3		
Cylinder number	3	2	1
Ignition	Compression Ignition	Compression Ignition	HCCI
Fuel	Diesel	Diesel	Hydrous Ethanol
Injection System	Direct Injection	Direct Injection	Port Fuel Injection
Cooling	Water-cooled		
Bore (mm)	102		
Stroke (mm)	120		
Rod Length (mm)	207		
Compression Ratio	16.6		
Swept Volume (dm^3)	2.941		

2. METHODOLOGY

One of the ways to achieve HCCI is by increasing charge temperature either by intake air heating or by hot EGR induction. Thus, two EGR routes were installed. One of them was recycling exhaust gases from the ethanol cylinder (cylinder 1) itself. A secondary route was recycling exhaust gases from the diesel cylinders 2 and 3. Especially the latter is able to supply hot air because the diesel cylinder works with very lean mixture at low loads. In other words, it works as a hot air supply more than EGR supply (figure 1).

A computational model of this engine was made with the simulation software GTPOWER. This was done in order to perform heat release analysis and to provide calculated values of data that is often difficult to obtain experimentally. Heat release analysis was performed with the TPA template (Three Pressures Analysis), which requires crank angle resolved data of in-cylinder pressure, as well as intake and exhaust pressures, all experimentally acquired. The inlet and exhaust temperatures were also be measured and inserted in the model.

For the acquisition of these data, pressure sensors were installed in the combustion chamber of cylinder 1 as well as on intake and exhaust runners. For measuring the temperatures, a set of K type thermocouples were used. Data acquisition was performed with a National Instruments board and Labview software.

In-cylinder pressure data was acquired on a crank angle degree basis, synchronized with a 0.1 degree resolution encoder installed on the crankshaft. In order to control fueling and air-fuel ratio, a FuelTech^{R} lambda meter was installed in the exhaust runner.

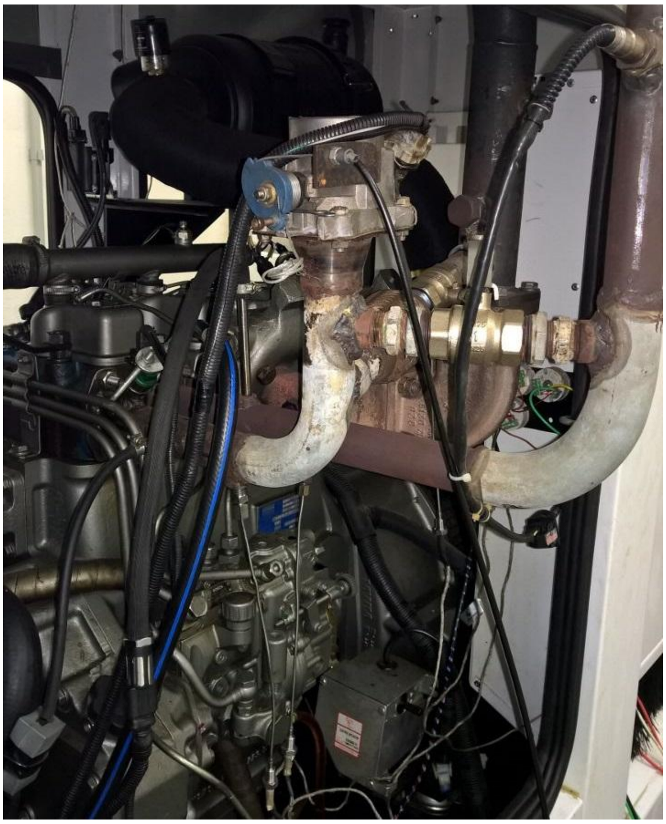

Figure 1. Engine setup

Since the engine was part of a generator set, the speed was always constant at 1800 rpm. The control was executed by the diesel controller that would always compensate diesel quantities as necessary. Load was applied by switching resistance wires immersed in water.

Before ever test, the engine was warmed up running only with diesel on the diesel cylinders.

After that, for each blend, ethanol injection was turned on and pulse with progressively increased until auto-ignition and stable combustion would take place on cylinder 1. Data was recorded for each test point, with fueling progressively increased until the knock threshold was reached or maximum rate of pressure rise was achieved.

Fuel consumption was measured with a volumetric burette set for timing the consumption of batches of 30ml each. The pressure data was an average of 200 engine cycles. Tests were conducted for blends of of 8%, 20%, 25%, 30% of water in ethanol, with a fixed total electric power generation of 10kW.

A logical representation of the computer model, peformed with GT-POWER, is shown in figure 2.

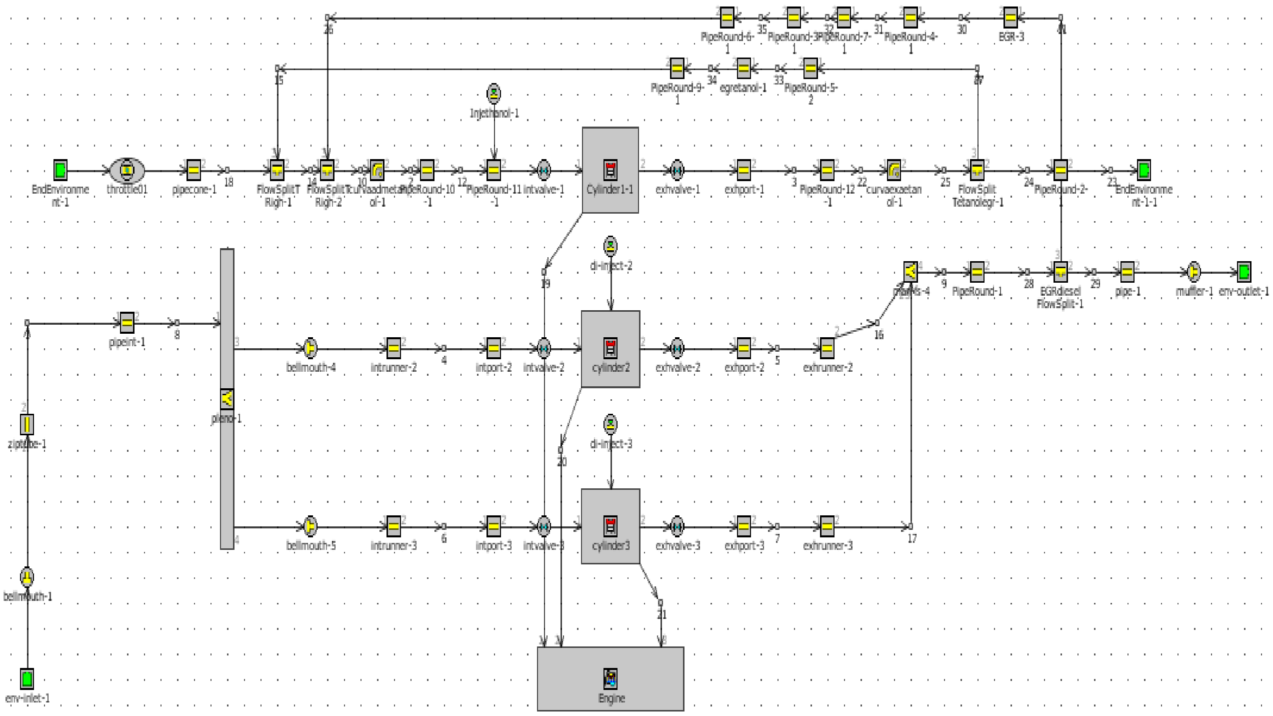

Figure 2. Computational model in software GTPOWER

3. RESULTS AND DISCUSSION

Table 2 shows the parameters found for each water content in ethanol. As fueling was increased, the throttle had to be closed to promote more EGR suction from the EGR pipes and thus increase intake temperatures to promote auto-ignition.

Table 2. Parameters for each water content in ethanol.

% H2O	Lambda	% EGR	Throttle Position (%)	Intake Temperature (°C)
8	1,75	40,60	71	91
20	1,08	46,13	38	177
25	1,09	42,72	42	128
30	0,98	60,59	27,8	170

The indicated mean effective pressure (IMEP) values of the cylinder running with hydrous ethanol compared with cylinder running with diesel are shown in figure 3.

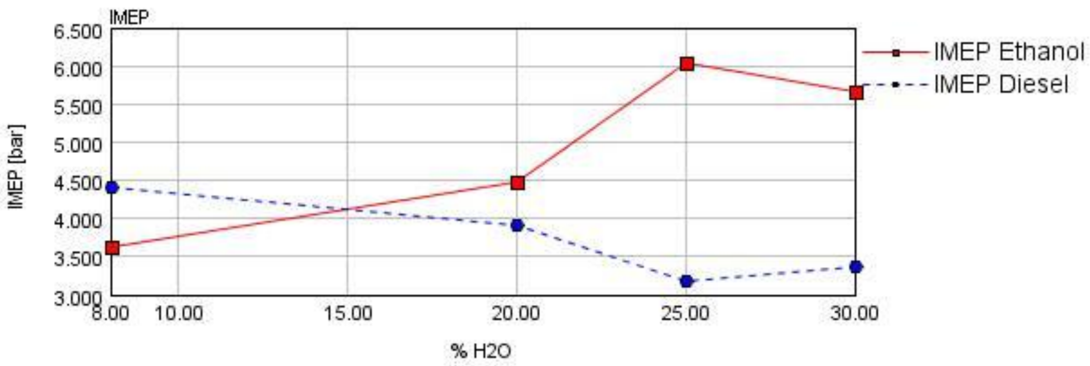

Figure 3. IMEP versus % H2O

As higher the water concentration in ethanol, higher was be the IMEP. Evaporation is an endothermic process, thus higher water concentrations produced lower in-cylinder temperatures due to the higher specific heat of water, allowing the injection of larger amounts of fuel.

Since the power required was constant (10kWe), the cylinders running with diesel had to compensate the lack or excess power in the cylinder running with wet ethanol by having the fueling rate adjusted by the diesel controller so as to keep constant 1800rpm speed. That means that when IMEP is low in the ethanol cylinder, it will be higher in the diesel cylinders.

Also, as Figure 4 shows, as ethanol fueling increased, despite of the greater concentrations of water, the rate of pressure rise increased accordingly up to a maximum of 17,5 bar/°CA.

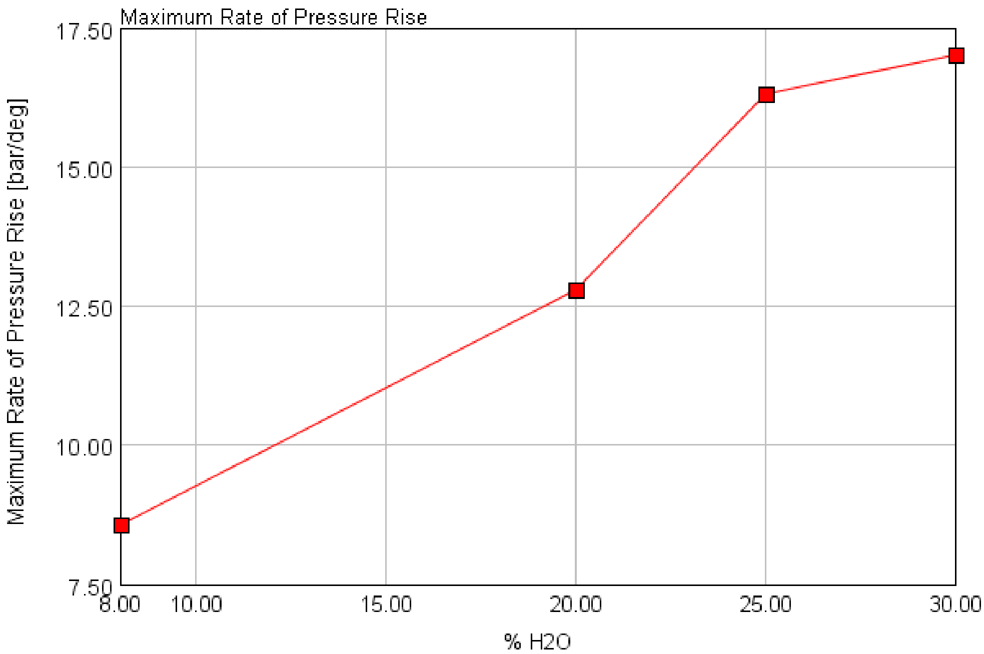

Figure 4. dP/dθ versus %H2O

With the increase of water content in the fuel there is an increase in total combustion duration, as illustrated by Figure 5.

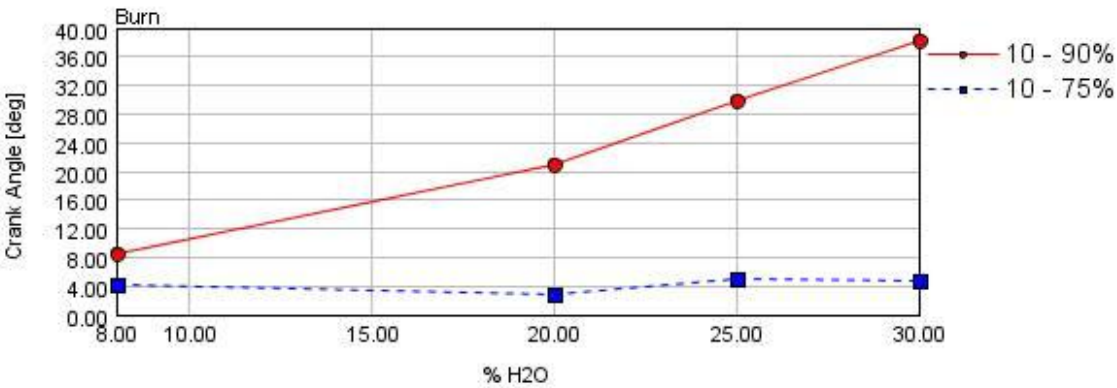

Figure 5. Combustion duration versus %H2O

This increase in combustion duration is due to the higher latent heat of evaporation of water, which tends to lower combustion speeds. However, this effect is more pronounced towards the end of combustion since the middle section of combustion duration was more or less constant during all tests, as seen by the 10-75% MFB curve. That seems to imply that ethanol burns and generates heat first, then it evaporates the remaining water.

The efficiency of both the ethanol and the diesel cylinders at the same IMEP values are shown in figure 6. It can be seen that the efficiency of the ethanol cylinder is higher with lower water concentrations, probably due to the higher amount of constant volume combustion produced by HCCI. As water concentrations go higher, the opposite happens to indicated efficiency. However, there seems to be a recovery of efficiency in both cases for higher loads. Is can be attributed to a probable better balance between heat losses and power.

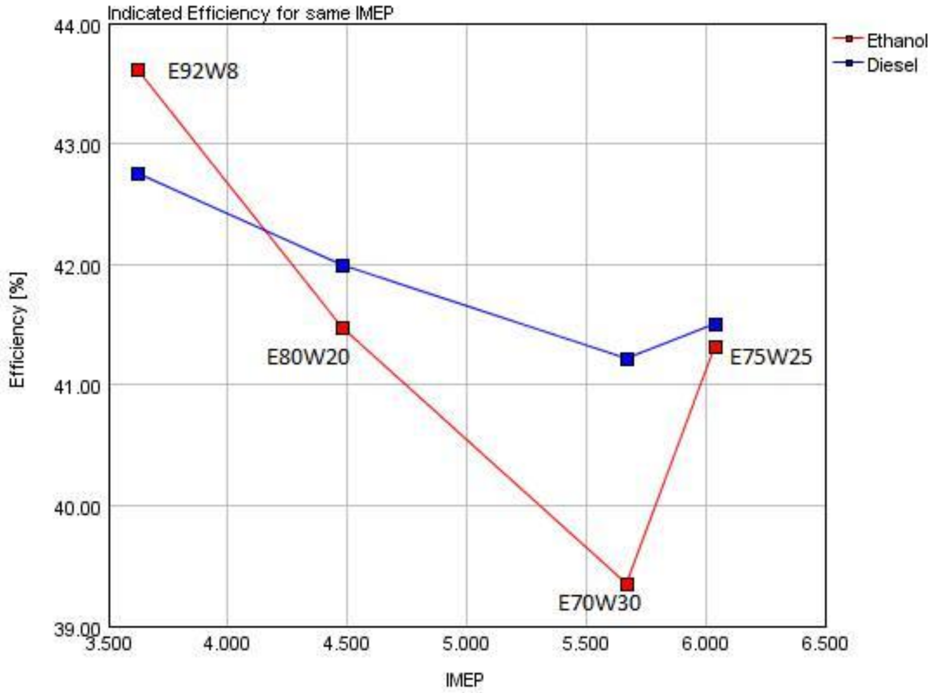

Figure 6. Efficiencies cylinder versus IMEP

The HCCI have a high velocity combustion, as figure 7 illustrates, with the heat release fraction for each blend. It is quite noticeable the very high combustion speeds for every blend, up to 70% mass fraction burned. That implies that the water addition does not change much combustion duration during this part and does not affect much its stability, as the COV values of less than 3.5 % tell. This characterizes a very stable and robust combustion (Figure 8).

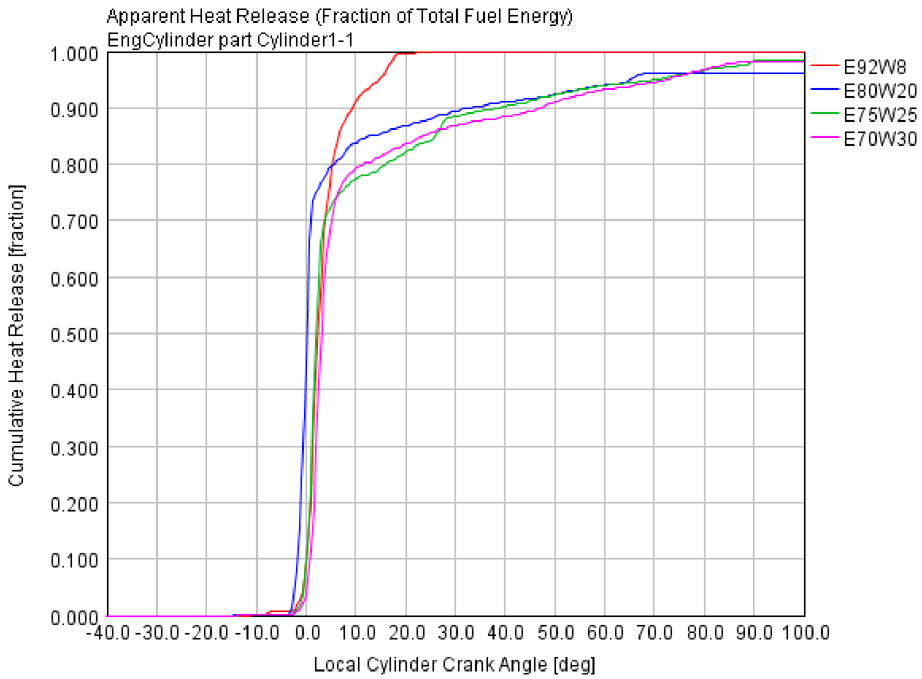

Figure 7. Cumulative heat release

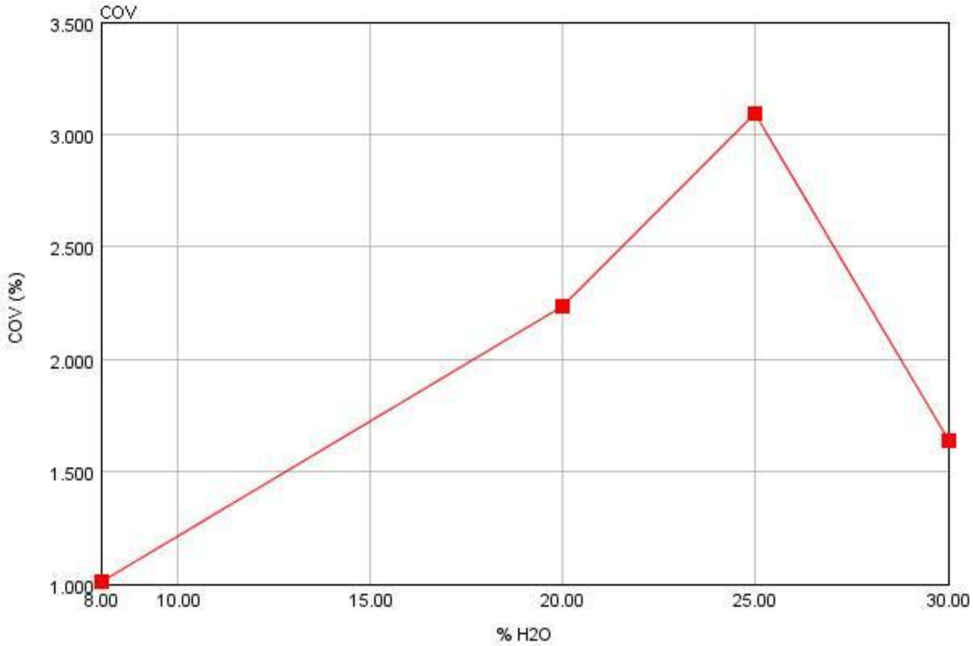

Figure 8. COV versus %H2O

Pressure wise, all blends were in the range of 70-80bar, not much different than the original diesel threshold. This implies that, stress wise, the engine was at a safe operation (figure 9).

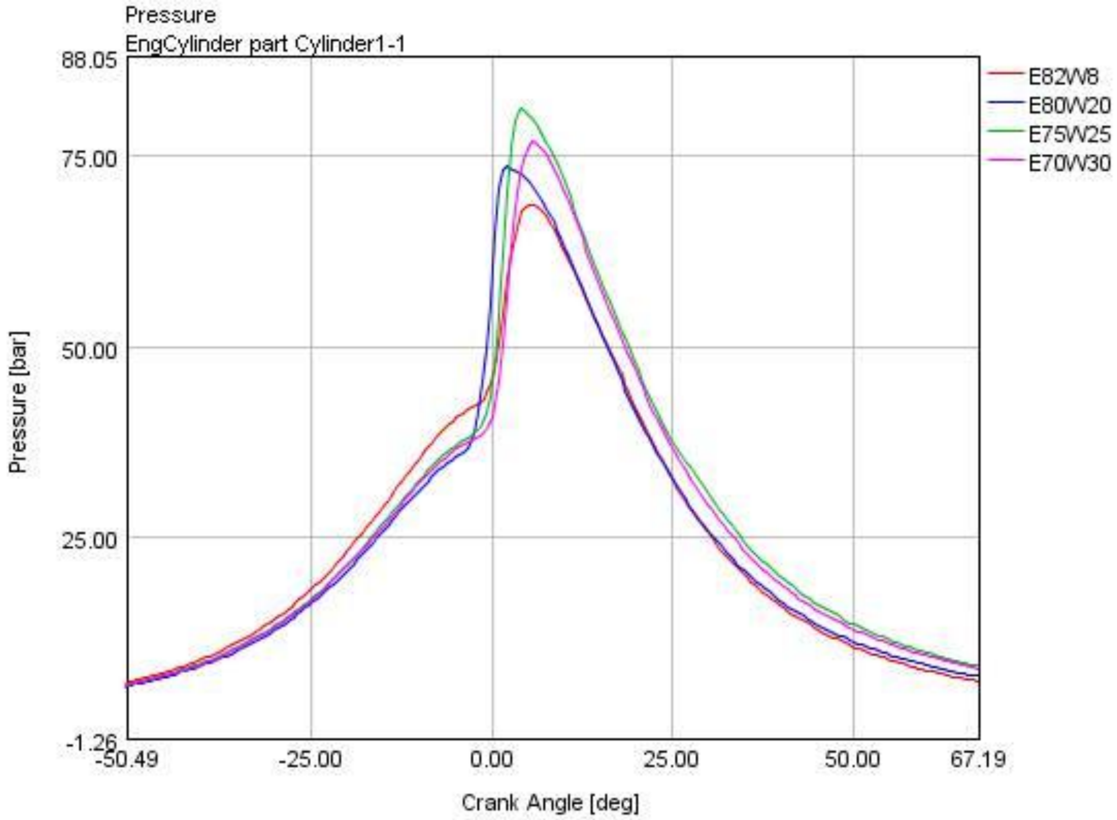

Figure 9. Cylinder Pressure versus crank angle

3.1 CONCLUSION

With this work it was verified that operating the engine with only one cylinder operation in HCCI mode and with high water content ethanol is possible without the need for major changes to the original engine. The use of an external heat source for heating the inlet gas was not necessary since the EGR from the diesel cylinder performed this function. Besides, with HCCI it is possible to use low grade fuels of otherwise difficult ignition, such as hydrous ethanol. The indicated efficiency when comparing the ethanol and diesel cylinder did not differ much, being possible to use ethanol and HCCI combustion without significant efficiency changes. This shows that using the arrangement of having a dedicated cylinder to induce HCCI on other cylinders is a viable solution for using low grade ethanol without significant engine changes.

Furthermore, the use of hydrous ethanol is advantageous because its production requires less energy and it becomes a low cost fuel. Although this study did not conducted emissions analysis, there is a large emissons reduction potential, which is one of the advantages of HCCI combustion.

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